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Wind energy generation systems – Part 24: Lightning protection

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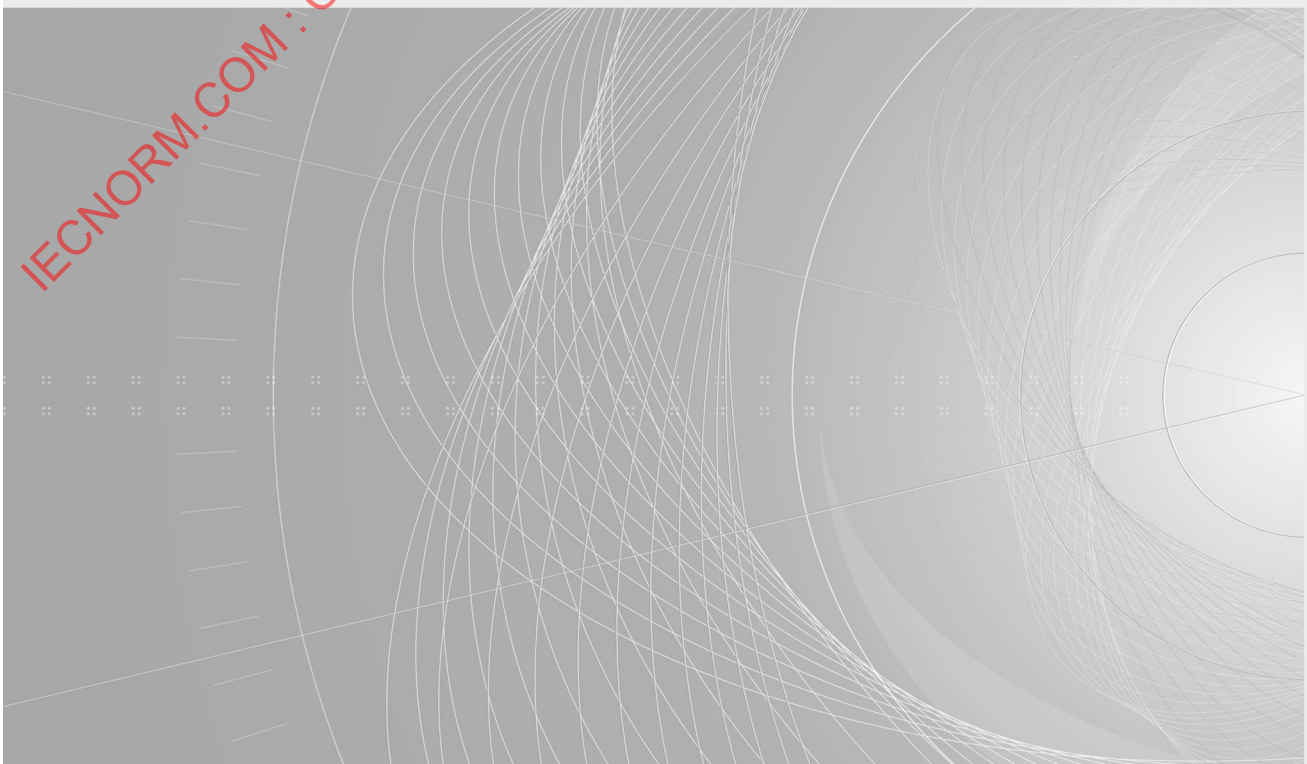

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WIND ENERGY GENERATION SYSTEMS –

Part 24: Lightning protection

FOREWORD

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IEC 61400-24 edition 2.1 contains the second edition (2019-07) [documents 88/709/FDIS and 88/713/RVD] and its amendment 1 (2024-11) [documents 88/1040/FDIS and 88/1054/RVD].

In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

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International Standard IEC 61400-24 has been prepared by IEC technical committee 88: Wind energy generation systems.

This second edition cancels and replaces the first edition, published in 2010. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) it is restructured with a main normative part, while informative information is placed in annexes.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

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- revised.

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INTRODUCTION to Amendment 1

This amendment to IEC 61400-24:2019 addresses an update of the content in Annex L regarding monitoring systems for detecting lightning strikes on wind turbines.

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WIND ENERGY GENERATION SYSTEMS –

Part 24: Lightning protection

1 Scope

This part of IEC 61400 applies to lightning protection of wind turbine generators and wind power systems. Refer to Annex M guidelines for small wind turbines.

This document defines the lightning environment for wind turbines and risk assessment for wind turbines in that environment. It defines requirements for protection of blades, other structural components and electrical and control systems against both direct and indirect effects of lightning. Test methods to validate compliance are included.

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

Guidance regarding personal safety is provided.

Guidelines for damage statistics and reporting are provided.

Normative references are made to generic standards for lightning protection, low-voltage systems and high-voltage systems for machinery and installations and electromagnetic compatibility (EMC).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60364-4-44, *Low-voltage electrical installations – Part 4-44: Protection for safety – Protection against voltage disturbances and electromagnetic disturbances*

IEC 60364-5-53, *Electrical installations of buildings – Part 5-53: Selection and erection of electrical equipment – Isolation, switching and control*

IEC 60364-5-54, *Low-voltage electrical installations – Part 5-54: Selection and erection of electrical equipment – Earthing arrangements and protective conductors*

IEC 60364-6, *Low-voltage electrical installations – Part 6: Verification*

IEC TS 60479-1, *Effects of current on human beings and livestock – Part 1: General aspects*

IEC TR 60479-4, *Effects of current on human beings and livestock – Part 4: Effects of lightning strokes*

IEC 60664-1, *Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests*

IEC 61000 (all parts), *Electromagnetic compatibility (EMC)*

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IEC 61000-4-5, *Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test*

IEC 61000-4-9, *Electromagnetic compatibility (EMC) – Part 4-9: Testing and measurement techniques – Impulse magnetic field immunity test*

IEC 61000-4-10, *Electromagnetic compatibility (EMC) – Part 4-10: Testing and measurement techniques – Damped oscillatory magnetic field immunity test*

IEC TR 61000-5-2, *Electromagnetic compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 2: Earthing and cabling*

IEC 61400-23, *Wind turbine generator systems – Part 23: Full-scale structural testing of rotor blades*

IEC 61587-3, *Mechanical structures for electronic equipment – Tests for IEC 60917 and IEC 60297 – Part 3: Electromagnetic shielding performance tests for cabinets and subracks*

IEC 61643-11, *Low-voltage surge protective devices – Part 11: Surge protective devices connected to low-voltage power distribution systems – Requirements and test methods*

IEC 61643-12, *Low-voltage surge protective devices – Part 12: Surge protective devices connected to low-voltage power distribution systems – Selection and application principles*

IEC 61643-21, *Low voltage surge protective devices – Part 21: Surge protective devices connected to telecommunications and signalling networks – Performance requirements and testing methods*

IEC 61643-22, *Low-voltage surge protective devices – Part 22: Surge protective devices connected to telecommunications and signalling networks – Selection and application principles*

IEC 61936-1, *Power installations exceeding 1 kV a.c. – Part 1: Common rules*

IEC TS 61936-2, *Power installations exceeding 1 kV a.c. and 1,5 kV d.c. – Part 2: d.c.*

IEC 62305-1:2010, *Protection against lightning – Part 1: General principles*

IEC 62305-2:2010, *Protection against lightning – Part 2: Risk management*

IEC 62305-3:2010, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC 62305-4:2010, *Protection against lightning – Part 4: Electrical and electronic systems within structures*

IECRE OD-501, *Type and Component Certification Scheme (wind turbines)*

ITU-T K.20, *Resistibility of telecommunication equipment installed in a telecommunications centre to overvoltages and overcurrents*

ITU-T K.21, *Resistibility of telecommunications equipment installed in customer premises to overvoltages and overcurrents*

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3 Terms and definitions

For the purposes of this document, the following terms and definitions apply. However, in general the definitions given in IEC 62305-1, IEC 62305-2, IEC 62305-3 and IEC 62305-4 will take precedence.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
air-termination system
part of an external LPS using metallic elements such as rods, mesh conductors or catenary wires intended to intercept lightning flashes

3.2
average steepness
maximum current of the impulse I divided by the front time of the impulse T_1

Note 1 to entry: See Definitions 3.2 and 3.4 and Figure A.3.

3.3
bonding bar
metal bar on which metal installations, external conductive parts, electric power lines, telecommunication lines and other cables can be bonded to an LPS

3.4
collection area
A_d
area of ground surface that has the same annual frequency of direct lightning flashes as the structure

3.5
connecting leader
lightning leader developing from a structure as a response to an external electric field imposed either by a charged cloud overhead or by a downward leader approaching the structure

3.6
conventional earthing impedance
ratio of the peak values of the earth-termination voltage and the earth-termination current that, in general, do not occur simultaneously

3.7
coordinated SPD system
SPDs properly selected, coordinated and installed to form a system intended to reduce failures of electrical and electronic systems

Note 1 to entry: Coordination of SPD protection includes the connecting circuits to provide insulation coordination of complete systems.

3.8
down-conductor system
part of an external LPS intended to conduct lightning current from the air-termination system to the earth-termination system

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3.9
downward flash
lightning flash initiated by a downward leader from cloud to earth

Note 1 to entry: A downward flash consists of a first impulse, which can be followed by subsequent impulses. One or more impulses may be followed by a long stroke.

3.10
earth electrode
part or a group of parts of the earth-termination system that provides direct electrical contact with and disperses the lightning current to the earth

3.11
earth-termination system
part of an external LPS that is intended to conduct and disperse lightning current into the earth

3.12
efficiency of a LPS
observed statistical number of strikes intercepted correctly (i.e. the interception efficiency) and conducted safely towards ground divided by the total number of strikes to the turbine/blade observed (in the field)

3.13
effectiveness of a LPS
observed statistical number of successful laboratory tests divided by the total number of laborarory tests

3.14
height
H
for a wind turbine, the highest point the blades reach, i.e. hub height plus rotor radius

3.15
external lightning protection system
part of the LPS consisting of an air-termination system, a down-conductor system and an earth-termination system

Note 1 to entry: The down conductor is often placed inside wind turbine blades.

3.16
flash charge
Q_{FLASH}
value resulting from the time integral of the lightning current for the entire lightning flash duration

3.17
front time
T_1
virtual parameter defined as 1,25 times the time interval between the instants when the 10 % and 90 % of the peak value are reached

Note 1 to entry: See Figure A.3.

3.18
foundation earth electrode
conductive part buried in the soil under a building foundation or, preferably, embedded in concrete of a building foundation, generally in form of a closed loop

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3.19
ground flash density
N_G
number of lightning flashes per square kilometre per year in the region where the structure is located

3.20
high voltage
voltage higher than 1,0 kV a.c. or higher than 1,5 kV d.c.

3.21
internal lightning protection system
part of the LPS consisting of lightning equipotential bonding and/or electrical insulation of external LPS

Note 1 to entry: Compliance with the separation distance and the reduction of the electromagnetic effects of lightning current within the structure to be protected may be considered as parts of an internal lightning protection system.

3.22
interception efficiency
probability with which the air-termination system of an LPS intercepts a lightning flash

3.23
leader connection point
place in the air gap between test object and HV electrode where positive and negative leaders meet and the discharge is initiated

3.24
lightning current
i
current flowing at the point of strike

3.25
lightning electromagnetic impulse
LEMP
all electromagnetic effects of lightning current via resistive, inductive and capacitive coupling that create surges and radiated electromagnetic fields

3.26
lightning equipotential bonding
EB
bonding to LPS of separated metallic parts by direct conductive connections or via surge protective devices to reduce potential differences caused by lightning current

3.27
lightning flash to a wind turbine
lightning flash to a structure
lightning flash striking a structure (wind turbine) to be protected

3.28
lightning flash to earth
electric discharge of atmospheric origin between cloud and earth consisting of one or more strokes

Note 1 to entry: A negative flash lowers negative charge from the thundercloud to the earth. A positive flash results in positive charge being transferred from the thundercloud to the earth.

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3.29
lightning protection level
LPL
number related to a set of lightning current parameter values relevant to the probability that the associated maximum and minimum design values will not be exceeded in naturally occurring lightning

Note 1 to entry: Lightning protection level is used to design protection measures according to the relevant set of lightning current parameters.

3.30
lightning protection system
LPS
complete system used to reduce physical damage due to lightning flashes to a structure

Note 1 to entry: It consists of both external and internal lightning protection systems but not measures taken to protect internal systems against the effects of LEMP.

3.31
lightning protection zone
LPZ
zone where the lightning electromagnetic environment is defined

Note 1 to entry: The zone boundaries of an LPZ are not necessarily physical boundaries (e.g. walls, floor and ceiling).

3.32
lightning stroke
single electrical discharge in a lightning flash to earth

3.33
line
power line or telecommunication line connected to the structure to be protected

3.34
long stroke
part of the lightning flash which corresponds to a continuing current

Note 1 to entry: The duration time T_{LONG} of this continuing current is typically more than 2 ms and less than 1 s (see Figure A.4).

3.35
magnetic shield
closed, metallic, grid-like or continuous screen enveloping the structure to be protected, or part of it, used to reduce failures of electrical and electronic systems

Note 1 to entry: The protection effect of a magnetic shield is achieved through attenuation of the magnetic field.

3.36
metal installations
extended metal items in the structure, which may form a path for lightning current, such as the nacelle bed plate, elevator guide rails and wires, ladders, platforms and interconnected reinforcing steel

3.37
multiple strokes
lightning flash consisting on average of 3 to 4 strokes, with typical time interval between them of about 50 ms

Note 1 to entry: Events having up to a few dozen strokes with intervals between them ranging from 10 ms to 250 ms have been reported.

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3.38
natural component of LPS
conductive component installed not specifically for lightning protection that can be used in addition to the LPS, or in some cases could provide the function of one or more parts of the LPS

Note 1 to entry: Examples of the use of this term include:

– natural air termination;
– natural down conductor;
– natural earthing electrode.

3.39
number of dangerous events due to flashes to a structure
N_D
expected average annual number of dangerous events due to lightning flashes to a structure

3.40
peak value
I
maximum value of the lightning current

3.41
point of strike
point where a lightning flash strikes the earth or a protruding structure (e.g. structure, LPS, line, tree)

Note 1 to entry: A lightning flash may have more than one point of strike.

3.42
receptor
form of air termination on wind turbine blades, for example discrete metal studs through the blade surface connected to a down conductor system

3.43
risk
R
probable average annual loss due to lightning, in a structure or in a considered zone of the structure

3.44
separation distance
necessary distance between a conductor carrying partial lightning current and other conductive parts to avoid dangerous sparking

3.45
personal safety distance
separation distance as defined in IEC 62305-3, as a minimum, to avoid uncontrolled flashovers to persons in the turbine

3.46
short stroke
part of the lightning flash that corresponds to an impulse current

Note 1 to entry: This current has a time T_2 to the half peak value on the tail typically less than 2 ms (see Figure A.3).

Note 2 to entry: For power lines, a suitable test current I_n is defined in the Class II test procedure of IEC 61643-11.

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3.47
specific energy
W/R
value resulting from time integral of the square of the lightning current for the entire flash duration

Note 1 to entry: It represents the energy dissipated by the lightning current in a unit resistance.

3.48
surge
transient created by LEMP that appears as an overvoltage and/or an overcurrent

Note 1 to entry: Surges caused by LEMP can arise from (partial) lightning currents, from induction effects in installation loops and as residual surges downstream of SPD.

Note 2 to entry: Surges can arise from other sources such as switching operations or fuses operating.

3.49
surge protection measures
SPM
measures taken to protect internal systems against the effects of LEMP

Note 1 to entry: This is part of the overall lightning protection.

3.50
surge protective device
SPD
device intended to limit transient overvoltages and divert surge currents; contains at least one nonlinear component

Note 1 to entry: An SPD is a complete assembly, having appropriate connecting means.

3.51
tolerable risk
R_T
maximum value of the risk that can be tolerated for the structure to be protected

3.52
upward flash
lightning flash initiated by an upward leader from an earthed structure to cloud

Note 1 to entry: An upward flash consists of a first long stroke with or without multiple superimposed impulses. One or more impulses may be followed by a long stroke.

3.53
voltage protection level
U_P
maximum voltage to be expected at the SPD terminals due to an impulse stress with defined voltage steepness and an impulse stress with a discharge current with given amplitude and waveshape

Note 1 to entry: The voltage protection level is given by the manufacturer and may not be exceeded by:

– the measured limiting voltage, determined for front-of-wave sparkover (if applicable) and the measured limiting voltage, determined from the residual voltage measurements at amplitudes up to I_n and/or I_{imp} respectively for test classes II and/or I;

– the measured limiting voltage determined for the combination wave measurements up to U_{oc} for test class III.

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4 Symbols and units

A_D	Collection area of lightning flashes to an isolated structure
A_{Deff}	Effective collection area of flashes to an isolated structure using effective height
A_{DWF}	Collection area of lightning flashes to a wind farm
A_L	Collection area of lightning flashes to a service line
A_I	Collection area of lightning flashes near a service line
A_M	Area of influence for lightning flashes near a structure
C_S	Latent heat of melting
C_t	Total value of structure in currency
C_W	Thermal capacity
C	Mean value of possible loss
C_E	Environmental factor
C_D	Location factor
C_{DWL}	Location factor due to winter lightning activity
C_{DC}	Location factor due to complexity of local terrain
C_{DH}	Location factor due the height above sea level
C_T	Correction factor for an HV/LV transformer on the service line
D_{1D}	Electric shock resulting from direct strike to human beings
D_{1T}	Electric shock to human beings resulting from resistive and inductive coupling
D_2	Dangerous sparking triggering fire or explosion
D_3	Surges due to all sources of damage
H	Height of the wind turbine
H_{eff}	Height of the wind turbine including local terrain variations
h_z	Factor increasing the loss when a special hazard is present
i	Current
I	Peak current
I_n	Nominal test current; discharge current
I_t	Current in cable shield
I_{imp}	Impulse test current
IC	Intra cloud lightning
di/dt	Time derivative of current, average steepness
$di/dt_{30/90\ \%}$	Current steepness between points of 30 % and 90 % peak amplitude on front
L_{AD}	Loss related to injury to human beings by electric shock resulting from direct strike to those human beings (flashes to structure)
L_{AT}	Loss related to injury to human beings by electric shock resulting from resistive and inductive coupling (flashes to structure)
L_B	Loss related to physical damage to a structure (flashes to structure)
L_C	Loss related to failure of internal systems (flashes to structure)
L_D	Typical mean ratio of persons injured by direct lightning stroke relative to the total number of persons exposed in the zone, due to one dangerous event
L_{F1}	Typical mean ratio of persons injured by fire or explosion relative to the total number of persons in the zone, due to one dangerous event

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L_{F2}	Typical mean ratio of physical damage of social relevance by fire or explosion relative to the maximum amount of damage of social relevance in the zone, due to one dangerous event
L_M	Loss related to failure of internal systems (lightning flashes near structure)
L_O	Typical mean ratio of persons injured by failure of internal systems relative to the total number of persons in the zone, due to one dangerous event
L_T	Typical mean ratio of persons injured by touch and step voltages relative to the total number of persons in the zone, due to one dangerous event
L_{UT}	Loss related to injury to human beings by electric shock resulting from resistive and inductive coupling (flashes to line)
L_V	Loss related to physical damage to a structure (flashes to line)
L_W	Loss related to failure of internal systems (flashes to line)
L_X	Loss consequent to damages
L_Z	Loss related to failure of internal systems (flashes near a line)
L_1	Injury to living beings
L_2	Physical damage to the structure and its content
L_3	Failure of electrical and electronic systems
N_D	Number of dangerous events due to lightning flashes to a structure per annum
N_X	Number of dangerous events per annum
N_d	Number of dangerous events due to flashes to structure
N_M	Number of dangerous events due to flashes near a structure
N_L	Number of dangerous events due to flashes near a line
N_L	Number of dangerous events due to flashes to a line
$N_{d,x}$	Number of lightning flashes to a structure at the "x" end of a line per annum
N_G	Annual lightning ground flash density
$N_{G\ LLS}$	Ground flash density obtained from lightning location system
$N_{G\ corrected}$	Corrected ground flash density obtained from lightning location system
N_{SG}	Annual lightning ground strike-point density
N_t	Total (ground CG + cloud IC) density of optical flashes per annum
P_{AT}	Probability that a flash to a structure will cause dangerous touch and step voltage
P_{AD}	Probability that a flash to a structure will strike a person
P_B	Probability of physical damage to a structure (flashes to a structure)
P_C	Probability of failure of internal systems (flashes to a structure)
P_{LD}	Probability that lightning flashes to a service line will cause failure of internal systems
P_{LI}	Probability that lightning flashes near a service line will cause failure of internal systems
P_M	Probability of failure of internal systems (flashes near a structure)
P_{SPD}	Probability that an apparatus will be damaged, in spite of protection by a coordinated SPD system
P_U	Probability of injury to human beings by electric shock (flashes to a connected line)
P_V	Probability of physical damage to a structure Probability of failure of internal systems (flashes to connected line)

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P_W	Probability of failure of internal systems (flashes to connected line)
P_X	Probability of damage
P_Z	Probability of failure of internal systems (flashes near a connected line)
r_t	Reduction factor associated with the type of surface soil
r_f	Factor reducing the loss due to physical damage depending on the risk of fire
r_p	Factor reducing the loss due to physical damage depending on provisions taken
R	Risk
r	Rolling sphere radius
R_S	Cable shield resistance per unit length
R_T	Tolerable risk
R_X	Risk component for a structure
S	Spacing between earth rods
T_p	Time in hours per annum in which persons are present in a dangerous place
t or T	Time
Δt	Time interval
T_X	Time parameter
t_{long}	Time duration of long stroke
u_a, u_c	Anode or cathode voltage drop
U_C	Voltage between shield and wires of cable
U_W	Impulse withstand voltage
U_p	Voltage protection level
Q	Charge of the lightning current
Q_{flash}	Flash charge
Q_{short}	Short stroke charge
Q_{long}	Long stroke charge
W/R	Specific energy
Z_T	Transfer impedance
α	Temperature coefficient of the resistance (1/K)
γ	Material density
μ_0	Permeability of air (vacuum)
Φ	Magnetic flux
ρ	Resistivity
ρ_0	Specific ohmic resistance at ambient temperature
Θ	Temperature
Θ_0	Start temperature
Θ_s	Melting temperature
Θ_u	Ambient temperature
A	Ampere
C	Coulomb
°C	Degrees Celsius
H	Henry

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K	Kelvin
S	Siemens
g	Gram
Hz	Hertz
J	Joule
m	Metre
Ω	Ohm
s	Second
V	Volt
Wb	Weber
W	Watt

5 Abbreviated terms

AC	alternating current
CFRP	carbon fibre reinforced plastic
CG	cloud to ground lightning
DE	detection efficiency
EB	lightning equipotential bonding
EGM	electro geometrical model
EMC	electromagnetic compatibility
GFRP	glass fibre reinforced plastic
IC	intra-cloud lightning
LEMP	lightning electromagnetic impulse
LLS	lightning location system
LPE	lightning protection environment
LPL	lightning protection level
LPS	lightning protection system
LPZ	lightning protection zone
LV	low voltage
HV	high voltage
OCPD	overcurrent protection device
PE	protective earth
QA	quality assurance system
SCIG	squirrel cage induction generator
SEMP	switching electromagnetic impulse
SPD	surge protective device
SPM	surge protection measures
WRIG	wound rotor induction generator
WTG	wind turbine generator

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6 Lightning environment for wind turbine

6.1 General

The lightning environment for wind turbines in terms of lightning current parameter values to be used for dimensioning, analysis and testing of the lightning protection systems is defined in IEC 62305-1.

An informative discussion of the lightning phenomenon in relation to wind turbines is included in Annex A.

6.2 Lightning current parameters and lightning protection levels (LPL)

In IEC 62305-1, four lightning protection levels (I to IV) are introduced. For each LPL, a set of maximum and minimum lightning current parameters is fixed.

The maximum values of lightning current parameters relevant to LPL I will not be exceeded with a probability of 99 %. The maximum values of lightning current parameters relevant to LPL I are reduced to 75 % for LPL II and to 50 % for LPL III and IV (linear for I, Q and di/dt, but quadratic for W/R). The time parameters are unchanged.

Table 1 – Maximum values of lightning parameters according to LPL (adapted from IEC 62305-1)

Current parameters		Symbol	Unit	LPL			
				I	II	III	IV
First positive short stroke	Peak current	I	kA	200	150	100	
	Charge	Q_{SHORT}	C	100	75	50	
	Specific energy	W/R	MJ / Ω	10	5,6	2,5	
	Time parameters	T_1 / T_2	µs / µs	10/350			
First negative short stroke [a]	Peak current	I	kA	100	75	50	
	Average steepness	di/dt	kA / µs	100	75	50	
	Time parameters	T_1 / T_2	µs / µs	1/200			
Subsequent short stroke	Peak current	I	kA	50	37,5	25	
	Average steepness	di/dt	kA / µs	200	150	100	
	Time parameters	T_1 / T_2	µs / µs	0,25 / 100			
Long stroke	Charge	Q_{LONG}	C	200	150	100	
	Time parameter	T_{LONG}	s	0,5			
Flash	Charge	Q_{FLASH}	C	300	225	150	

[a] First negative stroke concerns only calculations and not testing.

The maximum values of lightning current parameters for the different lightning protection levels are given in Table 1 and are used to design lightning protection components (e.g. cross-section of conductors, thickness of metal sheets, current loading capability of SPDs, separation against dangerous sparking) and to define test parameters simulating the effects of lightning on such components (see Annex D and IEC 62305-1).

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For wind turbines placed in certain geographical areas where they are exposed to high numbers of upward lightning, particularly during winter, it may be relevant to increase the required durability of air termination systems (e.g. receptors) with regard to flash charge to more than lightning protection level I, Q_{flash} = 300 C, as this parameter decides the wear (melting) of materials and therefore influences the need for maintenance of air termination systems, spark gaps etc. (i.e. components subject to erosion due to arcing). In locations exposed to winter lightning, charge levels may reach Q_{flash} = 600 C due to upward winter lightning. In addition, the exposure and thereby the number of incidents between maintenance needs to be considered (see Clause 7 and Annex B for further information. Table D.2 provides test current parameters for winter lightning).

Although derived for application for lightning protection on land, the lightning parameters given in Table 1 shall also be used for offshore wind turbines, as there is no evidence of lightning parameters being significantly different offshore.

NOTE 1 Protection against lightning whose maximum and minimum exceed those relevant to LPL I needs more efficient measures, which can be selected on an individual basis but always following this document (in terms of design guidance and tests).

NOTE 2 Cigré Brochure 549, Lightning Parameters for Engineering Applications, 2013, provides information about upward lightning [1][1].

NOTE 3 The statistical basis for the 600C representing the 99 percentile of the charge in upward winter lightning is available in [2].

The minimum values of lightning current amplitude for the different LPLs are used to derive the rolling sphere radius in order to define the lightning protection zone LPZ θ_B, which is not exposed to lightning attachment. The minimum values of lightning current parameters together with the related rolling sphere radius are given in Table 2. They are used for positioning of the air termination system and to define the lightning protection zone LPZ θ_B.

Table 2 – Minimum values of lightning parameters and related rolling sphere radius corresponding to LPL (adapted from IEC 62305-1)

Interception criteria			LPL			
	Symbol	Unit	I	II	III	IV
Minimum peak current	I	kA	3	5	10	16
Rolling sphere radius	r	m	20	30	45	60

7 Lightning exposure assessment

7.1 General

Lightning exposure assessment is used to determine two things:

1) The LPL necessary for the particular exposure, defining the maximum design requirement and test levels for the verification tests in Annex D.
2) The annual occurrence of lightning events used to define the required lifetime of wearing components and subsystems. The expected impact (occurrence and severity) shall be aligned with inspection, maintenance and replacement intervals.

If LPL I is chosen for the design by default, the risk exposure assessment does not need to include this part. Only the assessment of annual exposure for the turbine and site and the risk of injury to living beings shall be conducted and documented. Refer to Annex K for guidance on classification of lightning damage based on risk management.

[1] Figures in square brackets refer to the Bibliography.

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Wind turbines are tall structures and are often placed in such a way that they are very exposed to lightning. It has long been recognised that wind turbines generally need to be protected against lightning as a precaution against economical losses due to damage and loss of revenue, as protection against hazards to living beings (primarily service personnel) and as a means to reduce the maintenance required.

The design of any lightning protection system shall take into account the risk of lightning flashes striking and/or damaging the structure in question. Lightning damage to an unprotected wind turbine can take the form of damage to the blades, to the mechanical parts and to the electrical and control systems. Furthermore, people in and around wind turbines are exposed to hazards from step/touch voltages or explosions and fires caused by a lightning flash.

The goal of any lightning protection system is to reduce the hazards to a tolerable level R_T. The tolerable level is based on an acceptable risk if human safety is involved. If the risk is below the level acceptable for humans then the need for further protection may be based on a purely economic analysis, which is done by assessing the cost of the lightning protection system against the cost of the damage it will prevent over a certain period.

It is the responsibility of the authority having jurisdiction to identify the value of tolerable risk. A representative value of tolerable risk R_T, where lightning flashes may cause risk of loss of human life or permanent injuries is 10^{-5} year^{-1}.

NOTE 1 Values for tolerable risk are given in IEC 62305-2.

The risk of lightning flashes attaching to any structure is a function of structure height, the local topography and the local level of lightning activity. Risks associated with lightning can be assessed in detail in accordance with IEC 62305-2.

Assessing the frequency of lightning, as described in 7.2 follows the principles described in IEC 62035-2.

Lightning risk predictions require the estimation of lightning flashes to or near wind turbines and their service lines. During the last years, estimation of direct lightning flashes to wind turbines has been an object of discussion. The number of lightning flashes to wind turbines in a wind farm is difficult to predict because of the high influence of local topography together with local lightning activity. Moreover, wind turbines experience both downward and upward lightning in different percentages at different locations. A methodology used to estimate the total number of lightning flashes to the turbines of a wind farm as well as the percentage of upward flashes are described in Clause B.2.

Information about local lightning conditions should be collected whenever possible (for example at locations where upward lightning may pose a special threat, such as in mountains and in areas with winter lightning).

NOTE 2 Information about the worldwide occurrence of winter lightning is included in Annex B.

As a word of caution, such a risk assessment will never be more accurate than the information entered into the calculation, and furthermore, because the assessment is probabilistic, because lightning occurrence information is statistical averages, and because the lightning event in itself is stochastic in nature, the user should not expect very accurate short-term prediction of the number of lightning events for individual wind turbines or wind farms. However, a risk assessment does make it possible to evaluate the risk reduction achieved by applying lightning protection and will allow comparison of risks for different wind turbine projects. Further details are provided in Annex B.

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7.2 Assessing the frequency of lightning affecting a single wind turbine or a group of wind turbines

7.2.1 Categorization of lightning events

The average annual number of dangerous events that may endanger a wind turbine may be separated into:

N_D due to lightning flashes to the wind turbine [year^{-1}];

N_M due to lightning flashes near the wind turbine (within 350 m) [year^{-1}];

N_L due to lightning flashes to the service lines connecting the wind turbine, i.e. the power cable and the communication cable connecting the wind turbine [year^{-1}];

N_I due to lightning flashes near the service lines connecting the wind turbine, i.e. the power cable and the communication cable connecting the wind turbine [year^{-1}];

N_{DJ} due to lightning flashes to an adjacent wind turbine or another adjacent structure at the far end of the service lines connecting the wind turbine in question [year^{-1}].

7.2.2 Estimation of average number of lightning flashes to a single or a group of wind turbines

7.2.2.1 General

The effect of flashes with multiple ground strike-points is to double the values of lightning ground flash density N_G in accordance with IEC 62858 and hence:

$$N_{SG} = 2N_G \tag{1}$$

where

N_{SG} is the lightning ground strike-point density [km^{-2}·year^{-1}];

N_G is the lightning ground flash density [km^{-2}·year^{-1}].

NOTE Some lightning location systems LLS can directly give N_{SG}.

The average annual frequency of lightning flashes attaching to a wind turbine or a group of wind turbines can be assessed as:

$$N_D = N_{SG} \cdot A_D \cdot C_D \cdot 10^{-6} \tag{2}$$

Where

N_{SG} is the lightning ground strike-point density per km^2 per year;

A_D is the equivalent collection area of the structure [m^2];

C_D is the location factor of the structure.

NOTE In areas with isolated tall structures, a more accurate evaluation of N_D may be advisable. Further information may be provided by NCs.

A detailed description of each of the parameters composing Equation (2) is found in 7.2.2.3 and 7.2.2.4.

Before describing the different parameters, it is very important to note that, for complex environmental conditions, high prediction errors can occur because of increase in collection area (by means of effective height) or location factor. Guidelines on how to estimate the average number of lightning flashes can be found in Clause B.2.

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7.2.2.2 Annual average ground flash density N_G

When assessing the frequency of lightning flashes to a structure, the collection of data detailing the local ground flash density (N_G) is necessary.

NOTE 1 Particularly high and standalone structures can alter the lightning density at ground in their vicinity. The designer can investigate further with the LLS provider.

In areas without ground-based lightning location systems or lightning flash counters, the recommended estimate of ground flash density in temperate regions with limited accuracy is

$$N_G = 0{,}25 \cdot N_t \quad (3)$$

where N_t is the total (ground CG + cloud IC) density of optical flashes per km^2 per year, obtained through NASA's website [3].

NOTE 2 In most areas of the world, an indication of lightning activity can be obtained from observations of lightning optical transients. Satellite-based sensors respond to all types of lightning with relatively uniform coverage in all areas. With sufficient averaging, optical transient density data provide better estimates of ground flash density than thunder observations, which have a wide range of relations between ground flash density and thunderstorm hours or thunderstorm days. There are also regional variations in the ratio of ground flashes (CG) to total flashes (CG + IC).

Local ground flash density (N_G) with a higher accuracy can be obtained from Lightning Location System (LLS) data suppliers. When higher precision is required, it is necessary to correct local ground flash density (N_G) as:

$$N_{Gcorrected} = \frac{N_{G_{LLS}}}{DE} \quad (4)$$

where

$N_{Gcorrected}$ is the corrected annual average ground flash density considering detection efficiency of the LLS [km^{-2}·year^{-1}];

N_{GLLS} is the annual average ground flash or density obtained from the LLS [km^{-2}·year^{-1}];

DE is the flash or stroke detection efficiency per unit of the LLS-Network in the area of interest [p.u.].

NOTE 3 In general, long duration currents in upward lightning without any superimposed impulse currents are not detected by a typical LLS; only strokes in upward lightning with impulse currents can be detected by an LLS. Hence, detection efficiency from LLS for upward lightning generated by wind turbines is much lower than for downward lightning. Therefore, the ground flash or stroke density from LLS usually does not consider all upward lightning events.

NOTE 4 The detection efficiency, DE, can be discussed with the lightning location system data provider. A detection efficiency of one can be considered for a simple and low-precision estimation of this parameter.

NOTE 5 Further guidance on how to use lightning location systems for estimating lightning densities can be found in IEC 62858.

7.2.2.3 Collection area of a single wind turbine and a group of wind turbines A_D

The collection area of a structure is defined as an area of ground surface which has the same annual frequency of lightning ground flashes as the structure. For isolated structures, the equivalent collection area is the area enclosed with a borderline obtained from the intersection between the ground surface and a straight line with a 1:3 slope which passes from the upper parts of the structure (touching it there) and rotating around it.

It is recommended that all wind turbines are modelled as a tall mast with a height equal to the hub height plus one rotor radius. This is recommended for wind turbines with any type of blades including blades made solely from non-conductive material such as glass-fibre reinforced plastic.

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Figure 1 shows the collection area produced by a wind turbine placed on flat ground. Clearly this is a circle with a radius of three times the turbine height.

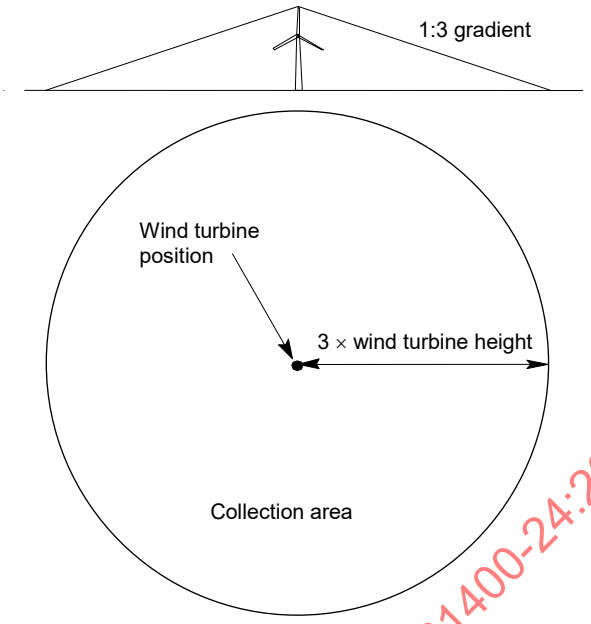

Figure 1 – Collection area of the wind turbine

The following Equation (5) can therefore be used when estimating the annual number of lightning flashes to a single wind turbine placed on flat ground (i.e. C_D = 1).

$$N_D = N_{SG} \cdot A_D \cdot C_D \cdot 10^{-6} = N_{SG} \cdot 9\pi \cdot H^2 \cdot 10^{-6} \quad (5)$$

where

H is the height of the wind turbine [m].

The collection area of a complete wind farm (A_{DWF}) should consider the overlap with neighbouring wind turbines. In such cases, the collection areas should simply be divided between the turbines where the 1:3 gradient lines from the top of the wind turbines intersect without taking into account height differences of the surrounding terrain. Figure 2 shows a general example of collection area for a wind farm composed of 10 wind turbines represented as points:

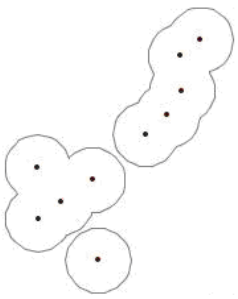

Figure 2 – Example of collection area for a complete wind farm (A_{DWF}) with 10 wind turbines (black points) considering overlapping

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7.2.2.4 Location factor C_D

Wind farms are located in different weather conditions and in different topographical regions. Wind farm location may have a high impact on the number of average annual lightning flashes to the wind turbines. Certain conditions lead to an increase of upward lightning being triggered from wind turbines or an increase of the number of downward lightning. The local topography of a mountain (mountain shape) and the height above sea level can have a high influence on the total number of lightning events during both warm and cold seasons. Moreover, winter lightning occurring during the cold season promotes the inception of upward lightning from tall structures. To estimate with higher accuracy the average annual frequency of lightning flashes attaching to a wind turbine or a group of wind turbines (N_D), it is recommended to increase the location factor to take into account the influence of local weather and topographical effects.

The three parameters mentioned previously (winter lightning activity, terrain complexity and effective height above sea level) are difficult to quantify and can vary significantly from site to site (see Annex B for further information). This is because winter thunderstorms have different features at different locations, and mountainous or hilly terrains can present multiple shapes and heights. Height above sea level where a wind farm is placed and cloud charge centre height can also have an influence during winter thunderstorms.

Wind farms placed offshore can also increase the average annual frequency of lightning flashes attaching to a wind turbine or a group of wind turbines (N_D), and it may be necessary to assign a higher location factor.

7.2.3 Estimation of average annual number of lightning flashes near the wind turbine (N_M)

Wind turbines may be endangered by lightning flashes near the wind turbine:

$$N_M = 0{,}5 \cdot N_{SG} \cdot A_M \cdot 10^{-6} \quad (6)$$

where

N_{SG} is the lightning ground strike-point density per km^2 per year;

A_M is the equivalent collection area of flashes striking near the structure (m^2).

The equivalent collection area A_M extends to a line located at a conventional distance of 350 m from the perimeter of the structure:

$$A_M = 350 \cdot 2 \cdot (L + W) + \pi \cdot 350^2 \quad (6.1)$$

When proper lightning protection is applied to a wind turbine and the service lines connecting it, it may be assumed that the protection also includes protection against damage to the wind turbine due to lightning flashes near the wind turbine and due to lightning flashes near service lines connecting the wind turbine.

NOTE N_M can be neglected for wind turbines with a total height of more than 100 metres. In this case, the conventional distance of 350 m is usually covered by direct strikes.

7.2.4 Estimation of average annual number of lightning flashes to the service lines connecting the wind turbines (N_L)

Large wind turbines are usually connected to a high-voltage power cable collection system and also usually connected to an external control centre via a communication line, both these service lines may be affected by lightning flashes to the service line or near to it (see Figure 3). In case the communication line is an optical fibre connection (which is recommended), the risk of lightning damaging the communication line may be neglected.

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The number of lightning flashes to a service line connecting a wind turbine can be assessed in accordance with IEC 62305-2, Annex A as:

$$N_L = N_{SG} \cdot A_L \cdot C_I \cdot C_E \cdot C_T \cdot 10^{-6} \quad (7)$$

where

N_L is the number of overvoltages of amplitude not lower than 1 kV (1/year) on the line section;

N_{SG} is the lightning ground strike-point density per km^2 per year;

A_L is the collection area of lightning flashes to the service line [m^2] – see Table 3;

C_I is the installation factor of the line: 1 for aerial, and 0,3 for buried (see IEC 62305-2 for more differentiated values of C_I);

C_E is the environmental factor: which is 1 for rural areas;

C_T is the line type factor.

The line type factor C_T = 1 if there is no transformer between the point of lightning attachment and the wind turbine, and C_T = 0,2 if there is. As there is usually a high-voltage transformer in large wind turbines, C_T = 0,2 can be assumed for the medium-voltage cables connecting the wind turbine to the grid (see IEC 62305-2).

NOTE N_L = 0 for submarine service lines (submarine high-voltage cables and communication cables).

7.2.5 Estimation of average annual number of lightning flashes near the service lines connecting the wind turbine (N_I)

The number of lightning flashes near a service line (i.e. close enough to affect the line) can be assessed as:

$$N_I = 0{,}5 \cdot N_{SG} \cdot A_I \cdot C_I \cdot C_E \cdot C_T \cdot 10^{-6} \quad (8)$$

where

N_I is the number of overvoltages of amplitude not lower than 1 kV (1/year) on the line section;

N_{SG} is the lightning ground strike-point density per km^2 per year

C_I is the installation factor of the line: 1 for aerial, and 0,3 for buried; see IEC 62305-2 for more differentiated values of C_I);

C_E is the environmental factor, which is 1 for rural areas;

C_T is the line type factor;

A_I is the collection area of lightning flashes near the service line [m^2] – see Table 3.

The line type factor C_T = 1 if there is no transformer between the point of lightning attachment and the wind turbine, and C_T = 0,2 if there is. As there is usually a high-voltage transformer in large wind turbines, C_T = 0,2 can be assumed for the medium-voltage cables connecting the wind turbine to the grid (see IEC 62305-2).

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Table 3 – Collection areas A_L and A_I of service line depending on whether aerial or buried

	Aerial	Buried
A_L	$(L_c - 3(H_a + H_b))\ 6\ H_c$	$L_c - 3(H_a + H_b)\sqrt{\rho}$
A_I	$1\ 000\ L_c$	$25\ L_c\sqrt{\rho}$
L_c	is the length of the service line from the wind turbine to the next structure on the line. A maximum value L_c = 1 000 m should be assumed [m].	
H_a	is the height of the wind turbine connected at the "a" end of the service line [m].	
H_b	is the height of the wind turbine (or other structure) connected at the "b" end of the service line [m].	
H_c	is the height of the service line conductors above ground [m].	
ρ	is the resistivity of the soil where the service line is buried [Ωm]. A maximum value ρ = 500 Ωm should be assumed.	

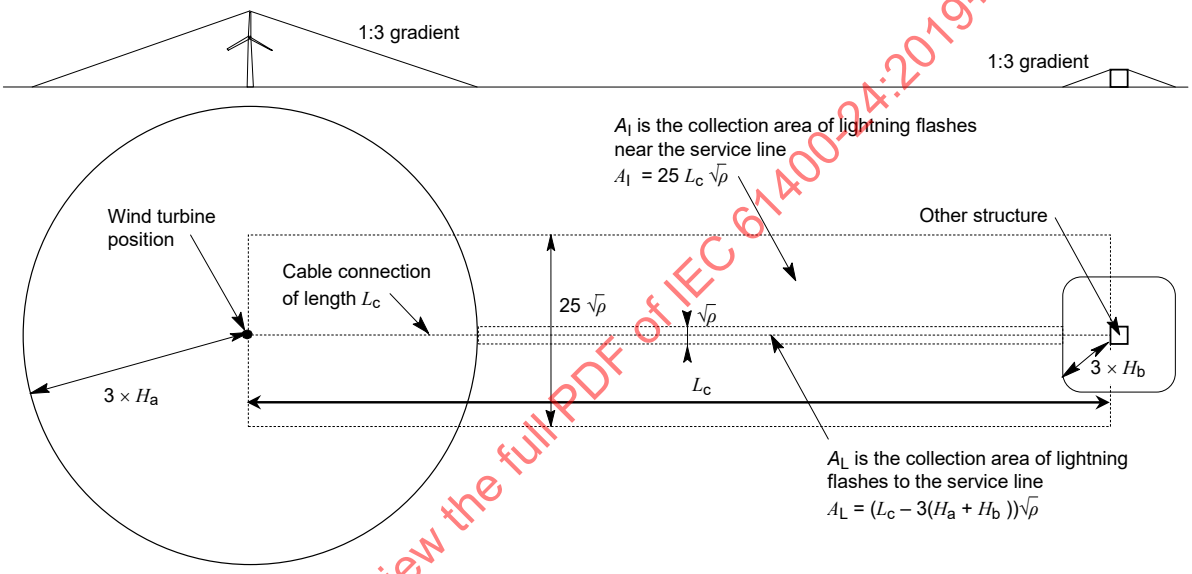

Figure 3 – Collection area of wind turbine of height H_a and another structure of height H_b connected by underground cable of length L_c

NOTE In wind farms, the collection areas of neighbouring wind turbines often overlap. In such cases, the collection areas can simply be divided between the turbines where the 1:3 gradient lines from the top of the wind turbines intersect.

7.3 Assessing the risk of damage

7.3.1 Basic equation

The risk of lightning causing damage to a wind turbine installation and thereby financial losses can be considered as the sum of many risk components. Each risk component may be expressed by the following general equation

$$R_X = N_X \cdot P_X \cdot L_X \quad (9)$$

where

R_x is the risk component for a structure (e.g. for the wind turbine);

N_x is the number of dangerous events per annum [year^{-1}];

P_x is the probability of damage;

L_x is the amount of consequent loss.

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This basic equation is to be used for assessing the risk of damage based on the probability of damage of various types and the consequent loss (see Annex B).

Protection against lightning is needed if the risk R is higher than the tolerable level R_T.

$$R > R_T \tag{10}$$

In this case, protection measures shall be adopted in order reduce the risk R to no more than the tolerable level R_T (i.e. $R \leq R_T$).

NOTE 1 The tolerable risk R_T can be stipulated by authorities or the manufacturer or be agreed between the manufacturer and the costumer.

NOTE 2 The risk components S1 to S4 can be evaluated for the specific project, either by the manufacturer, by the customer or by the two in cooperation.

7.3.2 Assessment of risk components due to flashes to the wind turbine (S1)

For evaluation of risk components related to lightning flashes to the wind turbine, the following relationships apply:

– component related to injury to human beings (D_{1D} and D_{1T})

$$R_{AT} = N_D \cdot P_{AT} \cdot P_P \cdot L_{AT} \tag{11}$$

$$R_{AD} = N_D \cdot P_{AD} \cdot P_P \cdot L_{AD} \tag{12}$$

– component related to physical damage to the structure

$$R_B = N_D \cdot P_B \cdot P_P \cdot L_B \tag{13}$$

– component related to failure of internal systems

$$R_C = N_D \cdot P_C \cdot P_P \cdot P_e \cdot L_C \tag{14}$$

Parameters to assess these risk components are given in Table 4.

NOTE In wind turbines t_z the time in hours per year that persons are present in a dangerous place is usually very low. Therefore, for personal safety refer to Clause 10, where it is mandatory that the wind turbine documentation shall define safe locations.

7.3.3 Assessment of the risk component due to flashes near the wind turbine (S2)

For evaluation of the risk component related to lightning flashes near the wind turbine, the following relationship applies:

– component related to failure of internal systems

$$R_M = N_M \cdot P_M \cdot P_P \cdot P_e \cdot L_M \tag{15}$$

Parameters to assess these risk components are given in Table 4.

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7.3.4 Assessment of risk components due to flashes to a service line connected to the wind turbine (S3)

For evaluation of risk components related to lightning flashes to an incoming service line connected to the wind turbine, the following relationships apply:

– component related to injury to human beings

$$R_U = (N_L + N_{DJ}) \cdot P_U \cdot P_P \cdot L_{UT} \quad (16)$$

– component related to physical damage

$$R_V = (N_L + N_{DJ}) \cdot P_V \cdot P_P \cdot L_V \quad (17)$$

– component related to failure of internal systems

$$R_{W1} = (N_L + N_{DJ}) \cdot P_W \cdot P_P \cdot P_e \cdot L_{W1} \quad (18)$$

Parameters to assess these risk components are given in Table 4.

7.3.5 Assessment of risk component due to flashes near a service line connected to the wind turbine (S4)

For evaluation of the risk component related to lightning flashes near a service line connected to the wind turbine, the following relationship applies:

– component related to failure of internal systems)

$$R_Z = N_I \cdot P_Z \cdot P_P \cdot P_e \cdot L_Z \quad (19)$$

For the purpose of this assessment, if $(N_I - N_L) < 0$, then assume $(N_I - N_L) = 0$.

Parameters to assess these risk components are given in Table 4.

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Table 4 – Parameters relevant to the assessment of risk components for wind turbine (corresponds to IEC 62305-2)

	Average annual number of dangerous events due to flashes
N_D [year^{-1}]	to the wind turbine
N_M [year^{-1}]	near the wind turbine
N_L [year^{-1}]	to a service line entering the wind turbine
N_I [year^{-1}]	near a service line entering the wind turbine
$N_{D,b}$ [year^{-1}]	to a structure at the "b" end of a service line (see Figure 3)
N_{SG} [year^{-1} km^{-2}]	lightning ground strike-point density
	Probability that a flash to the wind turbine will
P_{AT}	cause dangerous touch and step voltage
P_{AD}	strike a person
P_B	cause physical damage
P_C	cause failure of internal systems
	Probability that a flash near the wind turbine will
P_M	cause failure of internal systems
	Probability that a flash to a service line will
P_U	cause injury to human beings by electric shock
P_V	cause physical damage
P_W	cause failure of internal systems
	Probability that a flash near a service line will
P_Z	cause failure of internal systems
	Loss due to
L_{AT}	injury to human beings by electric shock resulting from direct strike to human beings (flashes to structure). See Clause B.5 for information on loss assessment.
L_{AD}	injury to human beings by electric shock resulting from resistive and inductive coupling (flashes to structure). See Annex B.
L_B	physical damage to a structure (flashes to structure). See Annex B.
L_C	failure of internal systems (flashes to structure). See Annex B.
NOTE Values of loss L_t; L_f; L_o; and the factors r_p, r_t, r_f reducing the loss are given in Annex B.	

8 Lightning protection of subcomponents

8.1 General

8.1.1 Lightning protection level (LPL)

All subcomponents shall be protected in accordance with LPL I unless a detailed and documented risk assessment (according to Clause 7) demonstrates that a protection level less than LPL I is economically optimal for specific wind turbines and locations. It may be lower overall risk to differentiate, for example, that wind turbine blades are protected to a higher LPL while other parts – repairable or replaceable at less costs – may be protected to a lower LPL.

Lifetime compliance with a certain LPL may require maintenance and inspections, which may be site specific. Maintenance and inspection requirements for the lightning protection system including the earthing system should be described in the service and maintenance manuals. Maintenance and inspection procedures are outlined in Clause 12.

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8.1.2 Lightning protection zones (LPZ)

A wind turbine shall be divided into physical areas which roughly define the level of the influence of a lightning flash on components in that zone. Defining the lightning exposure by division of the wind turbine into lightning protection zones is a tool to ensure systematic and sufficient protection of all components of the wind turbine. These lightning protection zones (LPZ) are defined depending on whether or not direct lightning attachment is possible and on the magnitude of the lightning current and associated magnetic and electrical fields expected in that zone (see Annex E). Lightning protection methods are then applied to ensure that components, for example blade parts, machinery, electrical systems or control systems, can withstand the effects of the magnetic and electrical fields, as well as the full or partial lightning current that may enter the zone in which the components are placed. See Annex E for further guidance on the use of LPZ.

8.2 Blades

8.2.1 General

Wind turbine blades are the most exposed parts of the turbine, and experience the full impact from the electric fields as associated with the lightning attachment process, the lightning currents, and the magnetic field associated with lightning currents. The formal explanation of the attachment process and the following current/charge conduction is included in Annex A.

Wind turbine blades are exposed to a lightning environment with distributed severity and occurrence along the blade length where the occurrence of the direct attachments are highest at the tip and decrease towards the blade root end. Field experience documenting the attachment point distribution (occurrence) is provided in Clause C.8. The manufacturer shall, in the documentation, define the lightning exposure (areas of likely attachment and corresponding lightning parameter levels) relevant for the blade in question. Guidance for defining the lightning environment is provided in the informative Annex E.

A general description of the different issues concerning lightning protection of blades is included in Annex C.

8.2.2 Requirements

The lightning protection shall be sufficient to enable the blade to intercept lightning flashes and conduct the lightning current identified by the lightning exposure assessment in Clause 7, without structural damage that would impair the functioning of the blade.

The manufacturer shall identify and implement the lightning attachment point distribution in the specific blade design, preferably based on well validated field data for similar blade designs. If field data is not available for similar blade designs, experience has shown that the outer part of the blade (typically comprising the outer 5 metres to 10 metres) is more exposed to lightning strike attachment than the remaining section of the blades. Examples are seen in Clause C.8.

The manufacturer shall document how the attachment point distribution is used in the lightning exposure assessment for the blade, by assessing risk of impact in the different span-wise areas, and ensuring that the blade can withstand the likely impact of the stroke currents for the selected LPL. The exposure shall be documented, for instance by defining the lightning environment along the blade, examples of which are given in Annex E.

The minimum topics involved to ensure proper performance are:

– definition of the lightning exposure of the actual blade, the severity and occurrence for the different strikes attaching to the blade verified as described in 8.2.3;

– correct strike interception at air termination points, discrete or distributed depending on the blade exposure;

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– a down conductor path for the lightning current; and

– insulation coordination by insulation, separation or bonding between the LPS and additional conductive paths if present, to minimise the risk of side flashes and overloading of bonding interfaces.

Damages to the blade's structural parts, the blade skin or the blade LPS due to lightning shall be limited to that which can be tolerated until the next scheduled maintenance.

8.2.3 Verification

The ability of the air-termination system and down-conductor system to intercept lightning flashes and conduct lightning currents shall be defined in accordance with the exposure considered for the specific blade, and verified by one or more of the following methods:

a) high-voltage and high-current tests in accordance with 8.2.5;

b) demonstration of similarity of the blade type (design) with a blade type previously verified by testing according to a). Two blades are defined as 'similar' if the differences do not affect the interception effectiveness, the current-carrying capability and the lightning protection insulation coordination as identified by testing or analysis. An informative checklist to validate similarity is provided in Annex N;

c) using analysis or simulations previously verified by comparison with test results according to a). In the documentation of the analysis or simulations, evidence of the applicability and validity of the analysis/methods applied shall be provided. Guidance on how to validate typical simulation methods is provided in Annex O.

The manufacturer shall clearly explain in the documentation how the verification plan is compiled based on the three methods above.

Testing according to point a) is mandatory for new blade protection designs unless similarity to previous designs is demonstrated. Annex N provides guidance on how to demonstrate similarity.

All conductive parts of the blade shall be considered in the verification process, to ensure that their interaction with the LPS during lightning interception and current conduction happens without structural damage that would impair the functioning of the blade.

The blade manufacturer shall produce documentation that describes which of the above methods are used and the results of the verification.

The high-voltage strike attachment tests used to determine the performance of the air termination system – position, integration and insulation coordination – cannot be used to determine the interception efficiency of the blade as identified for the specific LPL. The high-voltage tests are a means of verification of the performance, giving the processes and requirements in Annex D. The performance of the blade LPS concerning a specific LPL is established by the high-current verification tests, where compliance can be determined by the described test procedures and test levels.

8.2.4 Protection design considerations

8.2.4.1 General

The following subclauses describe the issues that are important for design and incorporation of the lightning protection systems associated with the blade.

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8.2.4.2 Air-termination system

The lightning air-termination systems are placed in the surface areas on the blade where connecting leaders might originate and cause lightning flash attachments or punctures if no air terminations are present. The air-termination systems may be part of the blade structure itself, components added to the blade, or combinations thereof.

Field experience has shown that the majority of lightning attachment occurs at the outer parts of the blade (see Clause C.8 for further information), hence the lightning exposure analysis identified for the blade shall reflect this fact. The air-termination system positioning tools (rolling sphere, protective angle, etc.) described in IEC 62305-3 do not consider probabilities of strike locations along the blade. Hence these tools shall not be used for blades.

The air-termination system shall therefore be designed according to the identified exposure in Clause 7, and shall be verified in accordance with 8.2.3.

The air termination system design shall ensure proper fixation in the mountings, and shall be made of materials able to withstand the expected wear due to the environment such as wind, moisture and pollution with salt and dirt particles, etc. Special attention should be paid to materials chosen for offshore and nearshore wind turbines owing to the harsh environment.

All internal parts of the air-termination system, the mounting of the air terminations and the connections to the down conductor shall be designed to minimise the risk of getting internal discharges (i.e. streamers and leaders) forming from these parts.

The air-termination system shall be designed so that parts of it that may be damaged or degraded by lightning or other environmental effects can be inspected, repaired or replaced according to procedures that shall be described in the service and maintenance manuals (instructions). The air terminations will wear over time owing to erosion at lightning arc roots. The erosion is related to the charge entering at the lightning arc root(s) and the surface material and geometry of the air termination system. Blades that receive large numbers of lightning flashes may eventually require replacement of the air terminations. The lifetime of the air termination system should be optimised through suitable selection of material and design and coordination with the maintenance and service cycles. The manufacturer shall define a procedure for correlating the design lifetime with the test performance to ensure that the suggested service/replacement intervals are adequate.

8.2.4.3 The lightning protection system and its connection components

The lightning protection system and its connection components is defined as all conductive parts of the blade which take part in conducting the lightning current from the air-termination system to the termination in the root end of the blade.

Interfaces to the LPS shall be firm and permanent and ensure that the entire system can withstand the combined impact of the electrical, thermal, and electrodynamic forces of the lightning current. Electrical connectivity across LPS connection components shall be verified with a suitable instrument such as a four-wire micro ohm meter. The ability of the lightning protection systems to withstand the mechanical stresses in the blades shall be verified by installing the system in a blade that is subjected to the tests in IEC 61400-23, while the ability of the system to sustain the electrodynamic forces shall be verified in accordance with 8.2.3. Limits and maximum deviation of measured resistance shall be specified beforehand by the manufacturer.

The cross-section of the down conductor and natural conductive parts of the blade used as down conductors (intended and unintended) shall be able to conduct their share of the lightning current corresponding to the chosen LPL. The design and installation shall be verified in accordance with 8.2.3.

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The lightning test current may be scaled based on the blade lightning exposure defined for the particular blade (see Annex E for guidance).

Testing of connection components shall be done in accordance with Annex D. The current test levels should be selected according to the first short stroke of the selected LPL. If non-rigid connections are used, such as rotating links, bearings or spark gaps, then testing should be done with the long stroke current as well. If several paths for the lightning current exist, the test current magnitude and waveforms for each path may be scaled according to the distribution of the current between the paths.

All internal parts of the down conductor system and connection components shall be designed to minimise the risk of internal discharges forming from these parts. The intention with this is to impede the development of electrical discharges from structures elsewhere than the external air termination system; whereby the risk of such internal discharges puncturing the blade skin is limited.

Down conductor and connection components subject to electrodynamic forces such as connections between blade down conductor and hub shall be tested according to Annex D in a test setup realistically representing the physical configuration in the wind turbine.

Externally mounted down conductors exposed to direct lightning attachment are defined as air-termination systems, hence the requirements in 8.2.4.2 apply.

The manufacturer shall define a procedure for regular inspection of any parts of the down conductor system and its connection components that may be degraded by service environments so that the lifetime and service intervals of these parts can be correlated.

Tests for verifying the capability of down conductors and connection components are described in Annex D.

Verification of the down conductor system and its connection components shall be done as described in 8.2.3.

8.2.4.4 Additional conductive components

If additional conductive components (conductive structural components, carbon fibre reinforced plastic, weights, tip brake cables, electrical cables for sensors, heating, warning lights, etc.) are present in the blade, the installation of these components shall be coordinated with the lightning protection system. Coordination can be achieved either by insulation or separation distance. If coordination cannot be ensured by insulation or separation, then suitable equipotential bonding shall be applied (see IEC 62305-3 for information about separation distance).

Insulation coordination and assessment of the current distribution dictated by the design shall be achieved by engineering analysis, numerical modelling, or testing. Possible verification methods are described in the IEC 60243 series, IEC TS 62561-8 or similar. Verification of engineering analysis and numerical modelling shall be provided by comparative testing. Examples of such validation is provided in Annex O.

Conductive components shall then be designed to conduct their share(s) of lightning current, and the required current-carrying capability of the different current paths shall be verified by high-current testing as described in 8.2.5.3.

Electrical and electronic equipment shall be protected with appropriate shielding, surge protection and equipotential bonding (see 8.5).

Attention shall be paid to the effects of electrodynamic forces.

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NOTE 1 The highest voltages appearing between conductive components typically occur during conduction of the subsequent stroke, whereas the highest specific energy and charge content flow in the different current paths during the first return stroke.

NOTE 2 The calculation of the separation distance in accordance with IEC 62305-3 and the testing methods provided in IEC 62561-8 consider the high voltages during conduction of negative subsequent negative short stroke.

8.2.4.5 Electrical field stress impact on composite material design

Owing to the elevation and exposure of wind turbine blades, the entire structure of the blade will be exposed to high electric fields many times during its service life. High static and transient electric fields are produced by thunder clouds and electrically applied to the blade structure. Approaching lightning leaders expose the blade structure to higher electric fields. In both cases, the electric fields may over time degrade the insulating properties of non-conducting composite materials. Therefore, the lightning protection systems should be designed considering high-voltage insulation design principles.

8.2.5 Test methods

8.2.5.1 General

The following test methods apply to entire blade designs or sub-sections such as blade tips or laminate coupons. The tests can be used as engineering tests supporting the design process and iterations, and are mandatory for the final verification of the blade designs.

8.2.5.2 High-voltage tests

Interception effectiveness of the air termination systems on the blade shall be evaluated using the initial leader attachment test described in Annex D, Subclause D.2.2.

Improvement of the ability of the blade laminate to impede internal discharges and prevent them from puncturing the blade skin can be achieved by increasing the electrical breakdown field strength of the materials, and designing internal parts to minimise field enhancements. The breakdown field strength of insulating composites and coating layers can be evaluated according to IEC 60060-1, IEC 60243-1 (AC), IEC 60243-3 (impulse voltage) and IEC 60464-2 (coating).

When electrical activity occurs on insulating surfaces (streamers, surface flashovers, etc.), the surface can deteriorate through tracking and electrical erosion. The impact, in connection with moisture, can change the properties of the insulating surface to be more conductive, and thereby increase the risk of direct lightning attachment. The resistance to tracking of various blade and coating materials can be evaluated and compared using IEC 60587.

8.2.5.3 High-current tests

The air termination systems will mainly be affected by the impact of the charge in the lightning flash (i.e. the time integral of the lightning current), which shall be evaluated by the high-current physical damage test in Annex D, Clause D.3.

Connection components and all parts of the down conductor system shall be tested by the high-current physical damage test in Annex D, Clause D.3.

The current test waveforms and levels should include the first short stroke and if relevant also the long stroke (continuing current) defined for the selected LPL. Based on the specific lightning environment defined for the blade in question, the lightning current magnitude and waveforms can be scaled to fit the actual exposure. Detailed test specifications are provided in Annex D.

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8.3 Nacelle and other structural components

8.3.1 General

Lightning protection of the nacelle and other structural components of the wind turbine should be made using the large metal structures as much as possible for lightning air termination, electrical bonding, shielding and conduction of lightning current to the earthing system. Additional lightning protection components such as air termination systems for protection of meteorological instruments and aircraft warning lights on the nacelle, down conductors and bonding connections shall be made and dimensioned in accordance with IEC 62305-3.

Insulation coordination and assessment of the current distribution (lightning current sharing) dictated by the design shall be achieved by engineering analysis, numerical modelling, or testing. All parts and connections exposed to lightning current shall be able to withstand the thermal and electromechanical effects associated with conducting the relevant levels of lightning current. Possible verification methods are described in the IEC 60243 series, IEC 62561-8 or similar. Verification of such engineering analysis and numerical modelling shall be provided by comparative testing. Examples of such validation are provided in Annex O.

Parts of the nacelle and other structural components used as natural down-conductors shall fulfil the requirements of natural down-conductors in accordance with IEC 62305-3. Verification by testing is not required for structural components with dimensions clearly fulfilling the requirements in IEC 62305-3.

Documentation of the LPS for all subsystems shall be provided as described in Clause 11.

8.3.2 Hub

The hub for large wind turbines is typically a hollow cast iron sphere of several metres in diameter. Hence the material thickness alone ensures that the hub structure itself is immune to lightning. In most cases, electrical and mechanical control systems and actuators are placed in the hub with circuits going to the outside of the hub, to the blades and to the nacelle. The hub should be made into a Faraday cage by providing magnetic shields in the openings in the hub towards the blades, the front and the nacelle (i.e. the hub could be defined as a LPZ). In many cases, these openings are closed by blade flange plates and the main shaft flange, which can be considered very effective magnetic shields. When the openings are closed with effective magnetic shields as described above, the contents of the hub require no particular lightning protection. Lightning protection of the hub is then limited to equipotential bonding and transient protection of systems placed outside the hub, such as blade actuator systems, and of electrical and control systems in the hub connected to circuits extending to the outside of the hub.

8.3.3 Spinner

Typically the hub has a glass fibre cover, called the spinner, which is mounted on the hub and rotates with it. As the rolling sphere model would always indicate that there is a possibility of lightning attaching to the front end of the spinner, lightning protection shall be considered. In some wind turbine designs there are also electrical and mechanical control systems and actuators placed outside the hub and covered by the spinner. Such systems shall be shielded from lightning attachment with air termination systems. In case no such systems are placed under the spinner, it may be reasonable to accept the risk of lightning puncturing through the spinner and not have any lightning protection of the spinner. However, in most cases, simple and practical lightning protection of the spinner can probably be made using the metal support structure for the spinner as air termination system and connection to the hub.

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8.3.4 Nacelle

The nacelle structure should be part of the lightning protection so that it is ensured that lightning attaching to the nacelle will either attach to natural metal parts able to withstand the stress or attach to a lightning air-termination system designed for the purpose. Nacelles with GFRP cover or similar should be provided with a lightning air-termination system and down conductors forming a cage around the nacelle. The lightning air-termination system including exposed conductors in this cage should be able to withstand lightning flashes corresponding to the chosen lightning protection level. Other conductors in the Faraday cage should be dimensioned to withstand the share of lightning currents that they may be exposed to. Lightning air-termination systems for protection of instruments, etc. on the outside of the nacelle should be designed according to the general rules in IEC 62305-3, and down conductors should be connected to the above-mentioned cage.

A metal mesh could be applied to nacelles with GFRP cover to provide shielding against external electric and magnetic fields, and magnetic fields from currents flowing in the mesh. Alternatively, all circuits inside the nacelle could be placed in closed metal conduits or cable trays, etc. An equipotential bonding system shall be established in which the major metal structures in and on the nacelle are included, as it is required in the electrical codes, and as it will provide an efficient equipotential plane to which all earthing and equipotential bonding connections should be made.

Lightning current from lightning attaching to the blades should preferably be conducted directly to the above-mentioned cage thereby completely avoiding lightning current passing through the blade pitch bearings and drive train bearings (see 8.2 and 8.4 for discussion of protection of blades and bearings). Different kinds of brush systems are commonly used for diverting lightning currents away from bearings. However, it may be difficult to construct brush and earth lead systems with impedance low enough to significantly reduce the current going through the low impedance of the main shaft and bearing systems to the nacelle bed plate. See 8.4.4 for further information.

NOTE A nacelle cover with such a magnetic shield will not be able to protect against effects of magnetic fields from lightning currents flowing inside the nacelle, such as in the main shaft.

8.3.5 Tower

A tubular steel tower, as predominantly used for large wind turbines, usually fulfils the dimensions required for down conductors stated in IEC 62305-3 and can be considered an almost perfect electromagnetic shield Faraday cage, as it is electromagnetically almost closed both at the interface to the nacelle and at ground level. It would therefore in most cases be reasonable to define the inside of the tower as lightning protection zone LPZ1 or LPZ2. In order to keep the tower as electromagnetically closed as possible, there should be direct electrical contact all the way along the flanges between tower sections. The tower and all major metal parts in it should be integrated into the protection earth conductor (PE) and equipotential bonding systems to make the best of the protection offered by the Faraday cage. With regards to bonding of metal structures and systems inside the tower such as ladders, wires and rails, see 9.3.5.

The interface towards the nacelle is usually closed with metal platforms and hatches, which can also serve as an electromagnetic shield closing the tower (see 8.4.2 for discussion of lightning protection of the yaw bearing).

The tower interface to the earthing system is discussed in Clause 9. If the tower is constructed as a Faraday cage as described above, then the contents of the tower require no particular lightning protection. The task of ensuring lightning protection of the tower is thereby limited to equipotential bonding and transient protection of electrical and control circuits extending to other lightning protection zones such as into the nacelle and to the outside of the tower.

Lattice towers naturally cannot be considered a very effective Faraday cage, although there will be some magnetic field attenuation and lightning current reduction inside the lattice tower.

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It is reasonable to define the inside of a lattice tower as $LPZ0_B$. Lightning down conduction should be via the lattice tower structural elements, which therefore have to fulfil the dimensions required for down conductors stated in IEC 62305-3 taking current sharing between parallel paths into account. Shields of cables in lattice towers may need to be bonded to the tower at certain interspacing in order to avoid puncture of cable insulation; this is to be assessed by calculation (see IEC 62305-2, Annex D).

In steel reinforced concrete towers, the reinforcement can be used for lightning down conduction by ensuring 2 to 4 parallel vertical connections with sufficient cross section which connect horizontally at top, bottom and for every 20 m in between. The steel reinforcement will provide quite effective magnetic field attenuation and lightning current reduction inside the tower if bonded in this way. IEC 62305-3 gives guidance on integrating steel reinforcement with lightning protection systems.

Documentation of the LPS shall be provided as described in Clause 11.

8.3.6 Verification methods

Testing methods are included in Annex D.

Suitable analysis and methods shall be used. Verification reports of analysis/methods used are required.

8.4 Mechanical drive train and yaw system

8.4.1 General

The wind turbine will in general have a number of bearings for blade pitching, main shaft rotation, gearbox, generator, and yawing systems.

Hydraulic or electrical actuator systems are used for control and operation of main components.

Bearings and actuator systems have moving parts that directly or indirectly bridge different parts of the wind turbine where lightning current may flow.

All bearings and actuator systems that may be in a lightning current path shall be protected as necessary to reduce the level of current passing through the component to a tolerable level.

8.4.2 Bearings

Bearings are difficult to monitor, and it is not acceptable that bearings have to be inspected after lightning attachment to a wind turbine. Systems for protecting bearings therefore shall be well proven and documented.

Protection can be a part of the bearing structure itself or it can be an external system installed across the bearing to bypass the current.

If the design exposes bearings to lightning current, it shall be demonstrated by analysis, documented experience relevant for the design in question, or by testing that the bearing can operate for the whole design lifetime, after being exposed to the relevant lightning current levels, and the number of lightning occurrences. If the bearing is not able to operate for the whole design life time, protection shall be applied (see 8.4.4).

The ability of the bearing to sustain lightning current to which it is exposed shall be verified by one or more of the following methods:

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a) high-current tests in accordance with 8.2.5;

b) demonstration of similarity of the bearing type (design) with a bearing type previously verified by testing according to a);

c) using analysis or simulations previously verified by comparison with test results according to a). In the documentation of the analysis or simulations, evidence of the applicability and validity of the analysis/methods applied shall be provided.

The manufacturer shall clearly explain in the documentation how the verification plan is compiled based on the three methods above.

If documentation is based on testing, then bearings with or without protection, and bypass systems for bearings shall be tested in a test setup realistically representing the operational conditions for the bearing and the protection/bypass system with regards to load, lubrication, rotation as relevant subject to design and application influencing the response to the lightning currents. Guidance for verification methods of different solutions are provided in Table 5. Whenever spark gaps are used, insulation coordination shall be determined by high-voltage testing or analysis to guarantee lightning current flow along spark gaps. Where insulation coordination relies on separation distance, this shall be based on separation distance as defined in IEC 62305-3.

Table 5 – 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
No protection	100 % in bearing	High-current testing of bearing
Bearing protection	Current sharing between bearing and its protection. Current sharing shall be determined	High-current testing of bearing and protection system
Bypass system	Negligible	High-current test of bypass system

The generic test setup for conducted current tests in D.3.3 applies. Guidance with regards to test of rotating and stationary bearings, including example test setup descriptions, is included in Annex P.

8.4.3 Hydraulic systems

If hydraulic systems are in the lightning current path, it shall be ensured that lightning current penetration will not affect the system. With hydraulic systems, it is necessary to consider the risk of fluid leaks due to damage at fittings and ignition of the hydraulic oil.

Protection measures such as sliding contacts or bonding straps can be used to make the current bypass actuator cylinders.

Hydraulic tubes exposed to lightning current shall be protected to avoid current penetration of the tubes. If hydraulic tubes have mechanical armour, it shall be bonded to the steel structure of the machinery at both ends of the tube. It shall also be ensured that the armour has sufficient cross section to conduct the parts of the lightning current, which it may be exposed to.

Similar considerations may apply to water cooling systems.

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8.4.4 Spark gaps and sliding contacts

For bypassing bearings and actuator systems, it shall be considered to use spark gaps or sliding contacts. Such bypassing systems including their connecting leads should have considerably lower impedance than the direct natural current path through the component in order to be effective.

Spark gaps and sliding contacts shall be able to conduct the level of lightning current that it may be exposed to at the place of use in the wind turbine. Test corresponding to the chosen LPL shall be done according to D.3.3.

Both spark gaps and sliding contacts shall be designed to maintain the required performance regardless of environmental effects such as rain, ice, pollution with salt, dust, etc.

If spark gaps or sliding contacts are used, these shall be considered to be wear parts and the service lifetime of these devices shall be calculated and documented. Adverse effects of pollution by wear dust on other components shall be considered in the design. Spark gaps and sliding contacts shall be inspected regularly in accordance with the service and maintenance manuals.

8.4.5 Verification

All systems for protection of bearings and actuator systems shall have a documented functionality. The documentation of this functionality is provided by performing impulse current tests with waveforms and amplitudes representing the expected lightning environment at the installation point of the protection system for the LPL selected.

Suitable engineering analysis, numerical modelling or testing shall be used. Verification reports of analysis/methods used are required.

It is recommended to perform impulse current tests on full-scale test objects where the important parts of the system are represented in a test mock-up.

It shall be demonstrated by testing (see IEC 62305-1 and Annex D for normative definition of test impulses) that the protection system can withstand the damaging effect of both the first short stroke as well as the long stroke current (continuing current) for the LPL chosen. The two tests shall be applied to the same test sample, but not necessarily in the same discharge. The test documentation shall describe the exact test sequence applied.

If sliding contacts are used as part of the system, mechanical tests shall be performed in order to document the stability of the system with special focus on wear of the contact with and without the erosion effects of lightning current. The wear has to be low enough to allow unaffected operation between the planned service intervals.

Tests can be done on subsets of the entire protection systems, but calculations shall be provided to demonstrate the scaling factors and effects.

Testing methods are included in D.3.3.

NOTE If evident by design or shown by analysis that the lightning current completely bypasses a component (i.e. negligible lightning current transfer through the component), then the high-current test is not required.

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8.5 Electrical low-voltage systems and electronic systems and installations

8.5.1 General

This subclause deals with the protection of the electrical and control systems of a wind turbine against the effects of current surges and voltage transients caused by

- lightning flashes attaching to the wind turbine;
- leader currents developing from the wind turbine;
- indirect lightning flashes (i.e. effect through LEMP of lightning flashes not affecting the wind turbine directly).

All types of lightning flashes generate lightning electromagnetic impulses (LEMP).

NOTE 1 For general requirements for electrical equipment on machines, see IEC 60204-1.

Electrical and control systems are subject to damage from LEMP. Therefore, surge protective measures (SPM) shall be provided to avoid failure of these systems. Effective protection of the electrical and control system of a wind turbine against LEMP requires the systematic approach of the lightning protection zone (LPZ) concept in accordance with IEC 62305-4. SPM is part of the lightning protection zone (LPZ) concept for the complete wind turbine, described in Annex E.

The wind turbine manufacturer shall provide a surge protection measures (SPM) system following the basic principles given in IEC 62305-4 for the complete electrical system. Given the space constraints in even large turbines, where the lightning current propagates only a few metres from sensitive equipment, special precautions shall be taken to ensure compliance with the lightning environment.

Examples of the application of the lightning protection zones (LPZ) concept in a wind turbine are given in Annex E. Protection against LEMP is based on the lightning protection zone (LPZ) concept: The wind turbine is divided into zones (i.e. volumes of space), which may correspond to parts of the wind turbine such as the inside of the large structural components: hub, the nacelle, the tower, and smaller components, such as cabinets and components. The subdivision of the structure in zones may be adapted to facilitate a convenient systematic definition of LEMP severity for each zone. Within these zones, it shall be documented that the LEMP severity is compatible with the withstand level of the internal systems enclosed.

Permanent failure of electrical and electronic systems due to LEMP can be caused by

- conducted and induced surges transmitted to equipment via connecting wiring,
- effects of radiated electromagnetic fields impinging directly onto equipment itself.

In order to characterize the LEMP severity (both conducted and radiated effects) of the individual LPZs of a wind turbine, the LEMP environment shall be assessed by verified analysis methods or in accordance with IEC 62305-3 and IEC 62305-4.

NOTE 2 It can be assumed that effective LEMP protection measures also provide effective protection against the effects of indirect lightning flashes.

Basic protection measures in a surge protection measures (SPM) system in accordance with IEC 62305-4 include:

- bonding – see 8.5.2;
- magnetic and electrical shielding of cables and line routing (system installation) – see 8.5.4;
- SPD protection – see 8.5.5;
- earthing – see Clause 9.

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Figures 4a) to 4d) give examples of possible SPM (surge protection measures) – derived from IEC 62305-4.

Additional methods include:

- insulation, circuit design, balanced circuits, series impedances, etc.

For the SPM, the following basic information shall be documented (see also Clause 11):

- definition of lightning protection level (LPL) according to IEC 62305-1;
- drawings of the wind turbine defining LPZ and their boundaries, circuit diagrams showing SPDs, cable shields and cable shield bonding points.

Figures E.6 and E.7 in Annex E provide basic examples of such documentation.

In the case of no partial lightning currents inside the LPZ, protection against over voltages is only necessary for cables passing from one zone into a zone with more sensitive components (i.e. from a lower LPZ number to a higher LPZ number), whereas internal connections within the zone may be unprotected. This approach is detailed further in IEC 62305-4, and it is discussed in Annex E. In the case of partial lightning currents flowing inside the LPZ, see Annex E.

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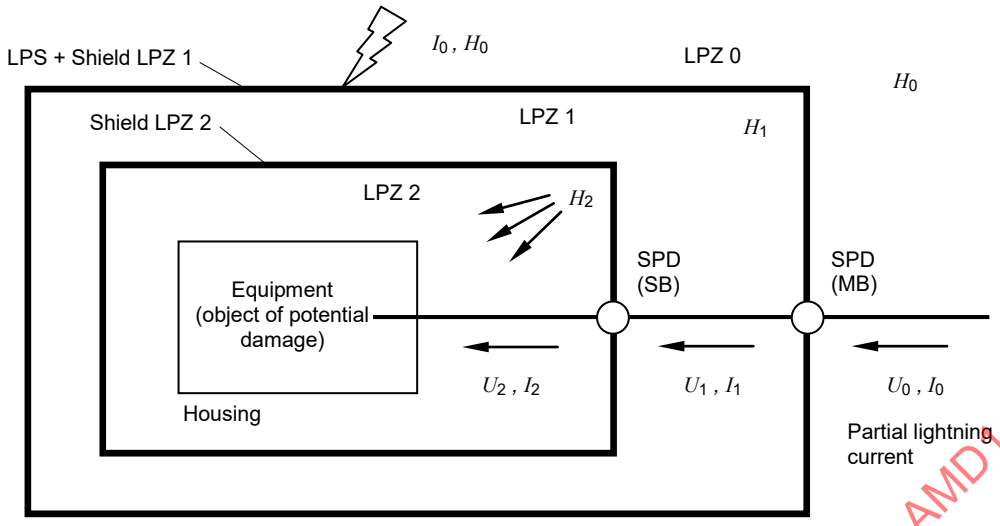
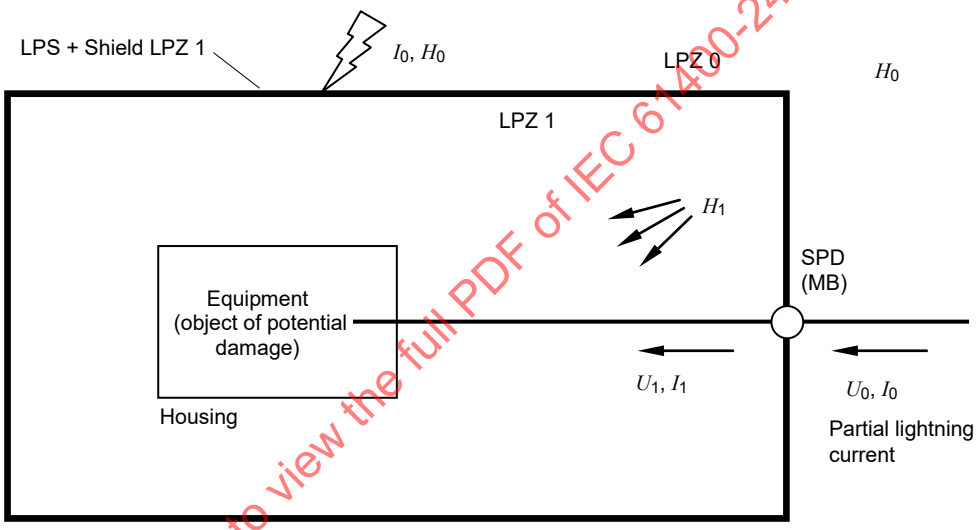


a) SPM using spatial shields and a coordinated SPD system – Equipment well protected against conducted surges (U_2<<U_0 and I_2<<I_0) and against radiated magnetic fields (H_2<<H_0)



b) SPM using spatial shield of LPZ 1 and SPD protection at entry of LPZ 1 – Equipment protected against conducted surges (U_1<U_0 and I_1<I_0) and against radiated magnetic fields (H_1<H_0)

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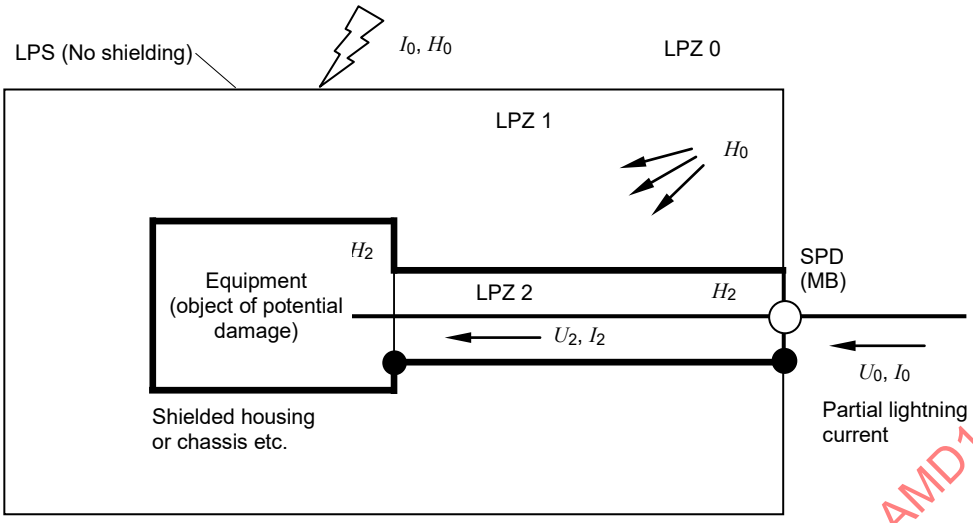
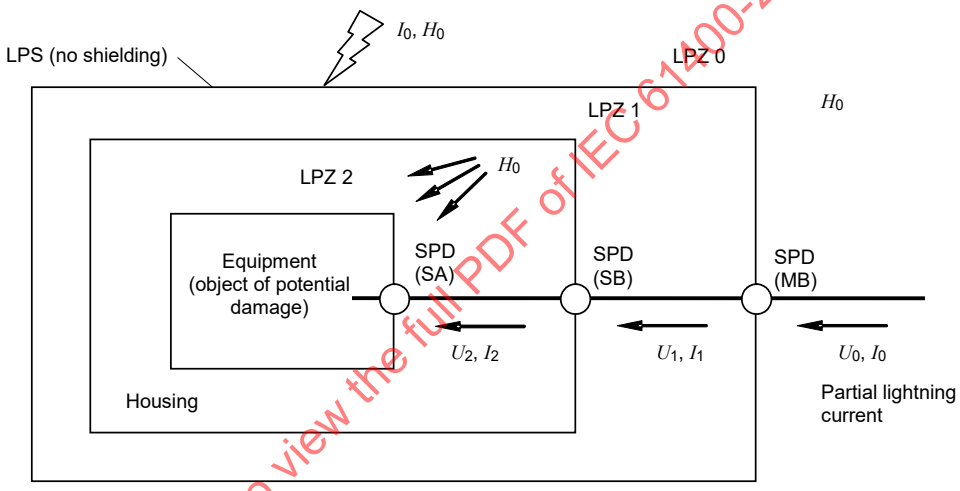


c) SPM using internal line shielding and SPD protection at entry of LPZ 1 – Equipment protected against conducted surges ($U_2<U_0$ and $I_2<I_0$) and against radiated magnetic fields ($H_2<H_0$)



d) SPM using a coordinated SPD system only –Equipment protected against conducted surges ($U_2<<U_0$ and $I_2<<I_0$), but not against radiated magnetic field (H_0)

Key

shielded boundary

non-shielded boundary

NOTE 1 SPDs can be located at the following points:

– at the boundary of LPZ 1 (e.g. at main distribution board MB);

– at the boundary of LPZ 2 (e.g. at secondary distribution board SB);

– at or close to equipment (e.g. at socket outlet SA).

NOTE 2 For detailed installation rules, see also IEC 60364-5-53.

NOTE 3 This figure is derived from IEC 62305-4.

Figure 4 – Examples of possible SPM (surge protection measures)

Figure 5 shows two LPZ 1 connected by electrical or signal lines. Special care should be taken if both LPZ 1 represent separate structures with separate earthing systems, spaced tens or hundreds of metres from each other. In this case, a large part of the lightning current can flow along the connecting lines, which are not protected.

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Figure 6 shows that this problem can be solved using shielded cables or shielded cable ducts to interconnect both LPZ 1, provided that the shields are able to carry the partial lightning current. The SPD can be omitted if the voltage drop along the shield is not too high.

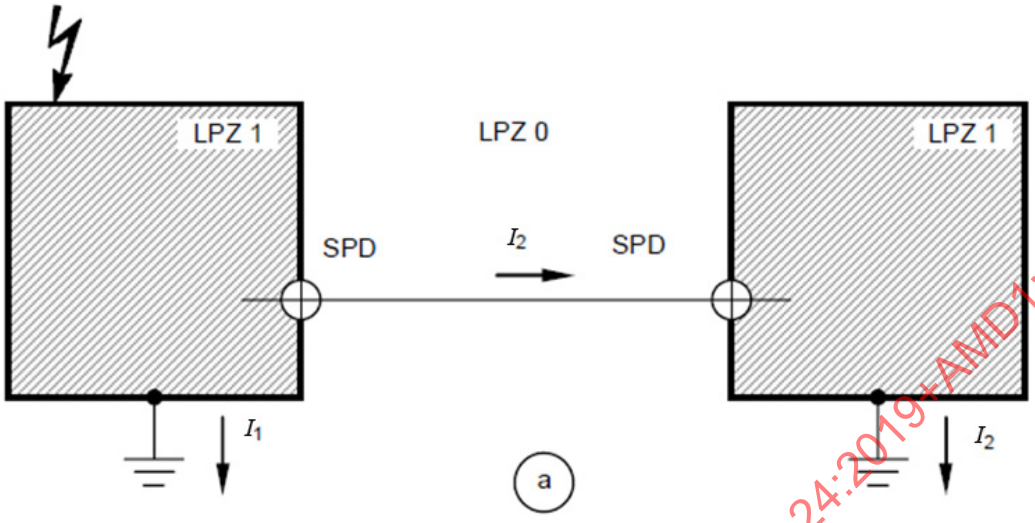

Figure 5 – Interconnecting two LPZ 1 using SPDs

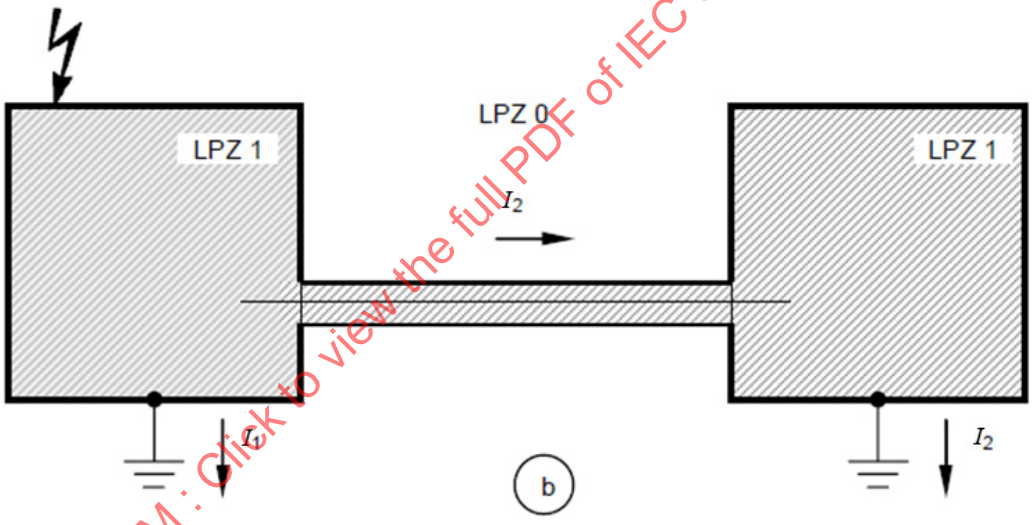

Figure 6 – Interconnecting two LPZ 1 using shielded cables or shielded cable ducts

8.5.2 Equipotential bonding within the wind turbine

Equipotential bonding in accordance with IEC 62305-4 and IEC TR 61000-5-2 shall be used within a wind turbine to ensure that potentially dangerous sparking and arcing caused by electrical discharges cannot take place between conducting parts of the wind turbine. These equipotential bonds provide protection against touch and step voltages during lightning attachment. Equipotential bonds play an important role in reducing the probability of damage to electrical and control systems. Low-impedance bonding connections prevent dangerous potential differences between equipment inside the wind turbines.

In order to be most effective, the bonding connections shall make maximum use of the large metal structures of the wind turbine (i.e. mainly tower, nacelle bed plate, nacelle frame and hub). Such bonding conductors may additionally reduce the magnetic field levels caused by lightning. Metal connections, such as those depicted in Figure E.3 and Figure E.4, facilitate uniform current distribution in the outer metal structures of the wind turbine and thus reduce the influence of the electromagnetic field inside the structure (e.g. inside nacelle or tower).

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The large metal structures provide maximum electromagnetic shielding when electrically interconnected. High electromagnetic shielding efficiency of a structure is obtained when permanent bonding of metal constructive elements are carried out at sufficiently small intervals.

For example, if bonding connections are placed between metal platforms and the tower wall at several positions distributed around the platform-tower interface, it will effectively provide electromagnetic shielding of the inside of the tower.

Much of the damage experienced in wind turbine control systems can be prevented by means of effective bonding and shielding. Some further considerations about the bonding needed in a wind turbine are discussed in Annex G.

8.5.3 LEMP protection and immunity levels

8.5.3.1 General

The transient voltage and current withstand levels (immunity) of the equipment shall be documented by testing in accordance with EMC test standards IEC 61000-4-X, and the immunity levels identified thereby shall be used for evaluating the necessity of additional protection for the equipment in the environments in the individual LPZs.

Notwithstanding the minimum withstand requirements stated herein, equipment shall always have an immunity level corresponding to the threat level of the environment wherein it is placed.

If a test fails, an individual analysis of the withstand level shall be performed. If manufacturer's specification requires external protection or measures that are clearly specified in the user's manual, the test requirements shall be applied with the external protection device or measures in place.

8.5.3.2 Withstand of equipment power ports

The equipment impulse withstand (or resistibility) levels for power ports are defined in IEC 61000-6-2 and tested in accordance with IEC 61000-4-5. A summary of the minimum impulse withstand requirements:

AC ports (230V / 400V):

- ± 2 kV line to ground;
- ± 1 kV line to line;
- further insulation/withstand level requirement in accordance with IEC 60664-1 shall be fulfilled as well.

DC ports (50V):

- ± 1,0 kV Line to ground
- ± 0,5 kV Line to line
- Further insulation/withstand level requirement in accordance with IEC 60664-1 shall be fulfilled as well.

8.5.3.3 Withstand of equipment signal ports

The equipment impulse withstand (or resistibility) levels for signal ports are defined by ITU-T Recommendations K.21 and K.20 for telecommunication and IEC 61000-6-2/ IEC 61000-4-5 for signal ports in general for equipment installed at customer's premises and exchange building respectively. A summary of the minimum impulse withstand requirements for equipment at customer's premises is:

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Telecommunication ports:

- Port connected to external line, i.e. a line that goes outside the building:
  - 1,5 kV common mode test (port to earth);
  - 1,5 kV differential mode test (between signal conductors).
- Port connected to unshielded internal line, i.e. line that remains wholly within the building (no direct connection to an external line):
  - 1 kV common mode test.

For signal ports in general:

- Signal port shall be tested regardless of their unshielded or shielded cable length:
  - 0,5 kV common mode test, tested as unshielded (port to earth).

8.5.3.4 Electromagnetic immunity of electronics

The equipment magnetic immunity (or resistibility) levels are defined in IEC 61000-4-9 and IEC 61000-4-10. A summary of the minimum impulse withstand requirements:

IEC 61000-4-9:

- ± 1 kA/m 8/20 [µs].

IEC 61000-4-10:

- ± 100 A/m (damped oscillatory).

The immunity shall be selected according to the application.

8.5.4 Shielding and line routing

Shielding is the means by which electromagnetic field levels are attenuated. The reduction of electromagnetic fields can substantially reduce levels of voltages induced into circuits.

The magnetic field caused inside an LPZ by lightning flashes to the structure or the nearby ground may be reduced by spatial shielding of the LPZ only. Surges induced into the control system via the connecting cabling can be minimised either by spatial shielding, or by line routing and shielding (e.g. shielded cables bonded at both ends), or by a combination of both methods.

Magnetic shielding and line routing in accordance with IEC 62305-4 should be used, and the general guidelines on EMC-correct installation practices described in IEC TR 61000-5-2 should be followed.

The requirements on material and dimensions of magnetic shields shall comply with IEC 62305-4:2010, Clause 6.

The use of shielding and line routing should be documented by analysis and/or testing.

The assessment of the magnetic field strength inside LPZ shall be based on magnetic field calculations according Annex A of IEC 62305-4:2010. Computer modelling can be used, provided that these models have been verified according Annex O.

The assessment for the shielding effect of enclosures shall be done in accordance with the methods described in IEC 61000-5-7 and IEC 61587-3.

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8.5.5 SPD protection

8.5.5.1 General

Coordinated SPD protection consists of a set of SPDs properly selected, coordinated and installed to reduce failures of electrical and electronic systems.

NOTE Coordination of SPD protection includes the connecting circuits to provide insulation coordination of complete systems.

Coordinated SPD protection limits the effects of lightning surges and internally generated switching surges. The protection of the electrical and control systems requires a systematic approach of coordinated SPDs for both electrical low-voltage power systems and control systems. Recommendations for coordinated SPD protection within wind turbines are given in Annex F.

8.5.5.2 Location of SPDs

According to IEC 62305-4, in a surge protection measures (SPM) system, SPDs shall be located at the line entrance into each LPZ:

- as close as possible to the boundary of LPZ 1, SPDs tested with I_{imp} (Class I test), as classified in IEC 61643-11, shall be installed;
- as close as possible to the boundary of LPZ 2 and higher, and if necessary as close as possible to the equipment to be protected, SPDs tested with I_n (Class II test), as classified in IEC 61643-11, shall be installed.

If not located at the LPZ entrance, it shall be documented that the equipment connected at both sides of the entrance can cope with the expected surge voltage. It shall as well be ensured that the conducted surge current does not compromise the magnetic environment in the entered LPZ, see Figure 7.

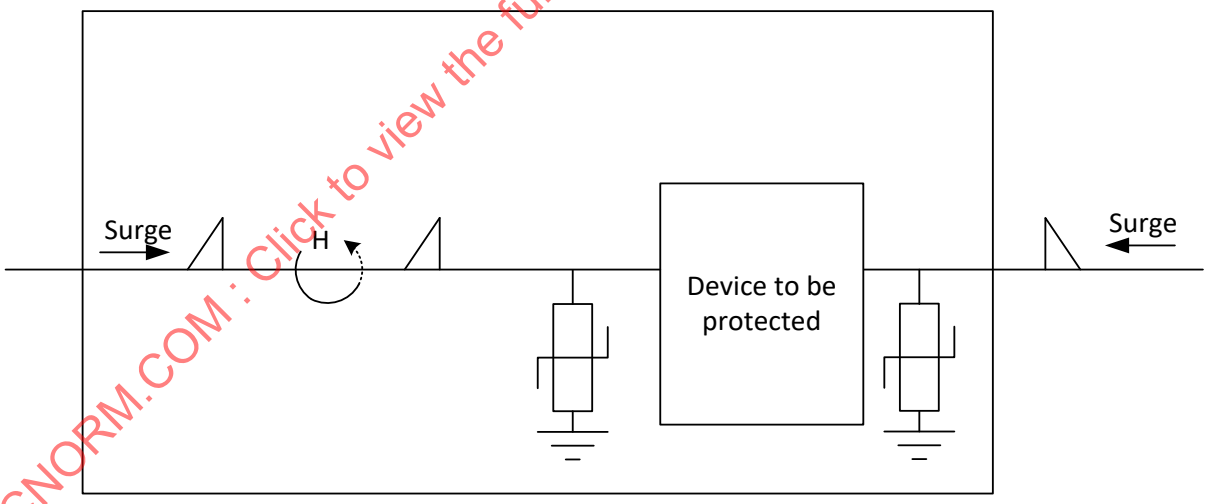

Figure 7 – Magnetic field inside an enclosure due to a long connection cable from enclosure entrance to the SPD

Where the distance between the SPD and the equipment to be protected is greater than 10 m (cable length), additional protective measures should be provided such as:

– Figure 8a: an additional SPD installed as close as possible to the equipment to be protected; its voltage protection level U_P shall in no case exceed the required rated impulse withstand voltage U_W of the equipment; or

– Figure 8b: the use of one-port SPDs at or near the origin of the electrical circuit; their voltage protection level U_P shall in no case exceed 50 % of the required rated impulse

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withstand voltage U_W of the equipment to be protected. This measure should be implemented together with other measures such as the use of shielded wiring in the whole protected circuit(s); or

– Figure 8c: the use of two-port SPDs (IEC 61643-11) at or near the origin of the electrical circuit; their voltage protection level U_P shall in no case exceed the required rated impulse withstand voltage U_W of the equipment to be protected. This measure should be implemented together with other measures such as the use of shielded wiring in the whole protected circuit(s).

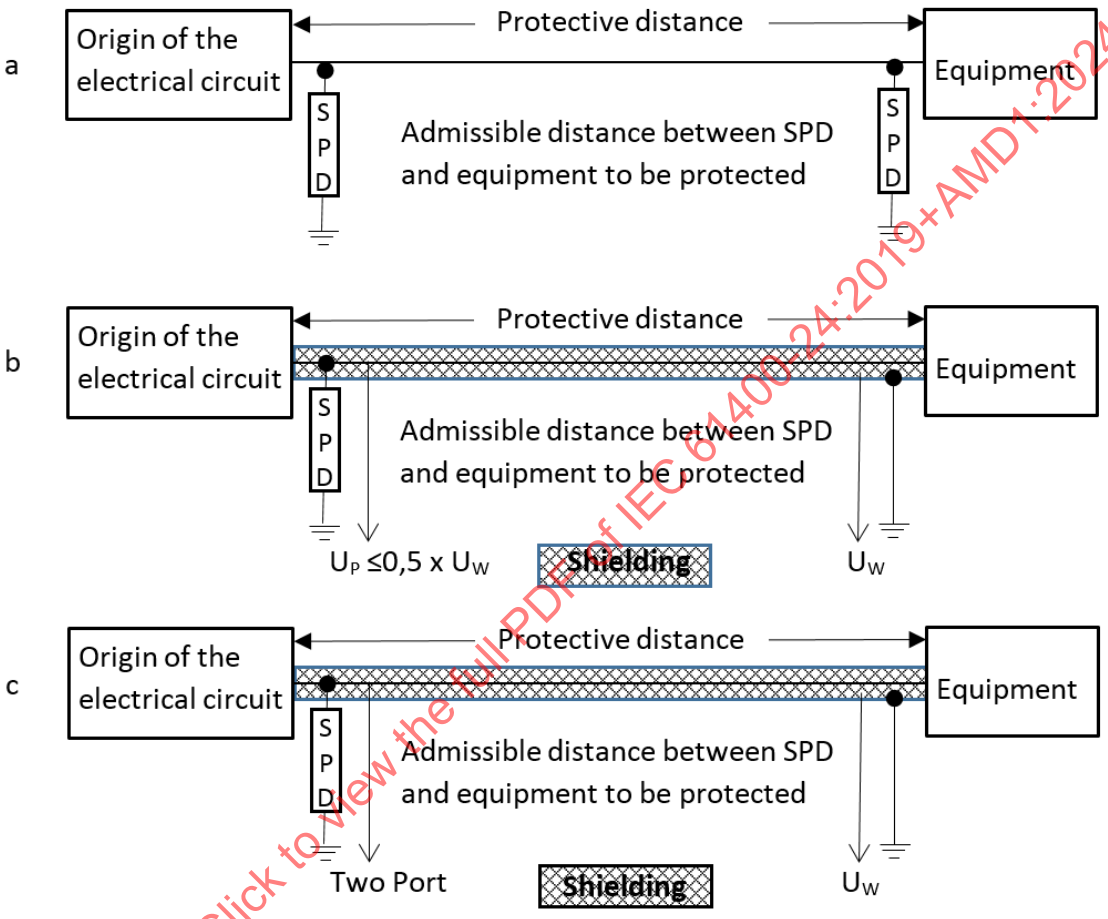

Figure 8 – Additional protective measures

8.5.5.3 Selection of SPDs

SPDs that shall withstand a partial lightning current with the typical waveform 10/350 µs require a corresponding impulse test current I_{imp}. For power lines, a suitable test current I_{imp} is defined in the Class I test procedure of IEC 61643-11.

SPDs which shall withstand induced surge currents with the typical waveform 8/20 µs require a corresponding impulse test current I_n. For power lines, a suitable test current I_n is defined in the Class II test procedure of IEC 61643-11.

SPDs shall comply with:

- IEC 61643-11 for power systems;
- IEC 61643-21 for telecommunication and signalling systems.

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8.5.5.4 Installation of SPDs

SPDs shall comply with the installation rules given in

- IEC 60364-4-44, IEC 60364-5-53 and IEC 61643-12 for the protection of power systems;
- IEC 61643-22 for the protection of the control and communication systems.

The installation locations of the SPDs shall be documented, e.g. by means of drawings and wiring diagrams according to the surge protection measures (SPM) system. For the SPDs installed at the different LPZ boundaries and possible surge protection components installed inside equipment, the requirements for energy coordination in accordance with IEC 62305-4 and IEC 61643-12 shall be fulfilled.

According to IEC 62305-4, considerations shall be made regarding the coordination of SPDs in the electrical and control systems. Sufficient information shall be provided in the documentation on how coordination between SPDs is achieved.

Further guidelines for the bonding (earthing) and cabling of electrical and control systems and installations are given in 8.5.1 to 8.5.4 and exemplified in Annex G.

8.5.5.5 Environmental stresses

SPDs shall withstand the environmental stresses characterising the installation place such as:

- ambient temperature;
- humidity;
- corrosive atmosphere;
- vibration and mechanical shock.

If no specific values are specified by the wind turbine manufacturer, SPDs installed in the nacelle or in the turbine tower could be stressed by vibrations with the following parameters:

– frequency: 0,1 Hz to 10 Hz;
– acceleration: 0,5 m/s^2.

These typical values of vibration withstand of SPDs used in wind turbine systems are based on EN 50539-22 and can be applied if no other information is available.

Depending on conditions at the point of installation within the wind-turbine, additional and specific requirements on the performance and installation of SPDs might arise. If necessary, the manufacturer of the wind turbine should take into account the environmental conditions for specific points of installation, e.g. nacelle and hub.

8.5.5.6 Maintenance

Maintenance and replacement of SPDs shall be done according to a maintenance plan provided in the wind turbine service and maintenance manuals.

SPDs shall be installed in such a way that they can be inspected and exchanged.

8.5.5.7 SPD monitoring

SPD protection of critical parts of the electrical and control systems of wind turbines may require monitoring.

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8.5.5.8 Selection of SPDs with regard to protection level (U_p) and system immunity

The required protection level U_p in an LPZ shall be defined in accordance with the established immunity levels of the equipment in the LPZ as described in 8.5.3.

8.5.5.9 Selection of SPDs with regard to continuous operating voltage (U_c)

Specific requirements with regard to continuous operating voltage (U_c) of the SPD might apply to SPDs owing to large voltage variations and temporary overvoltages within the electrical system of a wind turbine. In such cases, the relevant parts of the electrical systems and voltage levels, current levels and duration shall be identified by analysis and/or testing and SPDs selected accordingly.

For the selection of SPD protection, the source alternator excitation circuit and the line side circuit of the source, the following parameters need to be considered in addition:

- the maximum voltages (L-L and L-Earth) including regulation tolerances,
- U_c should be selected so as to sustain the stress of repetitive transients superimposed on the operating voltages,
- the maximum frequency,
- operating frequency should be selected taking into account the switching frequency of the source.

Further examples hereof are given in Annex F.

Evidence shall be provided that the selected SPDs can withstand these specific stress levels.

8.5.5.10 Selection of SPDs with regard to discharge current I_n and impulse current I_{imp}

An analysis of the lightning current distribution within the wind turbine in accordance with IEC 62305-1 and IEC 62305-4 is recommended. Based on these calculations, SPDs can be selected with regard to discharge current I_n and impulse current I_{imp}.

SPDs for particularly exposed circuits may require higher ratings than those given in IEC 60364-5-53 or such circuits could be shielded. Such circuits particularly exposed to either high stresses or repeated stresses should be identified by analysis. If applicable, such exposed circuits within the electrical and control systems of a wind turbine shall be documented in the wiring diagrams by the wind turbine manufacturer. Further information hereof is given in Annex F.

8.5.5.11 Selection of SPDs with regard to short-circuit current and the follow current interrupt rating

The short-circuit withstand current rating of the combination of the SPD and the overcurrent protective device (OCPD – e.g. a fuse) and the follow current interrupt rating of the SPD as declared by the SPD manufacturer shall be equal to or higher than the maximum short-circuit current expected at the point of installation. In addition, when a follow current interrupt rating is declared for the SPD, it shall be confirmed by either calculation or testing that the actual OCPD installed in the specific power circuit does not operate.

8.5.5.12 Behaviour of SPDs in case of multiple lightning flashes

Owing to the relatively high frequency of lightning flashes to wind turbines and the critical nature of the installation of SPDs within wind turbines, SPDs shall be able to withstand multiple lightning flashes.

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8.5.5.13 Protection against transient switching overvoltages created within wind turbines

Transient overvoltages and surges caused by switching operations in electrical systems (switching electromagnetic impulse, SEMP) needs to be considered as well. However, it is outside the scope of this document. For general information, the reader is referred to IEC TR 62066 for discussion of switching overvoltages.

Protection against transient switching overvoltages can be provided by installing SPDs located as close as possible to the origin of such threats. Overvoltages due to switching can be longer in duration and can contain more energy than the transient overvoltages of atmospheric origin. This has to be considered for the selection of SPDs with regard to nominal discharge current and impulse discharge current.

Clause F.7 gives some information on the selection of SPDs with regard to overvoltages created within wind turbines.

8.5.6 Testing methods for system immunity tests

System immunity tests in accordance with Annex H shall be performed for systems with power ports or signal ports connected to incoming lines coming from LPZ 0_A or 0_B (with partial lightning currents flowing on these lines). Typical examples are warning and control systems mounted on the top of the nacelle, e.g. aviation light, electronics inside blades.

For all other electrical systems, the tests in Annex H give additional information about the system level immunity – see also 8.5.5.8.

8.6 Electrical high-voltage (HV) power systems

Large wind turbines are usually connected via a high-voltage (HV) transformer to an underground HV cable system, which may connect an array of wind turbines either directly to the grid or to a transformer station stepping up the voltage to that of the sub-transmission system at for example 132 kV.

The wind turbine HV transformer is usually placed in the nacelle, in the bottom of the tower or next to the wind turbine tower.

HV surge protection devices are usually referred to as surge arresters. In a wind turbine application, surge arresters serve to protect the transformer and the high-voltage system in general against earth potential rise due to lightning currents passing through the wind turbine earthing system, and to protect against transients entering the wind turbines from the HV cable system outside the wind turbine. The need for surge arresters on the HV side of the transformer should be evaluated based on the principles in IEC 62305-2 and IEC 60071 (see Clause 7 and Annex B).

Assessment of the levels of transients coming from the HV cable system outside the wind turbine requires special transient electrical network simulations. The studies should be made in accordance with the IEC 60071 series. In case such studies are not performed, HV surge arresters are advisable as a general precaution. See also IEC 62305-4 for guidance on how to use transient network simulations.

HV surge arresters should be metal-oxide surge arresters without gaps in accordance with IEC 60099-4 and should be selected and applied in accordance with IEC 60099-5.

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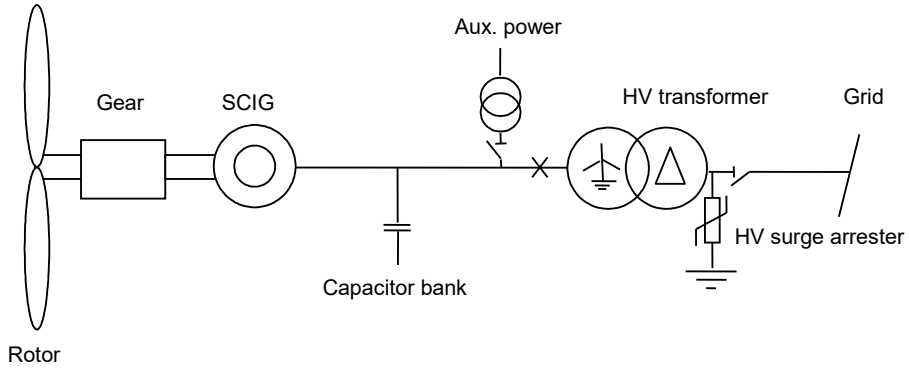
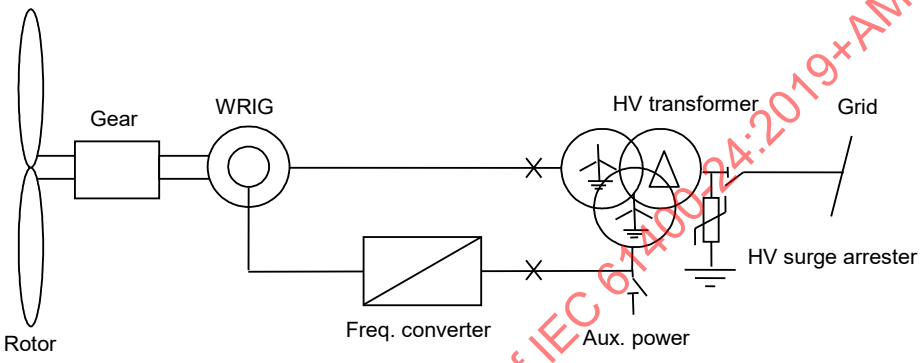


a) Squirrel cage induction generator (SCIG)



b) Doubly fed induction generator (DFIG)

Figure 9 – Examples of placement of HV arresters in two typical main electrical circuits of wind turbines

High-voltage surge arresters should preferably be placed at the HV transformer terminals as shown in Figure 9, thereby providing maximum protection for the transformer. However, as it may be convenient to place surge arresters at a distance from the object to be protected, the allowed distance shall be decided by calculation. A distance of up to 10 m between the arrester and the object to be protected can usually be allowed. If the distance is larger or circumstances require a closer study, it is necessary to decide if for instance arresters at the bottom of the tower can provide the needed protection for a transformer placed in the nacelle. If the transformer is placed outside the tower, it is important that the transformer earthing system is connected to the wind turbine earthing system, and preferably it should be one earthing system.

SPDs on the low-voltage (LV) side of the HV transformer are probably an appropriate general precaution, particularly if significant transients may pass through the transformer from the high-voltage side, in which case a type of SPD for transformer application should be chosen (i.e. SPDs with high energy absorption capability). The transient capacitive and inductive coupling between the HV and LV sides of a transformer, and therefore also the transient levels transferred to the LV side, depend very much on the design of the transformer and particularly on the earthing connection of the LV winding (refer to IEC 60071-2:2018, Annex E for further information). It is therefore advisable as a general precaution to install SPDs on the LV side of the transformer, or alternatively to obtain a sufficiently detailed transformer model from the manufacturer for transient studies in order to decide if SPDs are required on the LV side of the transformer.

NOTE IEC 60204-11 states general requirements for high-voltage systems on machinery.

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9 Earthing of wind turbines

9.1 General

9.1.1 Purpose and scope

To disperse lightning currents and prevent damage to a wind turbine, an efficient earthing system is essential. The earthing system shall furthermore protect people and livestock against electric shock. When faults occur in the electrical grid, it is necessary to keep the touch and step voltages and the overall earth potential rise to a safe level until protection devices have tripped and safely interrupted the flow of fault current. For lightning flashes, the earthing system shall be designed to disperse and conduct high-frequency and high-energy lightning current into the earth without any dangerous thermal and/or electrodynamic effects.

It is generally recommended that one earthing system is established for a wind turbine to be used for lightning protection as well as for power system earthing purposes. Furthermore, it is recommended to include metal parts in the foundation structures in the earthing system, because using the metal parts of the large foundation structures will result in the lowest possible earthing resistance, and because attempting to separate an earthing system from the metal parts of the foundation would represent a structural hazard, particularly for concrete foundations.

Concerning the design of the earthing system to prevent high-step and touch voltages due to failures in high-voltage components, please refer to high-voltage electrical codes such as IEC 61936-1 and IEC TS 61936-2, IEC 60364-5-54, IEC 60364-6 and relevant national standards. In relation to human safety, refer to IEC TS 60479-1 and IEC TR 60479-4.

It is outside the scope of this document to specify lightning protection systems and earthing systems for wind farms as a specific design study needs to be done for each wind farm considering the site-specific conditions and the power and communication interconnections between wind turbines and to the outside systems. Guidance with regards to earthing systems for wind farms is included in informative Annex Q.

9.1.2 Basic requirements

The earthing system of the wind turbine shall be designed to provide sufficient protection against damage due to fault currents and lightning strikes intercepted by the turbine. The design of the earthing system shall correspond to the LPL for which the wind turbine protection system is designed.

The earthing system shall be designed to meet four basic design requirements:

a) ensure personal safety with regard to the step and touch voltages which appear during earth faults and lightning current exposure;

b) prevent damage to equipment;

c) withstand the thermal and electrodynamic forces it will be subjected to during a fault current and lightning exposure;

d) have sufficient long-term mechanical strength and corrosion resistance.

9.1.3 Earth electrode arrangements

Two basic types of earth electrode arrangements that are described in IEC 62305-3 apply to wind turbines:

- type A arrangement: This arrangement is not recommended for wind turbines, but can be used for minor buildings (for example buildings containing measurement equipment or office sheds that are connected to a wind turbine farm). Type A earthing arrangements are made with horizontal or vertical electrodes connected to not less than two down conductors on the structures;

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NOTE For further information on type A arrangements, see IEC 62305-3:2010, 5.4.2.1.

- type B arrangement: The type B arrangement is recommended for use with wind turbines. This type of arrangement comprises either an external ring earth electrode in contact with the soil for at least 80 % of its total length or a foundation earth electrode. The ring electrodes and metal parts in the foundation shall be connected to the tower structure.

9.1.4 Earthing system impedance

The conventional earthing impedance of the earthing system does not affect the efficiency of the air termination system and down conducting system. The earthing system shall be designed to have as low an impedance as possible to reduce the total voltage drop when conducting transient lightning currents (i.e. minimise the earth potential rise), to reduce the partial lightning current flowing into the service lines connecting the wind turbine and to reduce the risk of sparks to other service lines close to the earthing system.

The party responsible for designing the foundation shall document the remedies implemented to reduce the earth potential rise when exposed to direct lightning attachment with stroke current of I rise time corresponding to LPL I. The documentation shall show how compliance with IEC 62305-3 is achieved, and how surge frequency impedances of the earthing system are considered with regard to touch and step voltage, DC and transient earthing system voltage rise.

Additional information is included in I.2.2.

9.2 Equipotential bonding

9.2.1 General

Equipotentialisation is achieved by interconnecting the LPS with

- structural metal parts;
- metal installations;
- internal systems;
- external conductive parts and service lines connected to the structure.

When lightning equipotential bonding is established to internal systems, part of the lightning current may flow into such systems and this effect shall be taken into account.

The manner in which lightning equipotential bonding of service lines such as telecommunication and power lines is achieved is important and shall be discussed with the operator of the telecommunication network, the electric power system operator and other operators or authorities concerned, as there may be conflicting requirements.

9.2.2 Lightning equipotential bonding for metal installations

Lightning equipotential bonding connections shall be made as direct and as straight as possible.

The minimum values of the cross section of the bonding conductors connecting different bonding bars/points and of the conductors connecting the bars/points to the earth termination system are listed in IEC 62305-3.

The minimum values of the cross section of the bonding conductors connecting internal metal installations to the bonding bars/points are listed in IEC 62305-3.

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9.3 Structural components

9.3.1 General

In general, all structural conducting components of the wind turbines will be able to conduct a part of a lightning current and thus equipotential bonding of structural conducting components shall be made.

9.3.2 Metal tubular type tower

The tower shall be considered as the primary protection earth conductor (PE) and equipotential bonding connection.

Due to the height of the towers, direct lightning attachment to the tower structure shall be expected and thus considered in the design of the tower. All electrical conducting components and all major metal parts that may conduct lightning current shall be bonded to the tower. The tower shall be used as the down conductor and constructed in such a way that lightning current can flow unobstructed.

9.3.3 Metal reinforced concrete towers

The tower shall be considered as the primary protection earth conductor (PE) and equipotential bonding connection. Due to the height of the tower, direct lightning attachment to the tower structure shall be expected and thus considered in the design of the tower (see IEC 62305-3).

External lightning protection systems can be considered for use with concrete towers, but should always be bonded to the steel reinforcement of the tower.

Equipotential bonding outlets connected to the steel reinforcement shall be placed at strategic termination points for bonding of equipment inside the tower. The reinforced concrete tower shall be designed in accordance with 9.3.6.

Due to the increasing height, towers are also designed as "hybrid towers" where the upper part is designed as a metal tubular tower (see 9.3.2). The lower part is designed as a metal reinforced concrete tower. Special attention shall be paid to the equipotential bonding connections placed between the upper and lower part of the tower. These connections need to be distributed around the platform-tower interface wall at several positions at equal spacing around the perimeter in order to effectively provide electromagnetic shielding of the inside of the tower and facilitate the protection of internal installations. These connections shall withstand the electromechanical and thermal effects of lightning current (see IEC 62305-3). This can be achieved by choosing components that have successfully been tested in accordance with IEC 62561-1.

For concrete towers wholly or partly constructed of elements and anchoring steel wires, tendons, flanges and similar designs (e.g. modular pre-cast towers), all parts and connections of such systems shall be able to sustain the effects of conducting the relevant level of lightning current and the corresponding electrodynamic forces (see IEC 62305-3) without compromising the mechanical design requirements.

9.3.4 Lattice tower

A lattice tower protects the inside of the tower against direct lightning attachment and provides some reduction of the lightning electromagnetic field, hence the space inside the tower is defined as LPZ 0_B. The lightning down conduction should be done via the lattice tower structural elements, which therefore have to fulfil the dimensions required for down conductors stated in IEC 62305-3 taking current sharing between the parallel paths into account.

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Some protection for cables can be achieved by placing them in the inside corners of the tower leg metal profiles. Shielding cable conduits or trays placed inside the lattice tower will also provide protection.

9.3.5 Systems inside the tower

The inside of the tower shall have its LPZ defined for which the protection level required for internal equipment shall be evaluated as discussed in 8.5.

Ladder systems shall be bonded to the tower at each end and at every platform. It shall be ensured by bonding that touch and step voltages never exceed values listed in IEC 62305-3.

Rails, guides for hoists, hydraulic piping, tendons, wires for personal protection and other components passing through a tower shall be bonded at each end.

If relying on separation distance in the design, this shall be specifically addressed and documented.

The HV transformer earthing system should be connected to the wind turbine earthing system. It is not recommended to use separate earthing systems for power systems and lightning protection.

9.3.6 Concrete foundation

Since the metal reinforcement of the wind turbine foundation will always be part of the lightning or fault current path to remote earth due to the mechanical and electrical connections to the tower, the metal reinforcement in a foundation shall always be considered a part of the LPS.

Electrical continuity of steelwork in reinforced concrete structures shall be ensured. Steelwork within reinforced concrete structures is considered to be electrically continuous if the major parts of vertical and horizontal bars are connected. Connections between metal reinforcement parts shall be either welded, clamped or overlapped by a minimum of 20 times their diameters and bound by conductive thread or otherwise securely connected. Special care should be exercised at the interconnections to prevent damage to the concrete due to localised arcing across poor contacts.

The connections between reinforcement elements shall be specified by the designer, and the installer shall carry out QA control of connections. The requirement for short and straight connections for the lightning protection earthing shall be recognised at all times.

If the metal reinforcement is used for the power system protective earth, the thickness of the metal reinforcement rods and the connections shall comply with the requirements for power system earthing systems which are usually stipulated in the electrical code.

Outlets for additional bonding, measurement or expansion of the earthing system shall be made at appropriate locations on the foundation.

9.3.7 Rocky area foundation

In rocky areas, the lowest resistivity is normally in the surface of the rock. ITU-R P.832-3 provides maps showing regions where high resistivity rock with conductivity of 1 mS/m or less (resistivity of 1 000 Ωm or more) is expected

The B type earth termination system shall be used. See I.1.1 for further information on design details.

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A low-frequency ground potential rise study needs to be done to analyse the conditions of the individual site, and the earthing system shall be designed based on this and fulfilling the requirements to allowed touch and step voltages.

Rock anchor bolts shall be interconnected to each other and to the ring earthing system. If metal reinforced concrete is used, please refer to 9.3.6.

In rocky areas, it may not be possible to reach a low earthing resistance without establishing very extensive earthing systems. In such areas, emphasis should therefore be on providing surface potential difference control to limit touch and step voltages at the surface where people and livestock are likely to be standing, such as by placing one or more ring electrodes around the wind turbines and other installations, while providing surge protection for all service lines connecting the wind turbines to the power collection system and communication systems (see 8.5).

9.3.8 Metal mono-pile foundation

A metal mono-pile foundation is by nature a large earth electrode. It shall be used as the primary earth electrode.

A ring electrode system for controlling the surface potential gradients close to the foundation may be necessary depending on soil resistivity.

9.3.9 Offshore foundation

The resistivity of seawater is considerably lower than most soils (See ITU-R P.832-3 for information on seawater resistivity). Therefore, for an offshore foundation, such as a mono-pile or metal reinforced concrete foundation, the earthing system requirements are considered fulfilled and no additional measures such as ring electrode, etc. are required. Interconnection of offshore foundations other than by the connection of power collection system cable shields to local earth at both ends is generally not required.

External earthing systems of copper cannot be used off shore due to corrosion issues.

9.4 Electrode shape dimensions

The minimum length, l_1, of earth electrodes depends on the lightning protection level (I-IV) and on the soil resistivity.

For soil resistivities higher than 500 Ωm, the minimum length, l_1, increases linearly up to 80 m at a soil resistivity of 3 000 Ωm.

A type B arrangement comprises either a ring conductor external to the structure to be protected, in contact with the soil for at least 80 % of its total length, or a foundation earth electrode. Such earth electrodes may also be meshed.

For the ring earth electrode (or foundation earth electrode), the mean radius, r_e, of the area enclosed by the ring earth electrode (or foundation earth electrode) shall not be less than the value l_1:

$$r_e \geq l_1 \tag{20}$$

Where l_1 is represented in Annex I, Figure I.1 according to LPS levels I, II, III and IV.

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When the required value of l_1 is larger than the convenient value of r_e, additional horizontal or vertical (or inclined) electrodes shall be added with individual lengths l_r (horizontal) and l_v (vertical) given by the following equations:

$$l_r = l_1 - r_e \quad (21)$$

$$l_v = (l_1 - r_e)/2 \quad (22)$$

The number of electrodes shall be not less than two.

The additional electrodes should be connected as equidistantly as possible.

The stated minimum length, l_1, can be disregarded if the earthing resistance of the earthing system is less than 10 Ω measured at a frequency different from power frequency (50 Hz to 60 Hz) and low order harmonics hereof.

Information about the soil resistivity, prospective earth fault current and clearance time is of utmost importance in the planning of the correct design and installation of the earthing system.

The soil resistivity will differ very much depending on the character of the soil. Methods for calculating the necessary earth electrode according to geometrical and physical shapes are given in Annex I.

9.5 Execution and maintenance of the earthing system

The earthing system designer shall prepare an installation plan, which describes the layout of the earthing system with details of connection points, the use of connectors, clamps and welds, the position and amount of outlets and their type and quality.

Inspection shall be carried out during construction work, particularly before casting of concrete.

NOTE Electrical codes can require measurement of the earthing resistance.

A service and maintenance manual shall describe how often and how to inspect and maintain the earthing system. The inspection intervals should be agreed between the designer and the operator of the wind turbines. It should take into account aggressive environments where more regular inspection might be necessary. If components in the earthing system are expected to have a certain service life time, the inspection interval cannot be longer than the shortest expected service life time of the components.

10 Personal safety

Erection of large wind turbines on land takes several days when including the time it takes to assemble and disassemble the very large cranes that are used. Offshore wind turbines on the other hand may be erected within less than a day by the use of special vessels or jack-ups. In any case, there is usually up to a few weeks of post erection completion work before the wind turbine is commissioned. During this time, many people work in, on and around the wind turbine, and they are at considerable risk of being affected if lightning strikes the wind turbine.

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Therefore safety procedures with regard to lightning should be established. Such procedures should include:

- regular checking of local weather forecasts (e.g. every morning);
- first aid training for personnel in relation to lightning injuries and injuries due to electrical accidents;
- application of intermediate earthing system connections as soon as possible;
- identification of safe locations;
- information about signal for lightning warning to everybody on the site;
- personnel instructions to
  - keep lookout for developing thunderclouds, audible thunder and visible lightning;
  - be aware of signs of high electrical fields from thunder clouds, such as hair standing on end, crackling sounds or light glow from pointed extremities such as air termination systems;
  - interrupt work and go to nearest safe location when lightning threat has been realised or lightning warning signal is received.

Such safety procedures should be included in the health and safety plan of the construction site and should be included in the wind turbine erection manual as well as the service and maintenance manual provided by the wind turbine supplier.

Safe locations should be clearly identified by marking (e.g. pictograms).

Weather bureaus usually provide reasonably accurate thunderstorm forecasts and even provide warning services by telephone, text messages, or internet, which should definitely be considered. However, it should not replace instruction of people on site to keep lookout for developing thunderclouds, thunder (audible within 10 km to 15 km) and lightning (visible within ~ 30 km). Local area and even portable lightning detection and thunderstorm warning devices, which could be useful, are available from different manufacturers. Refer to Annex L for further information on lightning monitoring systems.

Some lightning warning systems may not provide warning of all lightning flashes, especially of the first lightning flash in a developing storm (see IEC 62793 for information on thunderstorm warning systems). Therefore, it is essential that all personnel are made aware of the risk of lightning to their personal safety.

During construction work, connection of cranes, generators, etc. to the earthing system should be made as soon as possible.

People working on the outside of the nacelle and on the blades are definitely not safe, just as people stepping out of the wind turbine tower, standing next to the tower, climbing ladders, touching or working on electrical circuits, hardwired communication system etc. will be at risk if lightning strikes the wind turbine. They should therefore be instructed to stop work and go to safe locations until the danger is over.

Platforms inside tubular towers are in general considered safe locations, as the tower is a near to perfect Faraday cage. People in the wind turbine should be instructed to stop work and go to the closest platform inside the tower and stay there until the thunderstorm has passed. Other safe places are inside metal roof vehicles, metal containers, etc.

As it may be difficult to communicate effectively in a construction area, some kind of acoustic warning signal, radio or equivalent effective means of wide area warning should be agreed (it could just be repeated honking of a car horn or a compressed air horn).

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The wind turbine documentation shall define safe locations in the wind turbine including necessary personal safety distances and other precautions to be taken by people while at the safe location, such as instructions to stand or sit on the platforms and avoid touching electrically conducting systems extending vertically in the tower.

The separation distance as defined in IEC 62305-3 can be used to calculate the personal safety distance to avoid uncontrolled flashovers to persons at the safe locations.

11 Documentation of lightning protection system

11.1 General

This clause summarises all documentation required in other clauses. The descriptions are shortened and grouped for improved overview.

Documentation during assessment for design evaluation is given in 11.2, and for site assessment in 11.3. Documentation needed prior to inspection of lightning protection systems is given in 11.4, and manuals are listed in 11.5.

The documentation may either be a separate lightning protection document, or references to the other documentation where the information is available.

11.2 Documentation necessary during assessment for design evaluation

11.2.1 General

General documents (11.2.2) shall have the focus on the wind turbine as a whole and showing the protection philosophy used. They shall have links to the other, more detailed documents for rotor blades, mechanical, electrical, bonding, earthing and other systems (11.2.3 through 11.2.7).

11.2.2 General documentation

a) General arrangement drawing (single-line representation) of the wind turbines lightning-protection, comprising:
   1) the separate structures and the connections;
   2) circuit diagrams showing LPZ and their boundaries, Annex E give basic examples for such a documentation;
   3) lightning air termination systems;
   4) location of lightning down conductors;
   5) earth electrodes and surface potential control;
   6) location of the bonding conductors and bonding bars;
   7) location of SPDs;
   8) cable shield bonding points.

b) Design
   1) description of how the lightning current is conducted away from the interception points and through the wind turbine to the earthing system;
   2) lightning protection level used for the design;
   3) if less than LPL I is used the risk assessment should be documented;
   4) an analysis of the lightning current distribution within the wind turbine;
   5) selection and verification of SPD's energy coordination;
   6) specification of materials used, including corrosion properties and corrosion protection;
   7) identification of wear parts and maintenance-free parts of the LPS.

c) Personnel safety procedures with regards to lightning.

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11.2.3 Documentation for rotor blades

a) Drawing of the rotor blades containing:
   1) down conductor cross-sectional areas;
   2) any additional conductive components;
   3) connection between individual down conductor segments.

b) Description containing:
   1) mounting of the air termination and down conductor systems;
   2) measures taken to avoid internal arcing in the blade;
   3) definition of the required inspection and maintenance for the air termination system, spark gaps or sliding contacts;
   4) definition of required inspection and maintenance for down conductor system and connection components;
   5) instructions for inspection and maintenance, including definition of replacement criteria for wear parts.

c) Documentation of method of verification showing the ability of the air-termination and down conductor system to sufficiently intercept lightning strikes and conduct lightning currents.

11.2.4 Documentation of mechanical systems

a) Verification of lightning-current-conducting capability.

b) Descriptions of measures taken to protect bearings and hydraulic systems from the effect of lightning current. The description shall contain documentation and evidence of its proven technology and/or test reports verifying the effectiveness of protection measures.

c) If no protection is provided, test reports are required showing that even with regular lightning impacts, the bearings are able to be operated for the design lifetime.

11.2.5 Documentation of electrical and electronic systems

a) electrical and electronic systems shielding and installation design;

b) SPD selection and coordination;

c) immunity levels of the equipment;

d) maintenance plan for SPDs;

e) analysis defining the need for high-voltage arresters.

11.2.6 Documentation of earthing and bonding systems

a) general electric equipotential plan for all bonding and earthing in the turbine, showing the general electrical equipotential bonding system;

b) descriptions and drawings containing relevant data;

c) specification of materials used, including corrosion properties and corrosion protection applied;

d) description of QA (quality assurance) control to be made to connections in the LPS.

11.2.7 Documentation of nacelle cover, hub and tower lightning protection systems

a) Drawing containing the following information:
   1) nacelle cover, spinner showing metal parts used as lightning air termination system;
   2) air termination systems;
   3) bonding points;
   4) description and marking of earth system connection points if applicable;
   5) metal nets or closed metal conduits, where applicable;
   6) the shielding measures for the hub and nacelle;
   7) marking of measurement points.

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b) Test reports or certificates of used LPS components if applicable.

c) Bonding of external lightning protection systems for concrete towers to the reinforcement metal of the tower.

d) Lattice tower structural elements dimensions.

11.3 Site-specific information

Site-specific information and documentation is not part of the design evaluation of a wind turbine.

a) Lightning occurrence in the region of the wind farm site.

b) For earthing documentation additionally:

   1) soil resistivity;

   2) earth fault current;

   3) earth fault clearance time;

c) Health and safety plan for the construction site with respect to lightning and thunderstorms.

11.4 Documentation to be provided in the manuals for LPS inspections

a) description of the LPS;

b) description of earthing system;

c) reports of previous inspections, if relevant;

d) visual LPS inspection report template;

e) complete LPS inspection report template.

11.5 Manuals

The following manuals (instructions), which can be combined, shall cover relevant issues with regards to lightning protection and earthing systems:

a) foundation installation and maintenance manuals;

b) tower installation and maintenance manuals;

c) wind turbine transport, assembly and commissioning manuals;

d) wind turbine operation, service and maintenance manuals.

12 Inspection of lightning protection system

12.1 Scope of inspection

As part of the lightning protection concept, an inspection programme shall be defined and included in the wind turbine manuals. The objective of the inspections is to ensure that:

- the LPS continues to conform to the original design based on this document;
- all components of the LPS are in good condition and capable of performing their designed functions.

The LPS shall be designed in a way that enables the operator to inspect the vital parts of the system.

The manufacturer of the wind turbine is responsible for making an inspection plan/inspection instruction and including self policing points in work instructions, wind turbine service and maintenance manuals, and foundation maintenance manual, etc.

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12.2 Order of inspections

12.2.1 General

An inspection programme shall be established. Inspections should be performed in accordance with 12.1 and shall at least be performed during the following processes:

- production of the wind turbine;
- installation of the wind turbine;
- commissioning of the wind turbine;
- at reasonable intervals with regard to the location of the wind turbine (general maximum intervals between regular inspections are given in Table 6);
- after situations where parts of the wind turbine have been dismounted or repaired (i.e. blades, main components, controls systems, etc.).

12.2.2 Inspection during production of the wind turbine

The inspection programme can be done by quality inspectors or by self policing according to statements in the inspection plan. During the production, erection and installation of the wind turbine, it shall be secured that all installations and measures related to lightning protection are done properly. All important details shall be described in work instructions, etc.

12.2.3 Inspection during installation of the wind turbine

The earthing system shall be inspected carefully during the installation, with special focus on:

- mechanical damage during excavation and back filling;
- mechanical stability during casting;
- electrical connectivity to other steel parts (e.g. stairs on the outside);
- connection to foundation earthing systems;
- connection to external earthing systems;
- galvanic corrosion.

There might be other parts of the system not visible for inspection afterwards, which will require special focus during installation.

12.2.4 Inspection during commissioning of the wind turbine and periodic inspection

As part of the commissioning of the wind turbine, the lightning protection system shall be inspected. This shall be performed at least by visual inspection – and by continuity measurement in places where the LPS cannot be inspected. Continuity measurements shall be made in accordance with IEC 62305-3 and shall be made with an appropriate instrument, such as a four-wire micro ohm meter. Refer to Annex J for an example of defined measuring points.

NOTE Connections via brushes or spark gaps or equivalent can be short circuited if necessary to make a continuity measurement of other parts of the LPS.

When the inspection plan is made, it is important to take the following points into consideration:

- erosion and corrosion of air termination elements (only periodic inspection);
- mechanical and electrical properties of conductors, connections, sliding contacts or spark gaps;
- condition of connections, equipotential bonding, fixings, etc.;
- conditions of SPDs;

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- corrosion of earth electrodes (only periodic inspection).

With certain intervals (given in Table 6), a complete inspection including measurements of continuity in vital parts of the LPS and inspection of SPDs that are not monitored shall be performed.

The blade manufacturer and the wind turbine manufacturer may in his service and maintenance manuals define specific LPS inspection intervals as a function of N_d, the number of lightning flashes to the wind turbine per annum based on the durability of the lightning protection design documented by analysis and testing. Maintenance may depend on lightning strike occurrence if lightning strikes to the wind turbine are monitored.

Continuity measurements can be made with an appropriate four-wire resistance meter, to verify the continuity. The pass criterion to be used may depend on the design and shall therefore be defined by the manufacturer. Lack of continuity is clearly a failure, but measurement of continuity itself does not validate the design.

The objective with the measurement is to demonstrate the continuity of the connection and not to get a certain value.

The specific values can be used as references between periodic measurements. Measuring points and pass criteria shall be defined in the service and maintenance manual.

Preferably, continuity of down conductors in wind turbine blades should be ensured by the construction of the system and checked during manufacturing so that continuity measurements in the field are not needed.

The manufacturer shall provide an inspection plan for the different parts of the LPS that needs to be inspected. The plan shall define how often and how the different parts shall be visually inspected and/or inspected by measurement. A general LPS inspection plan is provided in Table 6, which shall be used if an inspection plan is not provided by the manufacturer. Other inspection intervals than those stated in Table 6 may be used if the manufacturer provides documentation for the inspection intervals relevant for the specific LPS design.

Table 6 – LPS General inspection intervals

Protection level	Visual inspection (every X year)	Complete inspection including continuity measurements (every X year)
I and II	1	2
III and IV	1	4

12.2.5 Inspection after dismantling or repair of main parts

After dismantling or repair of main parts of the wind turbine, it shall be ensured that all installations related to the LPS are restored properly. If necessary, a full inspection shall be performed.

When the wind turbine is in normal operation, the inspection frequency will be determined in accordance with the local environmental conditions, but it shall be specified that the wind turbine is inspected as defined in 12.2.4.

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12.3 Maintenance

Regular inspection is a fundamental condition for a reliable maintenance of a wind turbine LPS.

If the design of the LPS comprises wear parts (air termination points, mechanical sliding contacts, spark gaps, surge protection devices, etc.), it shall be ensured that these parts are maintained regularly during the periodic inspections – and in accordance with their expected service lifetimes – or that they are monitored by an automatic monitoring system that informs the operator of the wind turbine that a component is faulty.

All worn or defective components shall be changed without delay.

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Annex A
(informative)

The lightning phenomenon in relation to wind turbines

A.1 Lightning environment for wind turbines

A.1.1 General

The objective of this Annex A is to present in short form the most necessary information relevant for understanding the lightning phenomenon and the processes involved when lightning interact with wind turbines. More comprehensive information is available in the literature [4].

A.1.2 The properties of lightning

Lightning can be regarded as a current source, and the four lightning current parameters of concern in connection with design and dimensioning of lightning protection are: the peak lightning current (I), the steepness of the lightning stroke current impulses ($\mathrm{d}i/\mathrm{d}t$), the charge transferred (Q) and the specific energy (W/R).

The recorded values of peak lightning current produced by a single stroke are in the range 2 kA to 300 kA. The maximum recorded values of charge transfer and specific energy are some hundreds of Coulombs (C) and, on very rare occasions, up to 20 MJ/Ω, respectively. These lightning current parameters govern the amount of physical damage that is done to wind turbine blades and/or the lightning protection system hardware. The stroke currents produce the high pressures that sometimes rupture blade composite structures. They also influence the magnitudes of lightning-indirect effects on electrical and electronic systems. The charge transferred produce melting at places of lightning attachment, such as the receptors, and at other places where lightning currents pass across gaps in the current path. The effects of the four lightning current parameters on lightning protection systems are summarised in Table A.3.

The maximum values of these parameters occur in only a small percentage of lightning flashes. The median value of peak lightning current is approximately 30 kA with median values of charge transfer and specific energy of 5 C and 55 kJ/Ω, respectively. In addition, the electrical characteristics of a lightning current vary with the type of lightning flash, season of the year and the geographical location.

The electric fields that immediately precede lightning attachments are also part of the lightning environment. These fields determine where lightning will attach to a structure, and whether non-conducting surfaces of the structure get punctured by streamers and connection leaders induced by these fields from internal conducting elements.

A.1.3 Lightning discharge formation and electrical parameters

Lightning flashes are produced following a separation of charge in thunderstorm clouds by processes described in the scientific literature (e.g. [4]). A lightning flash is observed when this charge is discharged to the earth or to a region of opposite polarity charge within the same cloud or a neighbouring cloud. The discussion that follows is concerned only with lightning flashes striking earth, resulting in the transfer of charge between a thundercloud and the earth.

A lightning flash usually consists of several components. The whole event following the same ionised path is called a lightning flash, which lasts up to about 1 s. The individual components of a flash are called short strokes and long strokes, where the latter are more commonly known as continuing currents.

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Lightning flashes are one of two basic types, downward or upward initiated. A downward initiated flash starts at the thundercloud and heads towards the earth. In contrast, an upward initiated flash starts at an exposed location on the earth (for example a mountain top) or at the top of a tall earthed structure and heads towards a thundercloud. Commonly, these basic types are referred to as "cloud-to-ground flash" or "downward flash" and "ground-to-cloud flash" or "upward (initiated) flash", respectively.

Both types of lightning are further sub-divided according to the polarity of the charge removed from the thundercloud. A negative flash lowers negative charge from the thundercloud to the earth. A positive flash results in positive charge being transferred from the thundercloud to the earth. The majority of lightning flashes are negative, making up about 90 % of all cloud-to-ground flashes. Positive discharges make up the remaining about 10 % of all cloud-to-ground flashes. Normally, the positive flashes exhibit the most powerful current parameters (i.e. higher I, Q and W/R), while the negative flashes exhibit the steepest current impulses (i.e. highest di/dt).

Each lightning flash is different due to the natural variations in the thundercloud that produced it and the individual paths to ground. For example, it is not possible to predict that the next lightning flash to a particular structure will have a peak current of a given value. What can be said is that the structure has a given probability of being struck by a lightning flash with current parameters exceeding a certain value.

Probability distributions of the electrical parameters that are used to describe a lightning stroke have been produced using direct measurements of actual strokes to tall towers. This statistical data on lightning current parameters is used in the lightning protection standards of the IEC 62305 series (see Table A.1). Further information is now becoming available worldwide from regional and national lightning location systems. These systems can record the location of a lightning stroke and estimate the peak current.

The probability distributions that describe the current parameters of a lightning are different for each type of lightning (upward/downward and positive/negative first, subsequent and continuing current). The appropriate probability distributions are described below along with the typical wave shape of each type of discharge. The probability level given indicates the probability of the specified current parameter of a particular lightning exceeding the tabulated value.

A.1.4 Cloud-to-ground flashes

A.1.4.1 General

A cloud-to-ground flash (downward initiated discharge) is initially formed by a preliminary breakdown within the cloud. The physics of this process are not fully understood at this time. The parts of the discharge process taking place below cloud level are much better known.

A.1.4.2 Negative cloud-to-ground flashes

In the case of a negative flash, a stepped leader descends from the cloud towards the ground in steps of several tens of metres with a pause time between the individual steps of approximately 50 μs. The steps have short-duration (typical 1 μs) impulse currents of more than 1 kA. The leader channel contains, when fully developed, a total charge of about 10 C or more. The channel diameter is in the range of up to a few tens of metres. The total duration of the stepped leader process is a few tens of milliseconds. The faint leader channel is usually not visible to the naked eye.

The end of the leader, the leader tip, is at a potential in excess of 10 MV with respect to the earth. As the leader tip approaches the earth, this high potential raises the electric field strength at the surface of the earth. When the electric field at ground level exceeds the breakdown value of air, "answering" (upward moving) leaders are emitted from the earth or from structures on the ground. These upward moving leaders are commonly called connecting leaders. Connecting leaders play an important role in determining the attachment point of a lightning flash to an object.

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When the descending stepped leader meets the upward moving connecting leader, a continuous path from cloud to ground is established. The charge deposited in the leader channel is then discharged to ground by a current wave propagating up the ionised channel at about one third of the speed of light. This process is called the first return stroke. The first return stroke may have a peak value of up to a few hundred kilo amperes and duration of a few hundred microseconds. The process of downward propagating lightning attachment is illustrated in Figure A.1, where it is illustrated that, relative to reference conditions (e.g. sea level), the exposure of objects on the ground is enhanced in areas with elevated ground and on mountains.

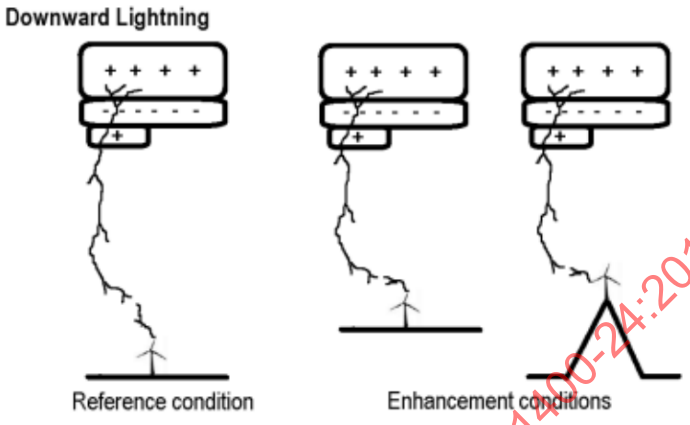

Figure A.1 – Processes involved in the formation of a downward initiated cloud-to-ground flash

After a time interval in the order of 10 ms to a few hundred ms, further leader/return stroke sequences may follow the path taken by the first return stroke. The (dart) leader preceding these subsequent return strokes is usually not stepped and much faster (duration of a few milliseconds). On average, a lightning flash contains three to four return strokes (including the first one). The return strokes constitute the visible part of the lightning flash.

Following one or more of the return strokes, a continuing current (also called a long stroke) may flow through the still-ionised channel. Continuing currents are quite different compared to the short-duration, high-amplitude currents of return strokes: the average current amplitude is in the range of a few hundred amperes, while the duration may be as long as several hundred milliseconds. Continuing currents transfer high quantities of charge directly from the cloud to ground. About one-half of all cloud-to-ground flashes contain a continuing current component.

Figure A.2 shows a typical profile of the lightning current in a negative cloud-to-ground flash. Following the contact of the stepped leader and the connecting leader, there is a first return stroke resulting (at ground) in a high-amplitude impulse current lasting for a few hundred microseconds. The current peak value is in the range of a few kA to 100 kA, the median value being about 30 kA (Table A.1). Following the first return strokes, subsequent return stroke(s) and continuing current(s) may occur. Although subsequent return strokes generally have a lower current peak value and a shorter duration than first return strokes, they generally have a higher rate of rise of current. Negative cloud-to-ground discharges may be composed of various combinations of the different current components mentioned above, as demonstrated in Figure A.5.

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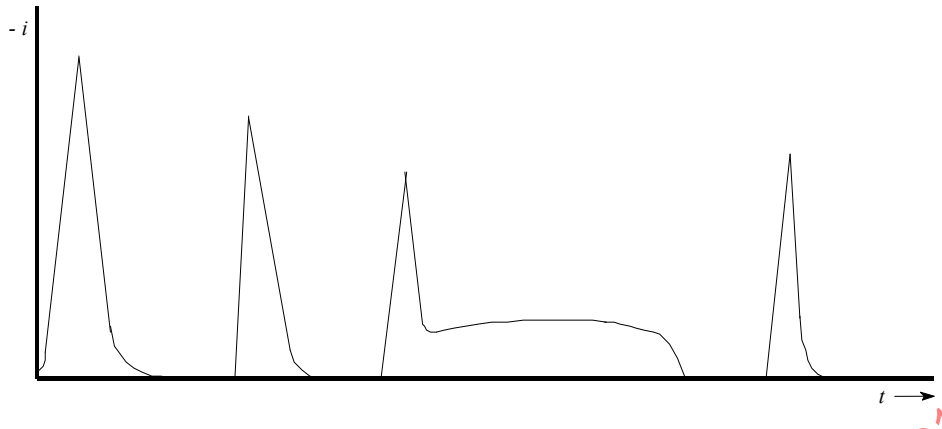
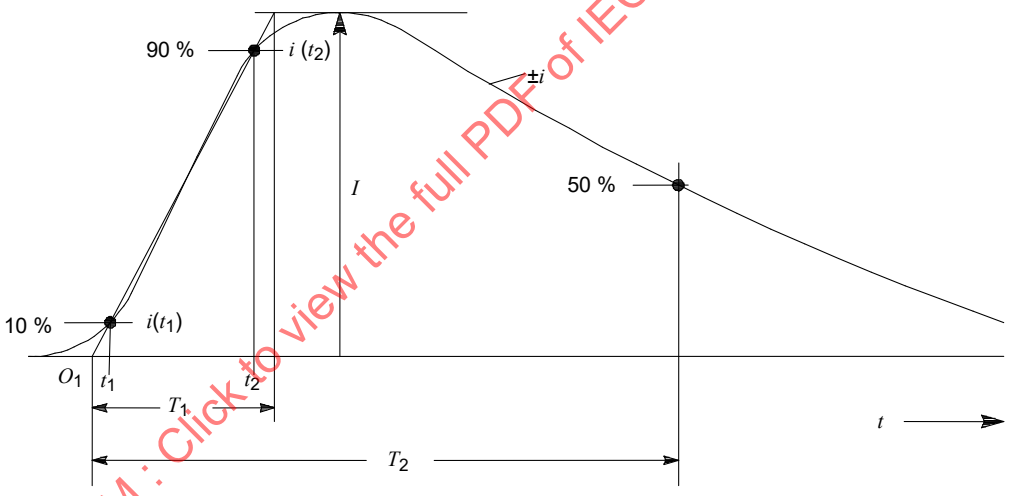


The drawing is not to scale.

Figure A.2 – Typical profile of a negative cloud-to-ground flash

A lightning current consists of one or more different strokes:

- short strokes with duration of less than 2 ms (Figure A.3);
- long strokes with duration of more than 2 ms (Figure A.4).



Key

O_1 virtual origin
I peak current
i current
t time
T_1 front time
T_2 time to half value

Figure A.3 – Definitions of short stroke parameters (typically T_2 < 2 ms)

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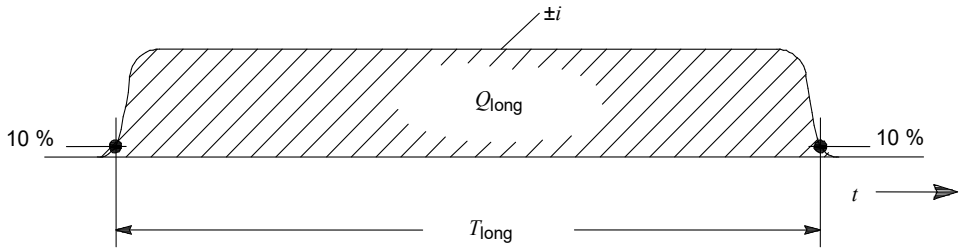

Key

T_{long} duration time

Q_{long} long stroke charge

This figure is adapted from IEC 62305-1.

Figure A.4 – Definitions of long stroke parameters (typically 2 ms < T_{long} < 1 s)

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Table A.1 – Cloud-to-ground lightning current parameters

Parameter	Fixed values for LPL I	Values			Type of stroke
		95 %	50 %	5 %	
I (kA)		4(98 %)	20(80 %)	90	First negative short stroke
	50	4,9	11,8	28,6	Subsequent negative short stroke
	200	4,6	35	250	First positive short (single) stroke
Q_{flash} (C)		1,3	7,5	40	Negative flash
	300	20	80	350	Positive flash
Q_{short} (C)		1,1	4,5	20	First negative short stroke
		0,22	0,95	4	Subsequent negative short stroke
	100	2	16	150	First positive short (single) stroke
W/R (kJ/Ω)		6	55	550	First negative short stroke
		0,55	6	52	Subsequent negative short stroke
	10 000	25	650	15 000	First positive short stroke
di/dt_{max} (kA/µs)		9,1	24,3	65	First negative short stroke
		9,9	39,9	161,5	Subsequent negative short stroke
	20	0,2	2,4	32	First positive short stroke
$di/dt_{30/90\ \%}$ (kA/µs)	200	4,1	20,1	98,5	Subsequent negative short stroke
Q_{long} (C)	200				Long stroke
t_{long} (s)	0,5				Long stroke
Front duration (µs)		1,8	5,5	18	First negative short stroke
		0,22	1,1	4,5	Subsequent negative short stroke
		3,5	22	200	First positive short (single) stroke
Stroke duration (µs)		30	75	200	First negative short stroke
		6,5	32	140	Subsequent negative short stroke
		25	230	2 000	First positive short (single) stroke
Time interval (ms)		7	33	150	Multiple negative strokes
Total flash duration (ms)		0,15	13	1 100	Negative flash (all)
		31	180	900	Negative flash (without single)
		14	85	500	Positive flash
This table is adapted from IEC 62305-1.					
NOTE The values of I = 4 kA and I = 20 kA correspond to a probability of 98 % and 80 %, respectively.					

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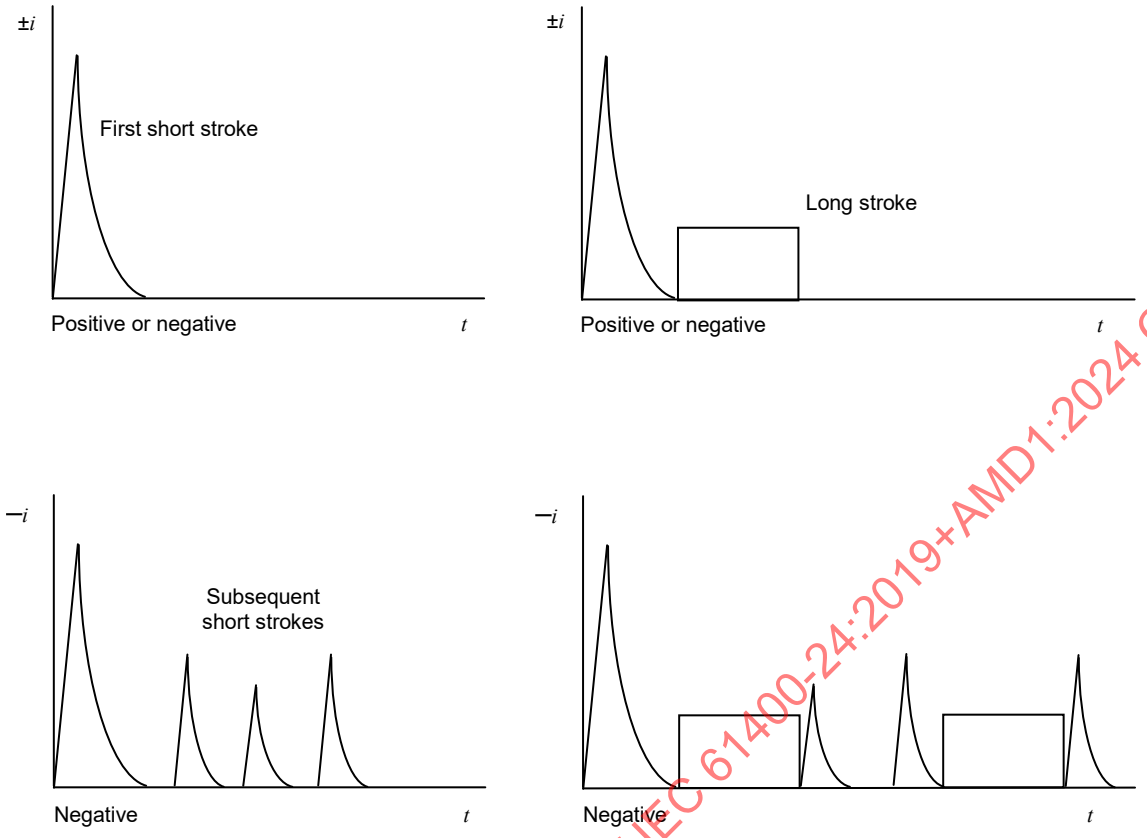

This figure is adapted from IEC 62305-1.

Figure A.5 – Possible components of downward flashes (typical in flat territory and to lower structures)

A.1.4.3 Positive cloud-to-ground flashes

In contrast to negative flashes, positive cloud-to-ground flashes are initiated by a continuously downward propagating leader which does not show distinct steps. The connecting leader and return stroke phases are similar to the processes described above for negative flashes. A positive cloud-to-ground flash usually consists of only one return stroke which may be followed by a continuing current.

Positive cloud-to-ground flashes are of great importance for practical lightning protection because the current peak value (I), total charge transfer (Q), and specific energy (W/R) can be larger compared to the negative flash. The return stroke tends to have a lower rate of current rise in comparison to a negative first return stroke. A typical current profile for a positive cloud-to-ground flash is shown in Figure A.6. Typical electrical parameters are summarised together with the parameters of negative discharges in Table A.1.

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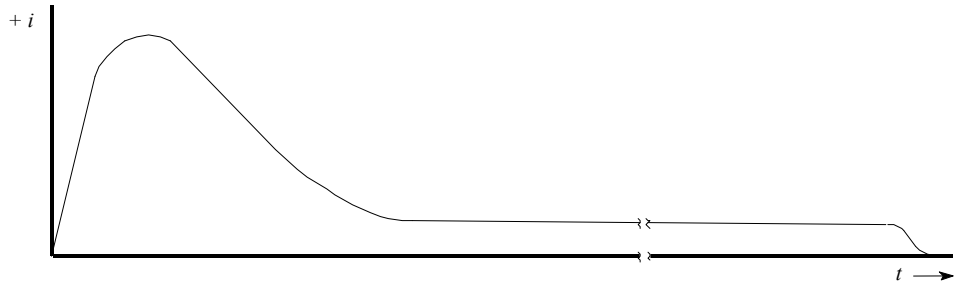

Figure A.6 – Typical profile of a positive cloud-to-ground flash

A.1.5 Upward initiated flashes

The charge in the thundercloud causes an elevation of the electric field on the surface of the earth, but usually not sufficient to launch an upward moving leader. However, the electric field may be significantly enhanced at mountains, objects placed on high ground, or at tall structures like towers or wind turbines (Figure A.7). At such locations, the electric field strength may become large enough to initiate an upward moving leader from ground towards the thundercloud. Structures with heights in excess of 100 m above the surrounding terrain (like modern wind turbines) are particularly exposed to upward initiated flashes.

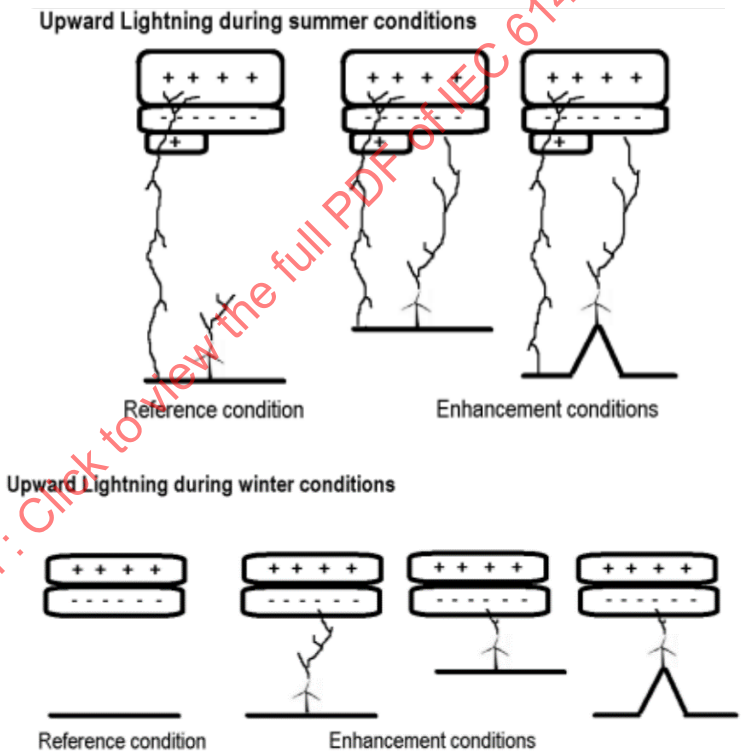

Figure A.7 – Processes involved in the formation of an upward initiated cloud-to-ground flash during summer and winter conditions

An upward initiated flash starts with a continuing current phase. Impulse currents can be superimposed on the continuing current (Figure A.8). The continuing current phase may be followed by subsequent return stroke(s) along the same channel. These return strokes are quite similar to the subsequent return strokes of cloud-to-ground flashes. Upward initiated flashes do not contain a component analogous to the first return stroke of cloud-to-ground flashes. The location where an upward lightning flash attaches to a structure is simply the same point where the upward leader is formed.

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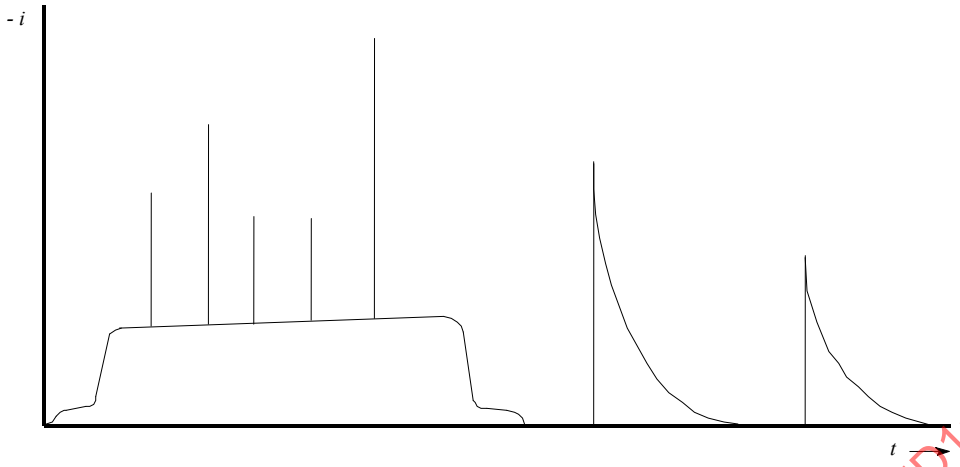

Figure A.8 – Typical profile of a negative upward initiated flash

Measurements of upward initiated flash parameters are made on tall objects that are prone to this type of flash. Detailed information from world-wide observations as well a comprehensive discussion of upward flashes by Rakov and Uman can be found in [4]. In recent years, upward flashes have also been studied by measurements on wind turbines.

The following information on current parameters relates to upward negative flashes since, although observed, upward initiated positive flashes are rare.

Although the current peak values of about 10 kA are relatively low, the charge transfer associated with the initial continuing current has in rare cases been as high as 300 C as shown in Table A.2 [4]. Upward initiated flashes, too, may be composed of various combinations of the different current components mentioned above, as illustrated in Figure A.9.

In general, upward initiated flashes have lower current parameter values when compared to downward lightning flashes, possibly with the exception of the total charge transferred. Furthermore, it is evident that tall objects placed at exposed locations may experience very frequent upward lightning flashes, particularly during winter thunderstorms where tens of upward lightning flashes have been observed on very exposed tall objects.

This is highly relevant for wind turbines because high and exposed locations are preferable for wind turbines owing to favourable wind conditions. Hence, it is necessary to consider the risk of upward lightning flashes, and developers are advised to seek information about winter lightning conditions at prospected sites. As upward lightning flashes originate from the extremities of the wind turbines (i.e. the blades and the air termination systems protecting the meteorological instrumentation on the nacelle), the point of attachment is given, and provided that the lightning protection is properly designed, it can be expected to function well also for upward lightning flashes.

However, a high frequency of winter lightning may make more durable air termination systems or periodic exchange of air termination systems necessary.

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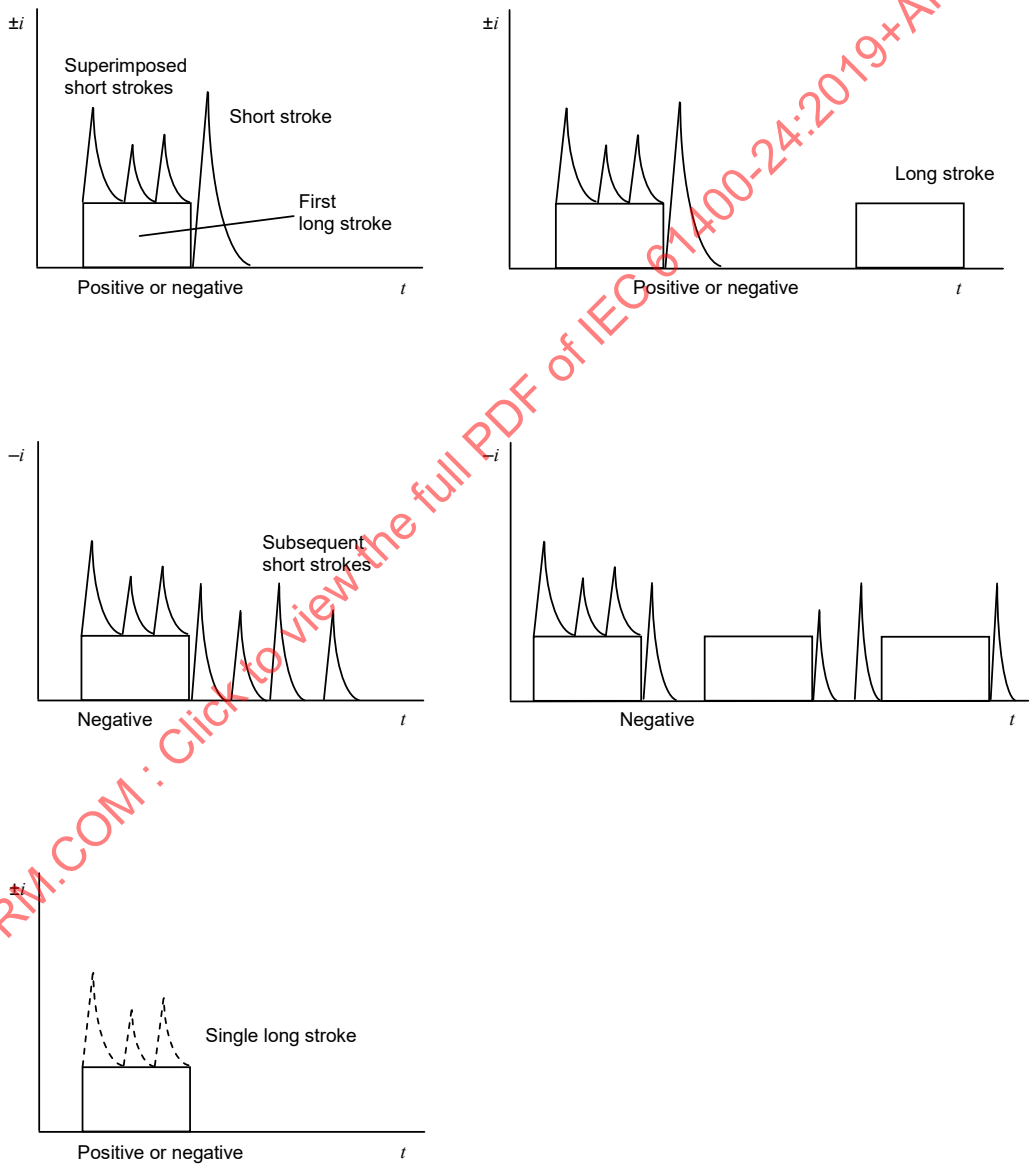
Table A.2 – Upward initiated lightning current parameters

Parameter		Maximum value
Total charge transfer	C	300[a]
Total duration	s	0,5 to 1,0
Peak current	kA	20[b]
Average rate of rise superimposed impulse currents	kA/μs	20
Number of superimposed impulse currents		50

[a] Extensive research shows that the total charge transfer in upward initiated winter lightning in Japan has a maximum value of 1 000 C.

[b] Extensive research shows that the peak current in upward initiated winter lightning in Japan has a maximum value of 100 kA.



This figure is adapted from IEC 62305-1.

Figure A.9 – Possible components of upward flashes (typical to exposed and/or higher structures)

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A.2 Lightning current parameters relevant to the point of strike

The lightning current parameters playing a role for the physical integrity of an LPS are in general the peak current I, the charge Q, the specific energy W/R, the duration T and the average steepness of the current di/dt. Each parameter tends to dominate a different failure mechanism. The current parameters to be considered for tests are combinations of these values, selected to represent in laboratory the actual failure mechanism of the part of the LPS being tested. Table A.3 records the maximum values of I, Q, W/R, T and di/dt to be considered for tests as a function of the protection level required (see IEC 62305-1, Annex D for further details).

Table A.3 – Summary of the lightning threat parameters to be considered in the calculation of the test values for the different LPS components and for the different LPL

Component	Main problem	Lightning threat parameters					Notes
Air termination	Erosion at attachment point (e.g. thin metal sheets)	LPL	Q_{long} C	T			
		I	200	< 1 s (apply Q_{long} in a single shot)			
		II	150				
		III-IV	100				
Air termination and down conductor	Ohmic heating	LPL	W/R kJ/Ω	T			Dimensioning with IEC 62305-3 renders testing superfluous
		I	10 000	Apply W/R in an adiabatic configuration			
		II	5 600				
		III-IV	2 500				
	Mechanical effects	LPL	I kA	W/R kJ/Ω			
		I	200	10 000			
		II	150	5 600			
		III-IV	100	2 500			
Connecting components	Combined effects (thermal, mechanical, and arcing)	LPL	I kA	W/R kJ/Ω	T		
		I	200	10 000	< 2 ms (apply I and W/R in a single impulse)		
		II	150	5 600			
		III-IV	100	2 500			
Earth terminations	Combined effects (thermal, mechanical, and arcing)	LPL	I kA	W/R kJ/Ω	T		Dimensioning usually determined by mechanical/ chemical aspects (corrosion, etc.)
		I	200	10 000	< 2 ms (apply I and W/R in a single impulse)		
		II	150	5 600			
		III-IV	100	2 500			
SPDs containing spark gaps	Combined effects (thermal, mechanical and arcing)	LPL	I kA	Q_{short} C	W/R kJ/Ω	di/dt kA/µs	Apply I, Q_{short}, and W/R in a single impulse (duration T < 2 ms); apply di/dt in a separate impulse
		I	200	100	10 000	200	
		II	150	75	5 600	150	
		III-IV	100	50	2 500	100	

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Component	Main problem	Lightning threat parameters					Notes
SPDs containing metal-oxide resistor blocks	Energy effects (overload)	LPL	Q_{short} C				Both aspects need to be checked
		I	100				
		II	75				
		III-IV	50				
	Dielectric effect (flashover/cracking)	LPL	I kA	T			Separate tests can be considered
		I	200	< 2 ms (apply I in a single impulse)			
		II	150				
		III-IV	100				
This table is adapted from IEC 62305-1.							

A.3 Leader current without return stroke

Upward leaders are initiated from the wind turbine itself when high electrostatic fields are present due to thunderclouds overhead or approaching leaders from thunderclouds. When such upward leaders do not connect to a leader from the cloud, there is no return stroke. The impulse currents associated with leaders are typically a few kA and can be up to 10 kA. The leaders can only start where high electrostatic fields can be generated. The magnitude as well as the current gradient implies an EM environment, which should be considered in the wind turbine EMC design.

A.4 Lightning electromagnetic impulse, LEMP, effects

LEMP effects cause overvoltages, which may include less energy than surges, caused by direct lightning strikes but which might occur more frequently. These kinds of overvoltages and surges might result from:

- conducted partial lightning currents;
- inductive/capacitive coupling;
- lightning flashes near the wind turbine;
- transmitted by line (power lines and/or communication lines due to lightning flashes to or near these lines).

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Annex B
(informative)

Lightning exposure assessment

B.1 General

In Clause B.2, a methodology to determine the average annual number of flashes to the wind turbines of a wind farm is presented and described. This methodology constitutes a guideline to estimate this parameter owing to the influence of many different conditions found throughout the world.

In Clause B.3, the terms used in this Annex B are explained.

Clause B.4 concerns the assessment of the probability of damage to the wind turbine.

In Clause B.5 concerns the assessment of the amount of loss L_X in a wind turbine.

B.2 Methodology to estimate the average annual flashes or strokes to the wind turbines of a wind farm and upward lightning activity in wind turbines

B.2.1 General

The methodology described in this clause can be used as a guideline to estimate the number of average annual flashes to the turbines in a wind farm. This methodology is not accurate in its current form and it is necessary to determine the values or range of values and the corresponding associated uncertainties of the different parameters. If a high accuracy of results is required, it is necessary to determine the values and reduce the uncertainties associated with each parameter. This can be done by means of field analysis and calibration.

B.2.2 Methodology to determine average annual flashes to turbines of a wind farm estimation by increase of the location factor to consider upward lightning from wind turbines

This methodology quantifies the increase of the average annual number of flashes by increasing the location factor, C_D. As described in Clause 7, the location factor can be used to consider local increase in lightning density (e.g. mountainous terrain) and quantify the increase of upward lightning being triggered in some conditions that favour the inception of triggered lightning from wind turbines.

N_{SG} defined in 7.2.2 is for downward lightning and has almost nothing to do with the frequency of upward lightning from tall structures; however, to estimate annual N_D it is recommended in 7.2.2.4 to use the location factor C_D for adjustment of the calculated N_D to match the actual frequency of lightning flashes attaching to a wind turbine increased by upward lightning. As a result, the location factor due to winter lightning activity C_{DWL} becomes relatively high in areas where winter lightning activity is relatively high (i.e. where winter lightning activity is high relative to the lightning activity in the summer/warm season).

The basic equation for flashes is:

$$N_D = N_{SG} \cdot A_D \cdot C_D \cdot 10^{-6} \quad \text{(B.1)}$$

Parameters in Equation (B.1), except the location factor, C_D, can be calculated as described in Clause 7. The increase of the annual average of lightning flashes per year in a wind farm is

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due to the amount of winter lightning activity, complexity of the mountain or hill and height above sea level where the wind farm is placed.

In order to quantify the different influence that location may have on wind turbines, the location factor, C_D, can be expressed as the sum of location factors:

$$C_D = C_{DWL} + C_{DC} + C_{DH} \tag{B.2}$$

where

C_{DWL} is the location factor due to winter lightning activity;

C_{DC} is the location factor due to complexity of local terrain;

C_{DH} is the location factor due to the height above sea level.

C_{DWL}, C_{DC} and C_{DH} are individual parameters that can be combined differently depending on local conditions.

In the following Table B.1, the recommended values of the specific location factors are summarized to be used in different locations.

Table B.1 – Recommended values of individual location factors

Winter lightning (C_{DWL})		Terrain complexity (C_{DC})			Height above sea level (C_{DH})	
Activity level	**C_{DWL} value[a]**	**Description**	**Complexity ratio[b]**	**C_{DC} value**	**Description**	**C_{DH} value**
No activity	0	Flat or moderate	< 0,3	1	< 800 m	0
Low activity	2	Hill	0,3 to 0,4	3	800 to 1 000 m	1
Medium activity	4	Mountain	> 0,4	4	> 1 000 m	2
High activity	6[c]					

[a] Degree of winter lightning may be found using the winter lightning world map in Figure B.1, or the detailed winter lightning maps in Figure B.2 (the Figure B.2, or by analysis of local lightning activity in the region of interest).

[b] Calculated according to Figure B.3.

[c] Could even be higher in some locations.

Terrain complexity considers the influence of the surrounding terrain on the increase of lightning activity (for both downward and upward lightning). This may be done by estimating the slope around wind turbines. Slopes may be calculated as the ratio between the height difference h and horizontal distance d from the turbine ranging from 300 m to 1 000 m. It is recommended to obtain the mountain profile and select the slope in the direction of highest value. In the range 300 m to 1 000 m, choose a distance value which leads to the highest slope. This slope method may not apply for all worldwide terrain complexities. Terrain definition given in Table B.1 can also be used to determine complexity (flat or moderate terrain, hill and mountain).

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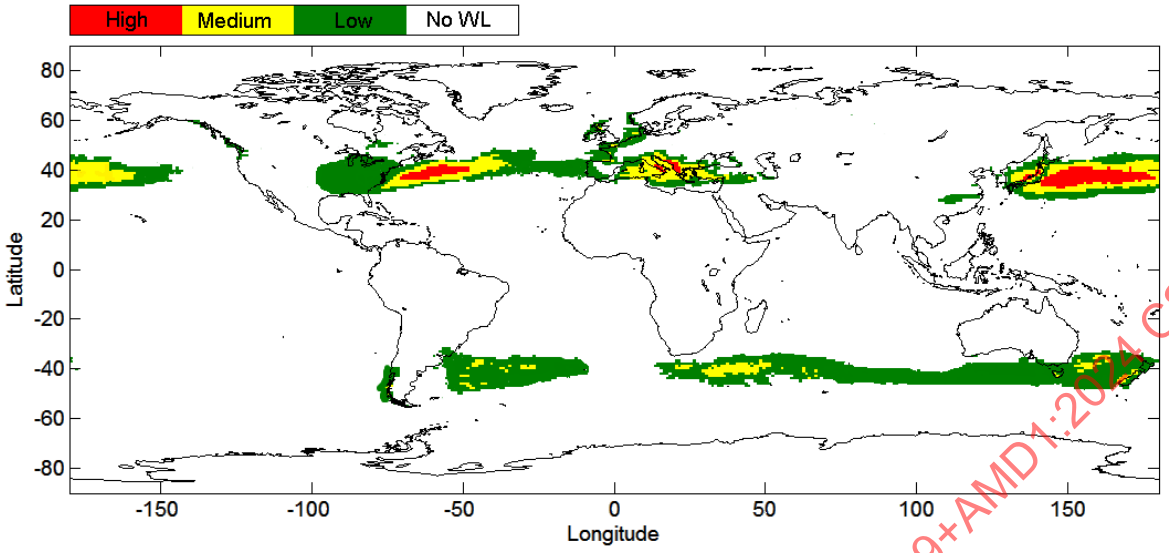

Colour scale indicates activity level high (red), medium (yellow), low (green) and no winter lightning (white).

Source: see [5]

Figure B.1 – Winter lightning world map based on LLS data and weather conditions

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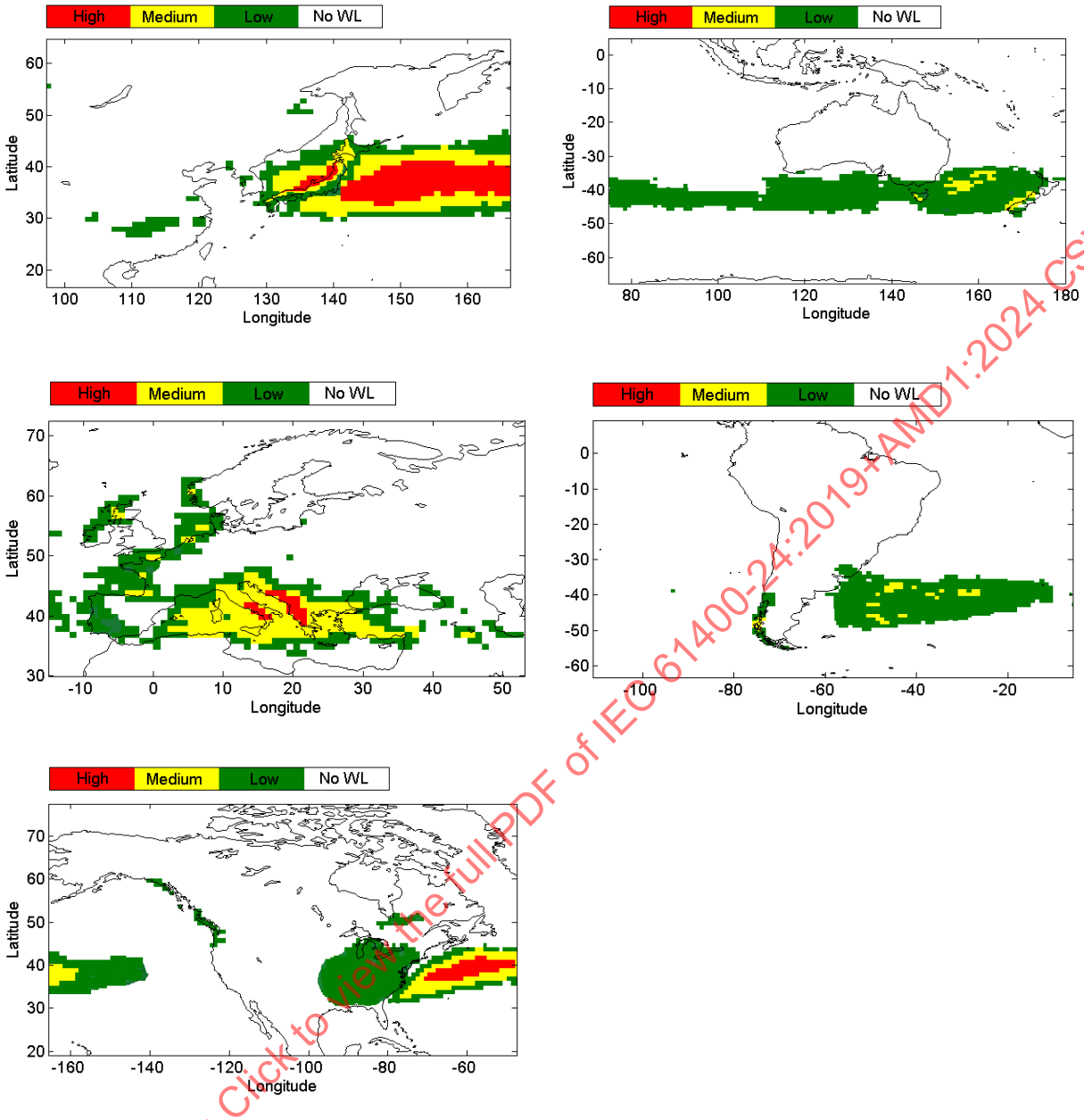
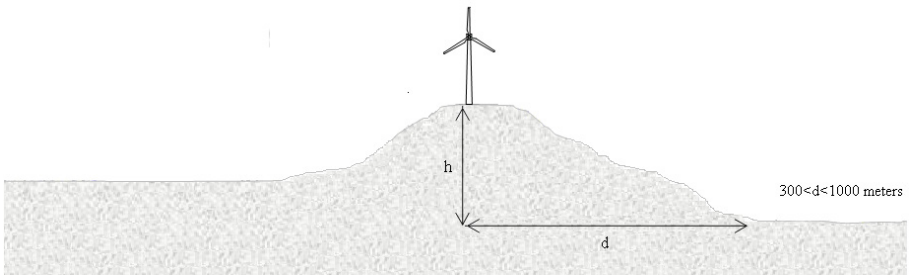


Colour scale indicates activity level high (red), medium (yellow), low (green) and no winter lightning (white).

Source: see [5]

Figure B.2 – Detailed winter lightning maps based on LLS data and weather conditions



d can take a value between 300 m and 1 000 m.

Figure B.3 – Ratio *h/d* description

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B.2.3 Upward lightning percentage in wind farms

Upward lightning activity should be expected for tall structures such as wind turbines as described in Annex A. Experience has shown that even wind turbines located in flat terrain without winter lightning activity can be affected by significant percentages of upward lightning activity. Upward lightning activity according to the mechanisms described in Annex A may be influenced by winter lightning activity as well as by local topographic conditions where the wind farm is erected. The following Table B.2 presents a percentage of upward lightning under winter lightning conditions for typical wind turbine heights in flat terrain. The percentages of upward lightning presented in Table B.2 may be higher for wind farms placed in mountainous terrain or at high elevation above sea level.

Table B.2 – Range of upward lightning activity as a function of winter lightning activity for wind farm located in flat terrain

Winter lightning activity level	Percentage of upward lightning %
High activity	80 to 99
Medium activity	40 to 90
Low activity	20 to 50
No activity	10 to 40

B.3 Explanation of terms

B.3.1 Damage and loss

Terms covering the topics damages and loss are defined in IEC 62305-2. Here are included the terms and topics considered relevant for wind turbines.

The lightning current is the primary source of damage. The following sources are defined depending on the lightning striking point:

S1: lightning flashes striking the wind turbine (flashes to the structure);

S2: lightning flashes striking near a wind turbine (flashes near a structure);

S3: lightning flashes striking a service line (incoming line e.g. power cable or telecommunication cable);

S4: lightning flashes striking near a service line (incoming line e.g. power cable or telecommunication cable);

NOTE 1 S2 lightning flashes striking near a wind turbine is not considered a threat when protection against direct lightning strikes to the wind turbine is provided.

NOTE 2 S4 lightning flashes striking near a service line is not considered a threat when protection against direct lightning strikes to the wind turbine is provided.

Four causes of damage are considered:

D_{1D}: electric shock to human beings resulting from direct lightning flashes strikes to those human beings;

D_{1T}: electric shock to human beings resulting from resistive and inductive coupling;

D_2: dangerous sparking triggering fire or explosion and/or leading to mechanical and chemical effects that may also endanger the environment;

D_3: surges due to all sources of damage.

The damage to a wind turbine due to lightning may be limited to a part of the wind turbine or may extend to the entire wind turbine.

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Lightning affecting a service line can cause damage to the service line system itself (e.g. the service line cable) or to electrical and electronic systems connected to the service line.

Each cause of damage, alone or in combination with others, may produce the following types of damages in the wind turbine. The types of damage considered relevant for wind turbines are:

L_1: injury to human beings. It is a consequence of D_{1D}, D_{1T}, D_2 and even D_3;

L_2: physical damage (thermal, mechanical, chemical or explosion etc.) of the wind turbine. It is a consequence of D_2 and even D_3 in structures with risk of explosion.

L_3: failure of electrical and electronic systems. It is a consequence of D_3.

The type of damage L_3 may unacceptably impair the availability of the internal systems of the wind turbine (e.g. the control system).

The risk R is the relative value of a probable average annual loss. For each type of damage which may appear in a wind turbine, the relevant risk should be evaluated.

To evaluate the risks, R, the relevant risk components (partial risks depending on the source and type of damage) should be defined and calculated.

Each risk, R, is the sum of its risk components. When calculating a risk, the risk components may be grouped according to the source of damage and the type of damage.

The risks to be evaluated due to lightning striking the wind turbine (source S1) are:

R_{AD}: risk component related to type of damage L_1 (injury to human beings), caused by a flash to human beings exposed on the wind turbine – owing to lightning striking wind turbine;

R_{AT}: risk component related to type of damage L_1 (injury to human beings) caused by electric shock due to touch and step voltages inside the wind turbine and outside in the zones within a distance of 3 m from the tower;

R_B: Component related to type of damage L_1 and L_2 (physical damage) caused by dangerous sparking inside the wind turbine triggering fire or explosion, which may also endanger the environment.

R_C: Component related to type of damage L_1 and L_2, caused by failure of internal systems because of LEMP.

The risks to be evaluated for a wind turbine due to lightning striking near the wind turbine (source S2) are:

R_M: Component related to type of damage L_1 and L_2, caused by failure of internal systems because of LEMP.

The risks to be evaluated for a wind turbine owing to lightning striking the service lines connected to the wind turbine (source S3) are:

R_U: Component related to type of damage L_1, caused by electric shock due to touch voltages inside the structure.

R_V: Component related to type of damage L_1 and L_2 caused by fire or explosion (triggered by dangerous sparking between external installation and metallic parts generally at the entrance point of the line into the wind turbine) due to lightning current transmitted through or along incoming lines.

R_W: Component related to type of damage L_1 and L_2, caused by failure of internal systems by overvoltages induced on incoming lines and transmitted to the wind turbine.

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The risks to be evaluated for a wind turbine due to lightning striking near the service lines connected to the wind turbine (source S4) are:

R_Z: Component related to type of damage L_1 and L_2, caused by failure of internal systems by overvoltages induced on incoming lines and transmitted to the structure.

B.3.2 Composition of risk

The risk R is the sum of the risk components according to the type of damage or the source of damage.

Composing the risk according to the type of damage:

$$R = R_{AT} + R_{AD} + R_B + R_C{}^2 + R_U + R_V + R_W{}^2 + R_Z{}^2 \quad \text{(B.3)}$$

Composing the risk according to the source of damage:

$$R = R_{S1} + R_{S2} + R_{S3} + R_{S4} \quad \text{(B.4)}$$

where:

$R_{S1} = R_{AT} + R_{AD} + R_B + R_C{}^2$

$R_{S2} = R_M{}^2$

$R_{S3} = R_U + R_V + R_W{}^2$

$R_{S4} = R_Z{}^2$

B.3.3 Assessment of risk components

Each risk component R_{AT}, R_{AD}, R_B, R_C, R_M, R_U, R_V, R_W and R_Z may be expressed by the following general equation:

$$R_X = N_X \cdot P_X \cdot L_X \quad \text{(B.5)}$$

where

R_X is the risk component for a structure (e.g. for the wind turbine)

N_X is the number of dangerous events per annum [year^{-1}];

P_X is the probability of damage to the structure (a function of various protection measures);

L_X is the amount of consequent loss.

This basic equation is to be used for assessing the risk of damage based on the probability of damage of various types and the consequent.

For evaluation of risk components owing to lightning flashes to the wind turbine (S1), the following relationships apply:

$$R_{AT} = N_D \cdot P_{AT} \cdot P_P \cdot L_{AT} \quad \text{(B.6)}$$

$$R_{AD} = N_D \cdot P_{AD} \cdot P_P \cdot L_{AD} \quad \text{(B.7)}$$

$$R_B = N_D \cdot P_B \cdot L_B \quad \text{(B.8)}$$

[2] Only in case failure of internal systems immediately endangers human life.

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$$R_C = N_D \cdot P_C \cdot P_P \cdot L_C \quad (B.9)$$

For evaluation of risk components owing to lightning flashes near the wind turbine (S2), the following relationship applies:

$$R_M = N_M \cdot P_M \cdot P_P \cdot L_M \quad (B.10)$$

For evaluation of risk components owing to lightning flashes to a line connected to the wind turbine (S3), the following relationships apply:

$$R_U = (N_L + N_{DJ}) \cdot P_U \cdot P_P \cdot L_{UT} \quad (B.11)$$

$$R_V = (N_L + N_{DJ}) \cdot P_V \cdot L_V \quad (B.12)$$

$$R_W = (N_L + N_{DJ}) \cdot P_W \cdot P_P \cdot L_W \quad (B.13)$$

For evaluation of risk components owing to lightning flashes near a line connected to the wind turbine (S4), the following relationship applies:

$$R_Z = N_I \cdot P_Z \cdot P_P \cdot L_Z \quad (B.14)$$

If the line has more than one section, the values of R_U, R_V, R_W and R_Z are the sum of the R_U, R_V, R_W and R_Z values relevant to each section of the line. The sections to be considered are those between the wind turbine and the first node. In any case, a maximum line length of 5 km for HV power lines and 1 km for LV power lines and TLC lines is to be assumed.

In the case of a wind turbine with more than one connected line with different routing feeding the same internal system, the calculations shall be performed for each line.

In the case of a structure with more than one line connected with the same routing to the same apparatus, the calculations shall be performed only for the line with the worst characteristics, i.e. the lines with the highest values of N_L and N_I , respectively (unscreened line versus screened line, LV power line versus HV power line with HV/LV transformer, etc.).

B.3.4 Frequency of damage

The frequency of damage F is the value of the number of damaging events caused by sources of damage S in the internal systems of the wind turbine to be protected. For each source of damage that may affect the wind turbine, the relevant frequency of damage may be evaluated as follows:

F_1: frequency of damage due to flashes to the structure (source S1),

F_2: frequency of damage due to flashes near the structure (source S2),

F_3: frequency of damage due to flashes to the line (source S3),

F_4: frequency of damage due to flashes near the line (source S4).

The frequency of damages F_1 and F_2 includes failure of internal systems caused by LEMP owing to flashes to the structure or to ground near the structure, respectively, whereas the frequency of damages F_3 and F_4 includes failure of internal systems caused by overvoltages transmitted from incoming lines to the structure.

The frequency of damage F is the sum of partial frequency of damage depending on the source of damage. For evaluation of the frequency of damage F, the following relationship applies:

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$$F = F_1 + F_2 + F_3 + F_4 \quad \text{(B.15)}$$

NOTE The value of frequency of damage F obtained by adding the two risk components F_2 and F_4 is overestimated. A more correct assessment of frequency could be made taking into account that a flash to ground simultaneously has influence on internal systems by direct inductive coupling and by the overvoltage induced on the connected lines, and so that their effects (component F_2 and component F_4) can be overlapped.

Each partial frequency of damage F_1, F_2, F_3, F_4, may be expressed by the following general equation:

$$F_X = N_X \cdot P_X \quad \text{(B.16)}$$

where

N_X is the number of dangerous events per annum (see also Annex A);

P_X is the probability of damage.

For evaluation of the frequency of damage related to lightning flashes to the wind turbine (S1) structure, the following relationship applies:

$$F_1 = N_D \cdot P_C \quad \text{(B.17)}$$

For evaluation of the frequency of damage related to lightning flashes near the wind turbine (S2), the following relationship applies:

$$F_2 = N_M \cdot P_M \quad \text{(B.18)}$$

For evaluation of the frequency of damage related to lightning flashes to an incoming line (S3), the following relationship applies:

$$F_3 = (N_L + N_{DJ}) \cdot P_W \quad \text{(B.19)}$$

For evaluation of the frequency of damage related to lightning flashes near a line connected to the wind turbine, the following relationship applies:

$$F_4 = N_I \cdot P_Z \quad \text{(B.20)}$$

According to IEC 62305-1 the frequency of damages F should be considered in the evaluation of the need of protection against lightning.

The following steps should be taken:

– calculation of the partial frequency of damage F_X
– calculation of the total frequency of damage F;
– identification of the tolerable frequency of damage F_T;
– comparison of the frequency of damage F with the tolerable value F_T.

B.3.5 Assessment of probability, P_X, of damage

The probabilities given in this Annex B, which is based on IEC 62305-2, are valid if protection measures conform to:

– IEC 62305-3 for protection measures to reduce injury to human beings and for protection measures to reduce physical damage;
– IEC 62305-4 for protection measures to reduce failure of internal systems.

Other values may be chosen, if justified.

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B.4 Assessing the probability of damage to the wind turbine

B.4.1 Probability, P_{AT}, that a lightning flash to a wind turbine will cause dangerous touch and step voltage

The values of probability P_{AT} that a damage due to touch and step voltage by a lightning flash to the wind turbine appear, depend on the protection measures provided:

$$P_{AT} = P_{TWS} \cdot P_{am} \cdot r_t \quad \text{(B.21)}$$

where:

P_{TWS} is the probability with which a thunderstorm warning system (TWS) does not detect a lightning related event in the target area.

P_{am} is the probability that a flash to a structure will cause damage owing to touch and step voltages according to different protection measures. Values of P_{am} are given in Table B.3.

r_t is the reduction factor as a function of the type of surface of soil or floor. Values of r_t are given in Table B.4.

NOTE P_{AT} = 0 may be assumed when the structure:

– has an extensive metal framework (see IEC 62305-3:2010, 8.1 and 8.2);

– is made of reinforced concrete cast on site, with the reinforcing rods perfectly done of building; (see IEC 62305-3:2010, E.4.3);

– is protected by an LPS complying with this document;

– is provided with a meshed earth termination system and there is no metal installation that can become a part of the path of the lightning current.

Table B.3 – Values of probability, P_A, that a lightning flash to a wind turbine will cause shock to human beings owing to dangerous touch and step voltages (corresponds to IEC 62305-2)

Protection measure	P_{am}	Comments
No protection measures	1	
Warning notices	10^{-1}	
Electrical insulation of exposed down-conductor (e.g. at least 3 mm cross-linked polyethylene)	10^{-2}	Not relevant for wind turbines using the tower structure as down conductor
Effective soil equipotentialization	10^{-2}	Mandatory for wind turbines holding HV equipment according to typical electrical codes

If more than one provision has been taken, the value of P_{am} is the product of the corresponding values.

Table B.4 – Values of reduction factor r_t as a function of the type of surface of soil or floor (corresponds to IEC 62305-2)

Type of surface	Contact resistance kΩ [a]	r_t
Agricultural, concrete	≤ 1	10^{-2}
Marble, ceramic	1 to 10	10^{-3}
Gravel	10 to 100	10^{-4}
Asphalt, wood	≥ 100	10^{-5}

[a] Values measured between a 400 cm^2 electrode compressed with force of 500 N at a point of infinity.

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B.4.2 Probability, P_{AD}, that a lightning flash to the wind turbine will cause injury to an exposed person on the structure

The values of probability, P_{AD}, that a lightning flash will strike a human being depend on the position of people in the exposed area, on the lightning protection (LPL) of adopted measures to protect the exposed areas of the wind turbine against direct lightning flash and on additional protection measures provided:

$$P_{AD} = P_{TWS} \cdot P_O \cdot P_{LPS} \quad \text{(B.22)}$$

where:

P_{TWS} is the probability with which a thunderstorm warning system (TWS) does not detect a lightning related event in the target area.

P_{LPS} is the probability depending on LPL of measures to protect the exposed areas of the structure against direct lightning flashes. Values of P_{LPS} are given in Table B.6.

If a TWS creates a warning message, immediate and complete evacuation of the exposed area shall be ensured. If this evacuation is not ensured or a TWS is not provided, P_{TWS} = 1 should be assumed. P_O is the probability factor according to the position of the person in the exposed area. Values of P_O are given in Table B.5.

Table B.5 – Values of factor P_O according to the position of a person in the exposed area (corresponds to IEC 62305-2)

Position of person	P_O
Close to the border of exposed area [a]	0,9
Far away from the border of the exposed area	0,1
[a] Within 3 m from the border of the exposed area	

Table B.6 – Values of probability, P_{LPS}, depending on the protection measures to protect the exposed areas of the wind turbine against direst lightning flash and to reduce physical damage (corresponds to IEC 62305-2)

Characteristics of wind turbine	Class of LPS	P_{LPS}
Wind turbine not protected by LPS	-	1
Wind turbine protected by LPS	IV	0,2
	III	0,1
	II	0,05
	I	0,02
Wind turbine with lightning protection of blades and nacelle conforming to LPS I with complete protection of any nacelle roof installations against direct lightning attachment and the tower acting as a continuous natural down conductor.		0,01

NOTE Values of P_{LPS} other than those in Table B.6 are possible if based on a detailed investigation – refer to IEC 62305-2:2010, Clause B.2.

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B.4.3 Probability, P_B, that a lightning flash to the wind turbine will cause physical damage

The probability P_B that a flash to a wind turbine will cause physical damage is given by:

$$P_B = P_S \cdot P_{LPS} \cdot r_f \cdot r_P \quad \text{(B.23)}$$

where:

P_S is the probability that a flash to a structure will cause dangerous sparking. Values of P_S are given in Table B.7.

P_{LPS} is the probability depending on the protection measures to reduce physical damage. Values of P_{LPS} are given in Table B.4.

r_P is the reduction factor as function of provisions taken to reduce the consequences of fire. Values of r_p are given in Table B.8.

r_f is the reduction factor as function of risk of fire or explosion of the wind turbine. Values of r_f are given in Table B.9.

Table B.7 – Values of probability P_S that a flash to a wind turbine will cause dangerous sparking (corresponds to IEC 62305-2)

Type of structure	P_S
Composite materials	1
Reinforced concrete or interconnected metalwork	0,5

Table B.8 – Values of reduction factor r_p as a function of provisions taken to reduce the consequences of fire (corresponds to IEC 62305-2)

Provisions	r_p
No provisions	1
One of the following provisions: extinguishers; fixed manually operated extinguishing installations[a]; manual alarm installations; hydrants; fire proof compartments; protected escape routes	0,5
One of the following provisions: fixed automatically operated extinguishing installations; automatic alarm installations[b].	0,2
[a] Provisons are effective only if operated by persons trained for this purpose.	
[b] Only if protected against overvoltages and other damage and if firemen can arrive within 10 min.	

If more than one provision has been taken, the value of r_p should be taken as the lowest of the relevant values.

NOTE 1 Risk of explosion is not considered relevant for wind turbines.

Table B.9 – Values of reduction factor r_f as a function of risk of fire of the wind turbine (corresponds to IEC 62305-2)

Risk of fire	r_f
High	10^{-1}
Ordinary	10^{-2}
Low	10^{-3}
None	0

NOTE 2 Structures considered as having a high risk of fire can be assumed to be structures with surface materials (blades and nacelle roofs) made of combustible materials with a specific fire load larger than 800 MJ/m^2.

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NOTE 3 Structures considered as having an ordinary risk of fire can be assumed to be structures with surface materials (blades and nacelle roofs) made of combustible materials with a specific fire load between 800 MJ/m^2 and 400 MJ/m^2.

NOTE 4 Structures considered as having a low risk of fire can be assumed to be structures with surface materials (blades and nacelle roofs) made of combustible materials with a specific fire load less than 400 MJ/m^2.

NOTE 5 Specific fire load is the ratio of the energy of the total amount of the combustible material in a structure and the overall surface of the structure.

B.4.4 Probability, P_C, that a lightning flash to the wind turbine will cause failure of internal systems

A coordinated SPD system is suitable as a protection measure to reduce P_C.

The probability, P_C, that a lightning flash to the wind turbine will cause failure of internal systems is given by:

$$P_C = P_e \cdot P_{SPD} \cdot C_{LD} \quad \text{(B.24)}$$

P_{SPD} depends on the coordinated SPD system conforming to IEC 62305-4 and on internal system characteristics. Refer to IEC 62305-2:2010, Annex B for values of P_{SPD}. For low-voltage systems and telecommunication systems.

P_e is the probability that equipment is exposed to damaging event,

C_{LD} is a factor depending on shielding, grounding and isolation conditions of the line to which the internal system is connected. Values of C_{LD} are given in IEC 62305-2 Annex B.

Values of P_{SPD} depend on the lightning protection level (LPL) for which the SPDs are designed.

NOTE 1 Only "coordinated SPD protection" is suitable as a protection measure to reduce P_C. Coordinated SPD protection is effective to reduce P_C only if the wind turbine hub, nacelle and tower are protected with an LPS, or if the structures with continuous metal or reinforced concrete framework act as a natural LPS where bonding and earthing requirements of IEC 62305-3 are satisfied.

NOTE 2 Shielding internal systems connected to external lines consisting of lightning protective cable or systems with wiring in lightning protective cable ducts, metallic conduit or metallic tubes; may not require the use of coordinated protection.

B.4.5 Probability, P_M, that a lightning flash near the wind turbine will cause failure of internal systems

Due to the height of the wind turbines, most lightning flashes will strike the turbines directly and not in the area near the wind turbine. Furthermore, the large metal structures will shield the internal systems. Hence the probability that a lightning flash near the wind turbine will cause failure of internal systems can be considered negligible when the wind turbine hub, nacelle and tower are protected with an LPS or when the structures with continuous metal or reinforced concrete framework act as a natural LPS where bonding and earthing requirements of IEC 62305-3 are satisfied.

NOTE R_M can be neglected for wind turbines with a total height of more than 100 m. In this case, the conventional distance of 350 m is usually covered by direct strikes

B.4.6 Probability, P_U, that a lightning flash to a service line will cause injury to human beings owing to touch voltage

The values of probability, P_U, of injury to human beings owing to touch voltage caused by lightning flashes to a service line (power cable or communication cable) entering the wind turbine depends on the characteristics of the service line shield, the impulse withstand voltage of internal systems connected to the service line, the typical protection measures (physical restrictions, warning notices, etc. [see Table B.8]) and the SPDs provided at the entrance of the service line in accordance with IEC 62305-3.

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NOTE A coordinated SPD protection in accordance with IEC 62305-4 is not necessary to reduce P_U in this case. SPD(s) in accordance with IEC 62305-3 are sufficient.

The value of P_U is given by:

$$P_U = P_{am} \cdot P_{EB} \cdot P_{LD} \cdot P_{TWS} \cdot C_{LD} \cdot r_t \quad \text{(B.25)}$$

where:

P_{am} depends on protection measures against touch voltages, such as physical restrictions or warning notices. Values of P_{am} are given in IEC 62305-2:2010, Annex B.

P_{TWS} is the probability with which a thunderstorm warning system (TWS) does not detect a lightning related event in the target area.

P_{LD} is the probability of failure of internal systems due to a flash to the connected line depending on the line characteristics. Values of P_{LD} are given in IEC 62305-2:2010, Annex B.

P_{EB} depends on the equipotential bonding conforming to IEC 62305-3. Values of P_{EB} are given in IEC 62305-2:2010, Annex B.

C_{LD} is a factor depending on shielding, grounding and isolation conditions of the line. Values of C_{LD} are given in IEC 62305-2:2010, Annex B.

r_t is the reduction factor as a function of the type of surface of soil or floor. Values of r_t are given in IEC 62305-2:2010, Annex B.

B.4.7 Probability, P_V, that a lightning flash to a service line will cause physical damage

The values of probability, P_V, of physical damage caused by a lightning flash to a service line entering the wind turbine depend on the characteristics of the service line shield, the impulse withstand voltage of internal systems connected to the service line and the SPDs provided for equipotential bonding at the entrance of the line in accordance with IEC 62305-3.

NOTE A coordinated SPD protection in accordance with IEC 62305-4 is not necessary to reduce P_V in this case. SPDs in accordance with IEC 62305-3 are sufficient.

The value of P_V is given by:

$$P_V = P_{EB} \cdot P_{LD} \cdot P_{TWS} \cdot C_{LD} \cdot r_f \cdot r_p \quad \text{(B.26)}$$

where:

P_{EB} depends on the equipotential bonding conforming to IEC 62305-3. Values of P_{EB} are given in IEC 62305-2:2010, Annex B;

P_{LD} is the probability of failure of internal systems due to a flash to the connected line depending on the line characteristics. Values of P_{LD} are given in IEC 62305-2:2010, Annex B;

P_{TWS} is the probability of a thunderstorm warning system (TWS) not detecting a lightning-related event in the target area;

C_{LD} is a factor depending on shielding, grounding and isolation conditions of the line. Values of C_{LD} are given in IEC 62305-2:2010, Annex B;

r_f is the reduction factor as a of provisions taken to reduce the consequences of fire. Values of r_f are given in Table B.9;

r_p is the reduction factor as a function of provisions taken to reduce the consequences of fire. Values of r_p are given in Table B.8.

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B.4.8 Probability, P_W, that a lightning flash to a service line will cause failure of internal systems

The values of probability, P_W, of failure of internal systems caused by lightning flash to a service line entering the wind turbine depend on the characteristics of the service line shielding, the impulse withstand voltage of internal systems connected to the service line and the coordinated SPD system provided.

The value of P_W is given by:

$$P_W = P_e \cdot P_{SPD} \cdot P_{TWS} \cdot P_{LD} \cdot C_{LD} \quad (B.27)$$

where:

P_e is the probability that equipment is exposed to damaging event;

P_{SPD} depends on the coordinated SPD system conforming to IEC 62305-4 and on internal system characteristics. Refer to IEC 62305-2:2010, Annex B for values of P_{SPD} for low-voltage systems and telecommunication systems;

P_{TWS} is the probability of a thunderstorm warning system (TWS) not detecting a lightning-related event in the target area;

P_{LD} is the probability of failure of internal systems due to a flash to the connected line depending on the line characteristics. Values of P_{LD} are given in IEC 62305-2:2010, Annex B.

C_{LD} is a factor depending on shielding, grounding and isolation conditions of the line to which the internal system is connected. Values of C_{LD} are given in IEC 62305-2:2010, Annex B.

B.4.9 Probability, P_Z, that a lightning flash near an incoming service line will cause failure of internal systems

The values of probability, P_Z, that a lightning flash near to a service line entering the structure will cause a failure of internal systems depend on the characteristics of the service line shield, the impulse withstand voltage of the system connected to the service line and protection measures provided.

The value of P_Z is given by:

$$P_Z = P_e \cdot P_{SPD} \cdot P_{TWS} \cdot P_{LI} \cdot C_{LI} \quad (B.28)$$

where:

P_e is the probability that equipment is exposed to damaging event;

P_{SPD} depends on the coordinated SPD system conforming to IEC 62305-4 and on internal system characteristics. Refer to IEC 62305-2, Annex B for values of P_{SPD} for low-voltage systems and telecommunication systems;

P_{TWS} is the probability of a thunderstorm warning system (TWS) not detecting a lightning-related event in the target area;

P_{LI} is the probability of failure of internal systems due to a flash near the connected line depending on the line and equipment characteristics. Values of P_{LD} are given in Table B.12 and IEC 62305-2:2010, Annex B;

C_{LI} is a factor depending on shielding, grounding and isolation conditions of the line. Values of C_{LI} are given in IEC 62305-2:2010, Annex B.

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Table B.10 – Values of probability P_{LI} depending on the line type and the impulse withstand voltage U_W of the equipment (corresponds to IEC 62305-2)

Line type	Voltage U_W in kV				
	1	1,5	2,5	4	6
	P_{LI}				
Power lines	1	0,6	0,3	0,16	0,1
TLC lines	1	0,5	0,2	0,08	0,04

B.4.10 Probability P_P that a person will be in a dangerous place

The probability P_P that a person will be in a dangerous place depends on the time t_z in hours per year for which the persons are present in the dangerous place:

$$P_P = t_z / 8\,760 \quad \text{(B.29)}$$

NOTE Where the value of t_z is not known, the ratio t_z / 8 760 should equate to the value of 1.

B.4.11 Probability P_e that equipment will be exposed to damaging event

The probability P_e that undamaged equipment is exposed to a damaging event depends on the time t_e in hours per year of exposure of equipment to the damaging event:

$$P_e = t_e / 8\,760 \quad \text{(B.30)}$$

NOTE Where the value of t_e is not known, the ratio t_e / 8 760 should equate to the value of 1.

B.5 Assessing the amount of loss L_X in a wind turbine

B.5.1 General

L_X represents the mean amount of loss consequent to a specified type of damage owing to a dangerous event, expressed in relative way related to the maximum amount of loss in the wind turbine to be protected.

The values of loss L_X should be evaluated and fixed by the lightning protection designer (or the owner of the wind turbine). The mean values of loss L_X in a wind turbine given here are considered typical values. Different values may be assigned by each national committee (or agreed between the manufacturer and the customer).

B.5.2 Mean relative loss per dangerous event

The loss L_X refers to the mean relative amount of a specified type of damage for one dangerous event caused by a lightning flash considering both its extent and effects.

The loss L_X varies with the cause of damage (D_{1D}, D_{1T}, D_2 and D_3).

The loss L_X should be determined for each zone of the wind turbine into which it is divided.

The loss L_X for each zone can be determined in accordance with Tables B.11 and B.12.

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Table B.11 – Loss values for each zone (corresponds to IEC 62305-2)

Typical loss
$L_{AT} = L_{UT} = L_T$
$L_{AD} = L_D$
$L_B = L_V = L_F = L_{F1} = L_{F2}$

where

L_T is the typical mean ratio of persons injured by touch and step voltages related to the total number of persons in the zone, owing to one dangerous event (see Table B.12);

L_D is the typical mean ratio of persons injured by direct lightning stroke related to the total number of persons exposed in the zone, owing to one dangerous event (see Table B.12);

L_{F1} is the typical mean ratio of persons injured by fire or explosion in relation to the total number of persons in the zone, owing to one dangerous event (see Table B.12);

L_{F2} is the typical mean ratio of physical damage of social relevance by fire or explosion related to the maximum amount of damage of social relevance in the zone, owing to one dangerous event (see Table C.2);

L_O is the typical mean ratio of persons injured by failure of internal systems in relation to the total number of persons in the zone, owing to one dangerous event (see Table B.12).

NOTE 1 Risk of explosion is not considered relevant for wind turbines.

NOTE 2 According to IEC 62305-2, a loss of social relevance is a loss which involves injury to human beings, unavailability of service to the public, damage of cultural heritage and in general costs that the society is forced to pay.

Table B.12 – Typical mean values of L_T, L_D, L_F and L_O (corresponds to IEC 62305-2)

Type of zones	L_T	L_D	L_{F1}	L_{F2}	L_O
Critical zones [a)]	0,01	0,1	0,01	0,1	0,0001
Normal zones [b)]	0,01	0,1	0,01	0,05	0,00001
[a)] Zones with essential equipment for carrying out processes (control, communication) [b)] Zones open to the public					

NOTE 3 Values of Table B.12 refer to continuous attendance of people in the structure.

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Annex C
(informative)

Protection methods for blades

C.1 General

C.1.1 Types of blades and types of protection methods for blades

Wind turbine blades are large hollow structures manufactured of composite materials, such as glass fibre reinforced plastic (GFRP), wood, wood laminate and carbon fibre reinforced plastic (CFRP). CFRP is typically used for reinforcement of the blade structure or for special components, such as the tip shaft for blades with tip brakes (tip-stall braking mechanism). Some parts and discrete components such as mounting flanges, balancing weights, hinges, assembly brackets for split blades, bearings, wires, electrical wiring, springs and fixtures are made of metal. Lightning strikes will attach to blades even without metallic components, and whenever a lightning arc is formed inside the blade, damage is severe.

The two sides or surface skins of a blade are normally manufactured as separate sheets of glass fibre, or other composite materials, glued together along the leading and trailing edges and to an internal load-carrying structure also made of glass fibre. Inside the blade, there are large air-filled cavities formed by the surface skin and the internal structure commonly stretching the entire length of the blade. Alternatively, the blade skins can supply the mechanical strength of the blade without a load-carrying spar. Finally, blades may be fabricated in one piece using advanced resin casting techniques without the above-mentioned glued interfaces.

There are several types of blades depending on the control and braking mechanism employed, and the use of insulating and conductive composites. Five main types are shown in Figure C.1.

Type A blades use a flap (aileron) in the outer part of the leading edge for braking. On type A blades, lightning attachment points are often found on the flap steel hinges, and severe damage is often seen since the cross-section of the steel wires used for operating the flap is usually insufficient for conducting the lightning current.

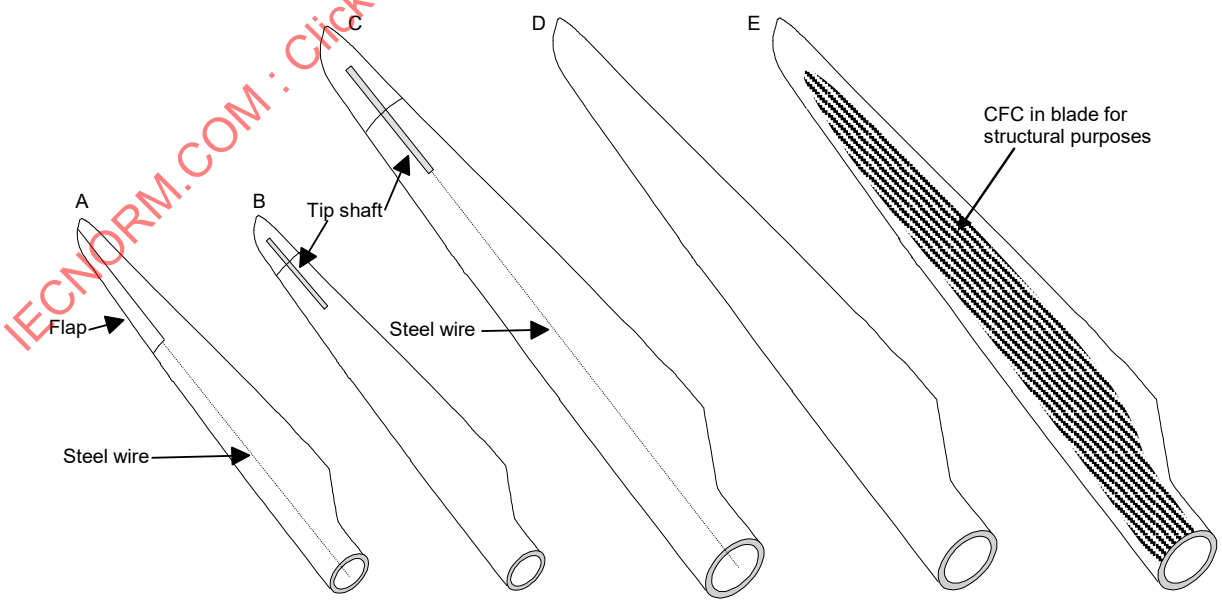

Figure C.1 – Types of wind turbine blades

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Type B blades use a tip brake which is retained by a spring and released at excessive rotational speed by centrifugal force. With type B blades, lightning attachment points are predominantly seen within a few tens of centimetres from the outermost tip, or on the sides of the tip at the position of the outermost end of the tip shaft. From the attachment point, a lightning arc is formed inside the tip section to the outermost end of the tip shaft, and from the other end of the shaft, an arc is formed inside the main blade down to the steel mounting flange at the blade root. Such internal arcs invariably cause catastrophic destruction to the blade. Blades of types A and B were commonly used with older wind turbines as large as 100 kW.

Type C is a blade with a tip brake controlled by a steel wire. With type C blades, lightning attachment points are predominantly found within a few tens of centimetres from the outermost tip of the blade, or on the sides of the tip at the position of the outermost end of the tip shaft. With type C as with type B blades, a lightning arc formed inside the tip section between the attachment point and the outermost end of the shaft causes severe damage. On type C blades, damage to the main blade is mostly seen when the steel wire has been unable to carry the lightning current. Steel wires used for this purpose are of a minimum diameter of 10 mm or 12 mm for 17-m-long blades. Such wires are capable of conducting most lightning currents, and thereby protecting the main blade from damage (see Clause C.6 for further discussion on dimensioning of protection systems).

Type D is a blade constructed entirely from non-conducting materials. Experiences with non-conducting blades are that, as with the other types of blades, lightning attachment points are mostly found close to the tip. Compared to the other types of blades, attachment points can also be found randomly distributed at other positions along the length of the blade.

Type E is a blade where some of the structural components are made with carbon fibre reinforced plastics (CFRP), since it has high stiffness for a given weight. Depending on the specific design, CFRP can be used as reinforcement of the blade skin, as well as for load carrying structural components, such as the internal spar. Owing to its electrical properties, CFRP should be coordinated carefully with the lightning protection system to ensure the necessary separation distance, electrical insulation and/or current carrying capability. The issues of lightning protection of wind turbine blades containing CFRP are treated in Clause C.3.

Lightning flashes attaching to non-conducting blades or to insulating parts of blades containing conducting parts may at least partly be explained by the fact that pollution and water make such blades more conductive over time. High-voltage laboratory experiments have shown that arc attachments occur to a non-conducting blade sprayed with saline water practically as if the blade was metallic. Another part of the explanation is that the blades are simply in the way of lightning striking the wind turbine. In addition, it is known that discharges develop along a surface more easily than through air, and especially if the surface is contaminated with saline pollution and water. In any case, practical experience shows that severe lightning damage to both non-conducting blades (type D) and blades containing CFRP (type E) is quite common and hence lightning protection is needed.

C.1.2 Blade damage mechanism

Typical types of damage at the lightning attachment points are delamination and incineration of the surface composite material, and heating or melting of metallic components serving as the attachment point.

The most severe damage to wind turbine blades occur, however, when lightning forms high energy arcs inside the blade due to attachment to an unprotected part of the blade skin. The arcs may form in the air volume inside the blade or along the internal surfaces. Another type of damage occurs when the lightning current or part of it is conducted in or between layers of composite materials or in glue cracks in connection with the down conductor system, presumably because such layers and cracks hold some moisture. The pressure shock wave caused by such internal arcs may literally explode the blade, ripping the blade surface skins apart along the edges and from the internal carrying spar. All grades of damage are seen

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ranging from surface cracking to complete disintegration of the blade. In some cases, pressure waves have propagated from the blade struck by lightning through the hub and into the other blades causing pressure damage to them.

Internal arcs often form between the lightning attachment point at the tip of the blade and some conducting component internal to the blade. With type C blades, the damage is often limited to the tip section, whereas the main blade is unharmed. Damage to type C main blades has normally been seen when an arc has formed inside the main blade. Typically, this has happened in cases where the steel wire controlling the tip brake was of insufficient cross-section to conduct the lightning current from the tip shaft to the hub. With type A blades, the main blade is destroyed.

The phenomenon responsible for the severe structural damage to wind turbine blades is therefore the formation of a pressure shock wave around an arc of lightning inside the blade. Minor damage can occur when a lightning arc is formed on the outside surface or when the lightning current is conducted by metallic components with insufficient cross-section.

The high-energy internal arcing responsible for the structural damage is not to be confused with the low-energy partial discharges mentioned in C.2.4.

C.2 Protection methods

C.2.1 General

The generic problem of lightning protection of wind turbine blades is to conduct the lightning current safely from the attachment point on the blade to the hub or nacelle in such a way that the formation of a lightning arc inside the blade is avoided. This can be achieved by diverting the lightning current from the attachment point along the surface to the blade root, using metallic conductors either fixed to the blade surface or inside the blade. Another method is to add conducting material to the blade surface material itself, thus making the blade sufficiently conductive to carry the lightning current safely to the blade root. Variations of both these methods are used on wind turbine blades (see Figure C.2).

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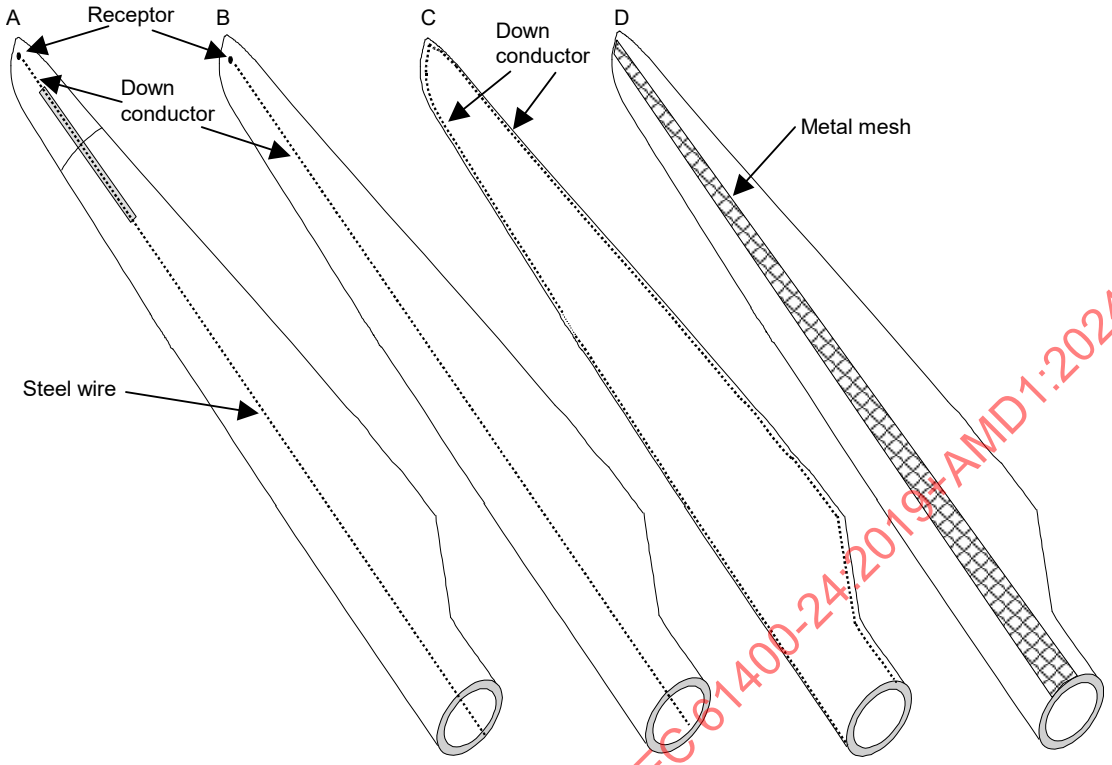

Figure C.2 – Lightning protection concepts for large modern wind turbine blades

C.2.2 Lightning air-termination systems on the blade surface or embedded in the surface

Metallic conductors on the blade surface serving as an air-termination system or a down conductor system should have sufficient cross section to be able to withstand a direct lightning attachment and conduct the full lightning current. In addition, certain dimensions are needed in order to achieve reliable fixing to the blade surface. The minimum cross section for aluminium is 50 mm^2 and achieving reliable fixing of such conductors may be problematic. Furthermore, conductors mounted on the blade surface may compromise the aerodynamics of the blade or generate undesirable noise.

For lightning conductors embedded in the blade surface, wires or braids of either aluminium or copper are used. Several protection systems exist where a metallic conductor connected to the blade root is placed either on the blade surface along the outside or embedded in the trailing edge. Some blade designs have metallic conductors placed along both the leading and the trailing edge (type C). In addition, some have metallic diverters placed on the surface around the blade at several radial locations along the blade, each of these being connected to conductors placed along the blade edges.

C.2.3 Adhesive metallic tapes and segmented diverter strips

Adhesive aluminium tape placed on the blade surface has been used in several investigations. However, such tapes tended to peel off within a few months. Provided that the problem of keeping the tape on the blade can be solved, it is possible that metallic tapes can be an interesting protection method, especially as a retrofit for existing unprotected blades. It should, however, be noted that large pressure waves are associated with guiding the flash close to the blade surface [6]. This may lead to structural damage.

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Some promising experiments with segmented diverter strips have been performed in the past. Such segmented strips are used on aircraft radomes because they do not interfere with the radar signal.

It is possible that metallic tape can be used as one-shot protection requiring replacement after a lightning stroke.

C.2.4 Internal down conductor systems

A common option is to place lightning conductors inside the blade. Metallic fixtures for the conductor penetrate the blade surface and serve as discrete lightning receptors. Such protection systems are used on aircraft [6].

The lightning protection system used on many blades currently in manufacture has discrete lightning receptors placed at the blade tip (types A and B in Figure C.2). From the receptors at the tip, an internal down conductor system leads the lightning current to the blade root. For blades with tip brakes, the steel wire controlling the tip is used as a down conductor (type A). If the blade is without tip brake, then a copper wire placed along the internal spar is used as a down conductor (type B).

Many thousands of blades with this lightning protection system (types A and B in Figure C.2) have been produced. The experiences with this lightning protection system for blades as long as 20 m are very positive. The principle with one or more external air terminations connected to an internal down conductor has up till the date of publication been used widely by many manufacturers for blades up to 60 m. For such long blades, experience has shown that there is a risk of direct lightning attachment through the laminate to the internal down conductor causing severe blade damage. These problems appear to be linked to uncontrolled partial discharges developing from the internal conductive parts (the down conductor, connection components, etc.).

When such low-energy partial discharges are allowed to be incepted from the interior metal parts of the blade, they will propagate as fast as the ones incepted from the air termination system. Once these internal discharges strike the interior surface of the blade, they will, in connection with partial discharges on the blades' exterior, intensify the electrical stress experienced by the laminate. The increased stress might not be a problem for a limited number of rapid field changes (lightning striking receptors or nearby structures), but when the blade is exposed to several impacts during its entire service lifetime, the stress might eventually develop into a complete electrical breakdown. The physical impact on the blade from such a high-voltage breakdown channel is rather limited, but the damage associated with the following lightning current may be disastrous as commented in C.1.2.

Such discharges may be impeded or delayed by encapsulating the internal down conductor and other conductive parts in the blade with electrically insulating material, thereby reducing the problem.

C.2.5 Conducting surface materials

An alternative to a lightning air-termination system placed on the blade surface is to make the surface itself conducting. In the aircraft industry, lightning protection of glass and carbon fibre composite material for wings and surfaces exposed to lightning is achieved by adding conducting material to the outer layers, thereby reducing damage to a small area at the attachment point. The conducting material can be metal sprayed onto the surface, metal-coated fibres in the outer layers of the composite material, metal wire woven into the outer layers of the composite material, or expanded metal foil mesh placed just beneath the outer surface of the composite. Lightning protection of wind turbine blades has been made with metal mesh placed along the sides of the blades just under the gel coat (D on Figure C.2). Sometimes, the extreme tip of the blade is made of metal or covered with a metal sheath.

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The advantage of using metal mesh or other thin conducting surfaces for lightning down conductors is that possible interior conductive elements (e.g. CFRP) are shielded from the electric field, and hence direct lightning attachments. The inductive voltage drop along the length of the conductor associated with the high current gradient will be slightly reduced, an important effect considering the risk of side flashes. However, the risk of getting direct lightning attachment to the edge of such thin geometries, and the possibility of uneven current distribution owing to skin effects should also be considered.

C.3 CFRP structural components

Carbon fibre reinforced plastics (CFRP) have been used for tip shafts for small blades and are now commonly used for reinforcement of large blades. The material is used either for the load-carrying centre spar or directly in the blade skins owing to a high strength-to-weight ratio. The use of CFRP for structural components is expected to increase even further as the size of blades increases owing to its weight decrease advantage.

The main issue with CFRP is how it reacts to the lightning current possibly entering and flowing within the material. Two electrical properties of CFRP make it remarkably different than isotropic conductor materials like metals – the conductivity and the degree of anisotropy.

The conductivity of CFRP is in the order of 1 000 times lower than that of aluminium. Depending on the actual construction and weaving technique, the conductivity of CFRP exhibits a very high degree of anisotropy, with higher resistance of the material in directions perpendicular to the fibre orientation. For CFRP coupons used for lightning tests in the aircraft industry, the conductivity has been measured and varies within four orders of magnitude for different current directions.

Therefore, the resistive heating of CFRP when exposed to high current densities might be critical. Especially at the lightning attachment points where high currents enter a rather confined area, the temperature due to joule losses might exceed the evaporation temperature of the resin. When the resin matrix evaporates, the pressure from evolving gases can cause rupture and delamination of the CFRP layers. The CFRP may even incinerate, in particular at the lightning attachment point.

Where CFRP is used in aircrafts, it is considered mandatory that lightning protection is provided for CFRP components that can be struck by lightning or can conduct lightning current.

There are examples of CFRP tip shafts for wind turbine blades having been damaged by lightning. Some laboratory experiments have also demonstrated problems with CFRP shafts conducting lightning current. Laboratory tests of blades with CFRP skin have shown surface delamination and incineration at the lightning attachment point. The protection concept for the blade should consider the exposure of direct strikes along the entire length of the blade, and document by testing and analysis that direct strikes to likely attachment points do not cause any damages compromising the performance requirement in 8.2.2.

Dependent on the specific blade design and LPS protection strategy, the CFRP structural components will either be considered as an integral part of the lightning current path or electrically isolated from the LPS.

It is critical that proper coordination between CFRP structural components, other conductive components and the LPS be made. Coordination should consider:

- electrical bonding and/or,
- electrical insulation and/or,
- physical separation.

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For each specific blade and LPS design, either all, or a subset of the above should be applicable.

If electrical bonding is implemented, then it should be determined whether the spacing between equipotential bonding points is adequate to avoid the development of critical voltages that could cause an uncontrolled flashover.

C.4 Particular concerns with conducting components

Conductive components in this clause cover all other conductive parts in the blade besides the receptors and down conductor system described in Clause C.2, and CFRP described in Clause C.3.

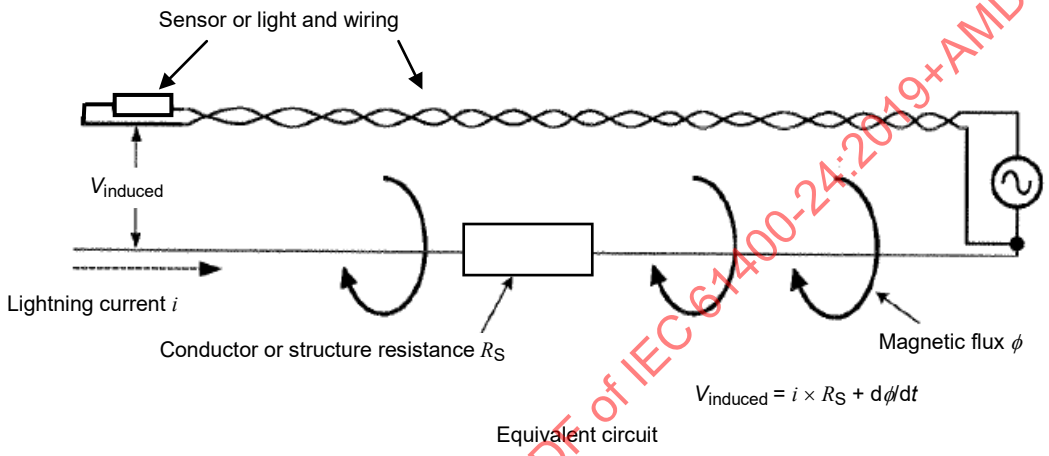

Figure C.3 – Voltages between lightning current path and sensor wiring due to the mutual coupling and the impedance of the current path

Wiring for sensors placed on or inside blades may be exposed to strong magnetic fields that can produce damaging voltages between the lightning conductor and other wiring in the blade, as illustrated in Figure C.3. Such wiring should be avoided if possible. The induced voltage is typically dominant compared to the resistive part, therefore great care needs to be taken when estimating induced voltages. The designer is advised to consult specialised literature on this issue.

If such installations are present, the protection should rely on careful coordination with the LPS. Coordination should consider:

- electrical bonding and/or,
- electrical insulation and/or,
- physical separation.

Having well exposed external lightning air termination systems directly outside of internal conducting components should protect the internal structures from direct lightning attachment. Furthermore, the risk of getting partial discharges from internal wiring is minimised by covering the conductive wiring carefully with electrically insulating materials. Note that high currents and voltages can be induced in isolated conductor loops in the vicinity of the down conductor system. Such surges can possibly result in internal sparking. It is possible that designs that integrate electrical wiring associated with sensors, lights and other systems with the lightning protection system, including the lightning down conductor, may be the most successful in avoiding damage to these systems. Careful coordination of designs of all

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systems contained within a blade is essential for successful lightning protection of the blade and functioning of the systems contained within the blade.

Metallic structural components within the blade, i.e. weights, dampers, platforms, etc. should be treated similarly. All conductive parts in the blade should be designed to minimise electric field enhancement and be coordinated carefully with the blade LPS to ensure the necessary separation distance, electrical insulation and/or current carrying to reduce the risk of internal discharges. As with the wiring, it is important that the external air terminations shield off the internal conductive components from the electric field, hence protecting these areas from direct lightning attachment.

If other conductive components are located within the blade, (e.g. blade tip navigation light, lightning sensors, condition monitoring equipment), it should always be shielded by external lightning receptors, thereby minimising the risk of direct lightning attachment to the structures. As described previously, the risk of internal discharges possibly leading to puncture of the blade skin can be minimised by encapsulating all internal conductive parts carefully in electrical insulation material.

C.5 Interception efficiency

The interception efficiency is defined as the number of strikes to the blades intercepted correctly by the air terminations relative to the total number strikes to the blade. In this sense, the interception efficiency is a parameter describing the ability of the blade LPS to intercept the strikes safely. The interception efficiency is affected by the following factors:

- the design and exposure of the air termination system (position and geometry);
- insulation level of internal conductive parts;
- the result of the HV initial leader attachment test in Annex D (interception effectiveness).

Any air terminations and extensions of air terminations (solid conductors and segmented diverters on the surface) should be placed in such a way that the likelihood of lightning puncturing insulating surfaces is reduced to an acceptable level.

The placement of air terminations would be such that the flashover voltage along the blade non-conducting surface is smaller than the breakdown voltage of the blade skin. In practice, both the breakdown voltage of the blade skin and the surface flashover voltage will be difficult to establish, as variations due to different composite materials as well as influence of ageing, cracks, humidity and pollution should be expected. Furthermore, the interception efficiency of segmented diverters and discrete air terminations will be influenced by the presence of conducting materials inside the blade [6].

Recent publication of lightning attachment distribution for wind turbine blades shows that the majority of lightning flashes attaches to the tip region of the blade, and that the likelihood of attachment decrease rapidly towards the blade root. More details are provided in Clause C.8.

High-voltage strike attachment tests on test specimens representing the design are useful for revealing interception effectiveness, and thereby identify and resolve design issues before implementing in final production.

Numerical methods used to determine likely attachment areas on blades and nacelles and estimates of the annual number of direct lightning flash attachments to certain structures are currently being developed. It is not likely, however, that numerical simulation methods can predict with certainty whether a non-conductive blade structure would be punctured, or establish the number and location(s) of receptors necessary to prevent punctures. This is owing to the complexity of most blade structures, and the dynamics of multiple streamer origination and growth. Thus, the numerical methods are useful in the design phase. Whether numerical methods or empirical evidence is used, high-voltage attachment tests, as described in Clause D.2, of candidate designs, should be used to provide additional assurance of protection effectiveness.

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C.6 Dimensioning of lightning protection systems

The materials used for lightning protection of wind turbine blades should be able to withstand the combined effects of the electric, thermal and electrodynamic stresses imposed by the lightning current. Nominal dimensions for materials used for air termination and down conductors are listed in Table C.1 (see also IEC 62305-3).

Table C.1 – Material, configuration and minimum nominal cross-sectional area of air-termination conductors, air-termination rods, earth lead-in rods and down conductors[a] (corresponds to IEC 62305-3)

Material	Configuration	Nominal cross-sectional area mm^2
Copper,	Solid tape	50
Tin plated copper	Solid round[b]	50
	Stranded[b]	50
	Solid round[c]	176
Aluminium	Solid tape	70
	Solid round	50
	Stranded	50
Aluminium alloy	Solid tape	50
	Solid round	50
	Stranded	50
	Solid round[c]	176
Copper coated aluminium alloy	Solid round	50
Hot-dip galvanised steel[b]	Solid tape	50
	Solid round	50
	Stranded	50
	Solid round[c]	176
Copper coated steel	Solid round	50
	Solid tape	50
Stainless steel[e]	Solid tape[d]	50
	Solid round[d]	50
	Stranded	70
	Solid round[c]	176

[a] Mechanical and electrical characteristics as well as corrosion resistance properties should meet the requirements of the IEC 62561 series.

[b] 50 mm^2 (8 mm diameter) may be reduced to 25 mm^2 in certain applications where mechanical strength is not an essential requirement. Consideration should, in this case, be given to reducing the spacing between the fasteners.

[c] Applicable for air-termination rods and earth lead-in rods. For air-termination rods where mechanical stress such as wind loading is not critical, a 9,5-mm diameter, 1-m long rod may be used.

[d] If thermal and mechanical considerations are important, then these values should be increased to 75 mm^2.

The cross-sectional areas given above are provided as a guideline derived for simple conductors. For such geometries, the temperature rise associated with the lightning current might be evaluated analytically or numerically. Considering components for special applications, such as flexible down conductors, and more complex geometries such as air terminations, connection components, expanded foil, etc., different dimensions can be considered. For such components, design verification should be based on laboratory tests.

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When the individual lightning protection components are put together forming the entire blade installation, testing of the final solution is recommended.

Components under load such as the steel wires for tip brakes may have to be even more solid as the mechanical strength is reduced if heated to high temperatures. There are a few experiences with steel wires for tip brake control that have broken or melted due to lightning currents even for wires of up to 10 mm diameter (cross-sectional area 78 mm^2).

The temperature rise of conductors carrying lightning current can be evaluated as shown in Equation (C.1) (see also IEC 62305-1). The designer should consider the temperature rise of all components subjected to all, or parts of, the lightning current and ensure that such components have sufficient strength to fulfil their function immediately after a lightning stroke.

$$\theta - \theta_0 = \frac{1}{\alpha} \cdot \left\{ \exp\left[\frac{(W/R \cdot \alpha \cdot \rho_0}{q^2 \cdot \gamma \cdot c_W} \right] - 1 \right\} \quad \text{(C.1)}$$

where

$\theta - \theta_0$ is the temperature rise of the conductors [K];

α is the temperature coefficient of the resistance [1/K];

W/R is the specific energy of the current impulse [J/Ω];

ρ_0 is the specific ohmic resistance of the conductor at ambient temperature [Ωm];

q is the cross-sectional area of the conductor [m^2];

γ is the material density [kg/m^3];

c_w is the thermal capacity [J/kgK].

Table C.2 shows the inputs to this equation for common materials, and Table C.3 shows temperature rises for different conductors. It should be noted that in the case of pre-loaded wires, the temperature rise does not have to reach the melting point to cause failure.

Table C.2 – Physical characteristics of typical materials used in lightning protection systems (corresponds to IEC 62305-1)

Quantity	Material			
	Aluminium	**Mild steel**	**Copper**	**Stainless steel[a]**
ρ_0 [Ωm]	29×10^{-9}	120×10^{-9}	$17{,}8 \times 10^{-9}$	$0{,}7 \times 10^{-6}$
α [1/K]	$4{,}0 \times 10^{-3}$	$6{,}5 \times 10^{-3}$	$3{,}92 \times 10^{-3}$	$0{,}8 \times 10^{-3}$
γ [kg/m^3]	2 700	7 700	8 920	$8{,}0 \times 10^3$
θ_s [°C]	658	1 530	1 080	1 500
c_s [J/kg]	397×10^3	272×10^3	209×10^3	–
c_w [J/kgK]	908	469	385	500
θ_s [°C] is the melting temperature;				
c_s [J/kg] is the latent heat of melting.				
[a] Austenitic non-magnetic.				

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Table C.3 – Temperature rise [K] for different conductors as a function of W/R (corresponds to IEC 62305-1)

Cross-section mm^2	Material											
	Aluminium			Mild steel			Copper			Stainless steel[a]		
	W/R MJ/Ω			W/R MJ/Ω			W/R MJ/Ω			W/R MJ/Ω		
	2,5	5,6	10	2,5	5,6	10	2,5	5,6	10	2,5	5,6	10
4	–	–	–	–	–	–	–	–	–	–	–	–
10	566	–	–	–	–	–	169	541	–	–	–	–
16	147	454	–	1 114	–	–	56	143	309	–	–	–
25	52	132	283	211	912	–	22	51	98	938	–	–
50	12	28	52	37	96	211	5	12	22	188	460	938
100	3	7	12	9	20	37	1	3	5	45	102	188

[a] Austenitic non-magnetic.

Considering the impact on the air termination, IEC 62305-1 suggests the use of the anode or cathode voltage-drop model to calculate the volume subject to erosion. Several attempts have been made to correlate this model with test and field experience, without any success. Further research is required to achieve a fully verified model.

C.7 Blade-to-hub connection

At the root of the blade, the down conduction system is usually either terminated via the blade mounting flange, to the hub, or directly to the nacelle (bypassing pitch bearings and main rotor bearings) using a special connection system.

If the blade is pitch regulated (type D), the lightning current is either allowed to pass through the pitch bearing or around the bearing using a sliding contact, an air gap or a flexible bonding cable with enough slack to allow for the pitch motion. The flexible bonding across the bearing can be integrated with the innermost part of the down conductor from the blade.

In blades with tip brake (type C), the hydraulic system, which actuates the control wire, should be protected. Standard hydraulic cylinders that are normally used can be damaged by flashovers from the rod to the cylinder housing. Usually, the hydraulic cylinder is protected by diverting the lightning via a flexible bonding strap with sufficient slack to allow for the motion, or alternatively a sliding air gap or brush is used to divert lightning current away from the hydraulic cylinder. Care should be taken to reduce the slack in such bonding straps, since the inductive voltage drop across the slack may become very high, thus resulting in ineffective protection of the cylinder.

No matter what type of blade to hub interface is used, the component/design should be verified using the high current physical damage test in D.3.3.

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C.8 WTG blade field exposure

C.8.1 General

WTG blades are the components most exposed to direct lightning strikes in the field. As described in C.8.2, lightning strike attachment probability cannot be determined by means of the high-voltage test described in Annex D, therefore, the best way to determine this probability is by analysis of field data for similar blades. Experience with different blades from different manufacturers have shown that the outer part of the blade receives the majority of the direct strikes. These studies indicate that the probability of direct lightning strikes increases closer to the blade tip.

C.8.2 Application

The objective of presenting field data concerning the attachment point distribution on WTGs is to ensure that manufacturers target the design and placement of the lightning protection system in an efficient manner, i.e. placing the protection emphasis at the tip region of the blade. The presented field data is based on several blade designs investigated over the past decade, revealing a clear distribution of lightning attachments and damages at different span-wise locations. The data is publicly available and show unambiguously the trend of higher strike probability towards the tip region of the blade.

The attachment point distribution presented here may differ from the findings for specific blades at specific sites, and provided manufacturers have collected such information on their own blade designs at relevant sites, such data should be used for the design inputs.

C.8.3 Field exposure

Several field campaigns are reported in literature where attachment points are identified by inspecting blades and evaluating successful lightning strike protection as well as strikes causing blade damage. The blade inspections cover blades on onshore and offshore turbines, blades made of CFRP and GFRP main laminates, and blades with different air termination and down conductor layout. The considered blade lengths range from 39 m to 45 m, with the following distribution of strikes to WTG blades vs. the distance from the blade tip. The results of these investigations are summarised in Table C.4, which can be used for reference if no specific information is available.

Table C.4 – 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
4 to 6	0 to 10
6 to 8	0 to 4
8 to 10	0 to 4
Rest	0 to 4

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Annex D
(normative)

Test specifications

D.1 General

This annex describes test methods for verifying blade designs with respect to their capability of handling the impact of a lightning discharge. The tests are described for blades herein, but may also be applied to other objects such as the spinner, hub, nacelle or parts thereof.

The manufacturer shall define the number of samples of the items to be tested. The items to be tested would be specimens of the blade, including the tip and sufficient portions of the blade inboard of the tip to represent the complete lightning protection design and the blade specimen structure, as well as the interaction of the air termination system, lightning down conductors, down conductor connection components, other components of the lightning protection system, and the blade specimen structure. The test specification is divided into two sub-sections.

The high-voltage strike attachment tests are applied to determine specific lightning attachment points and breakdown paths across or through non-conducting materials, such as wind turbine blades and nacelle covers. Since the currents that flow during these tests are representative only of lightning leader currents, and not the much more intense stroke currents, the attachment tests are intended only to show the path(s) that may be taken by lightning discharges. The damage caused by these tests is not comparable to possible damage from the lightning currents.

The high-current physical damage tests are used to assess actual damage from lightning currents. The test methods presented are applicable to both complete tip designs, and to smaller sections of the down conductor, such as connection components. These tests do not give any information about the most likely attachment points.

Pass/fail criteria for each test are described in the following subsections.

D.2 High-voltage strike attachment tests

D.2.1 Verification of air termination system effectiveness

These verification tests are used to verify the effectiveness of the air termination system on wind turbine blades. For development and design purposes, different test setups and considerations than required by the normative tests may be used.

The evaluation based on the strike attachment tests cannot be correlated with interception efficiency as stipulated by the selected LPL. The actual interception efficiency can only be verified by field observations.

NOTE For two-bladed rotors, the attachment distribution along the blades will differ from three-bladed rotors. Hence, the high-voltage initial leader attachment test required in D.2.2 can to be done with even lower angles (i.e. closer to horizontal / zero degrees) to demonstrate adequate interception efficiency for the tip as well as for inboard sections of the blade.

D.2.2 Initial leader attachment test

D.2.2.1 Test purpose

This test is intended for wind turbine blades. This test shall be used to verify the following:

- effectiveness of the air termination system for the blade in question;

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- location of possible leader attachment points and flashover or puncture paths on blades and other non-conducting structures;
- flashover or puncture paths along or through dielectric surfaces;
- performance of protection designs and/or devices.

D.2.2.2 Test specimen

The test specimen is a full-scale blade or blade tip section including all relevant design details as being present in series production. In selecting the appropriate blade length, the blade design details and the likelihood of test strike attachment to the crane slings, to other details being part of the test setup and to the root end of the blade sample shall be considered. Experience has shown that a blade length of approximately 15 % of the total blade is applicable for 10° or lower test angles.

The blade section shall be long enough to include samples of all applicable elements of the lightning protection system installed in a production representative condition. The test report shall detail the applicability rationale of the test section with respect to the full blade design.

Electrically conducting components, such as lights and sensors and the lightning conductor(s), normally installed on or within the test specimen (a single blade, a blade tip or a mid-section of a blade), shall be represented within the test specimen.

These items shall be positioned at the same locations within the test specimen as they would be in the blade. If the conducting specimens may be oriented in several positions, those that represent worst cases should be represented in the tests. Normally these are the positions that result in the smallest distances to the non-conducting skins, or the strongest electric field intensities in directions normal to the exterior surface. Either new blade samples or samples that have previously been aged mechanically could be used as long as they are undamaged by the mechanical aging process.

NOTE 1 The test description in this annex is mandatory for blade tips. The same test principles can be applied for inboard blade sections to verify performance of air termination systems in these regions, or determine likely attachment points along the blade.

NOTE 2 Experience has shown that testing blades in angles of 10° to the horizontal plane requires test samples of minimum length 10 m to avoid flashovers from the end of the blade sample.

D.2.2.3 Test setups

D.2.2.3.1 General

The initial leader attachment test is used for design and verification purposes. The verification test for blades is described in the present subclause, and the test used are test setup A or B, whereas development tests may benefit from different test setups and test configurations.

Each test arrangement is intended to result in initiation of electrical activity, such as corona, streamers and leaders, at the test specimen (and not at the external electrode) as occurs at a wind turbine blade just before a lightning attachment. Once ionisation of the air at the test specimen is initiated, the streamer will progress toward the opposite electrode which is to be a large geometric shape intended to represent an electric field equipotential surface some distance from a blade extremity. In this way, the influence of the external test electrode on test results is minimised. Overviews of the test arrangements showing the high-voltage generator, test specimen and external electrode in test setups A and B are illustrated in Figure D.1, Figure D.4 and Figure D.5.

Test setup A is the most desirable arrangement, since it usually allows a larger dimension external electrode (i.e. a conductive surface on the laboratory floor) and a more realistic electric field environment around the blade specimen to be provided.

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Test setup B is intended to create a similar electric field arrangement about the test specimen as in test setup A while allowing larger or heavier test specimens and support structures to be placed on the laboratory floor. In this arrangement, a large diameter electrode shall be suspended above the test specimen. A large diameter is essential to avoid non-realistic field intensifications owing to the edges of the suspended electrode, potentially causing flashovers between the edges of the electrode and the test sample, or between the edges of the suspended electrode and a ground plane on the laboratory floor, bypassing the blade test specimen altogether.

NOTE For very flexible blade samples, it might be considered to pitch the blade in an angle such that the force of gravity bends the blade into a geometry closer to operational conditions. This principle of a fixed blade setup applies to both setups A and B.

D.2.2.3.2 Test setup A

Test setup A is applicable for tests of large portions of a blade that includes representative portions of the lightning protection system. The general test arrangement for test setup A is illustrated in Figure D.1.

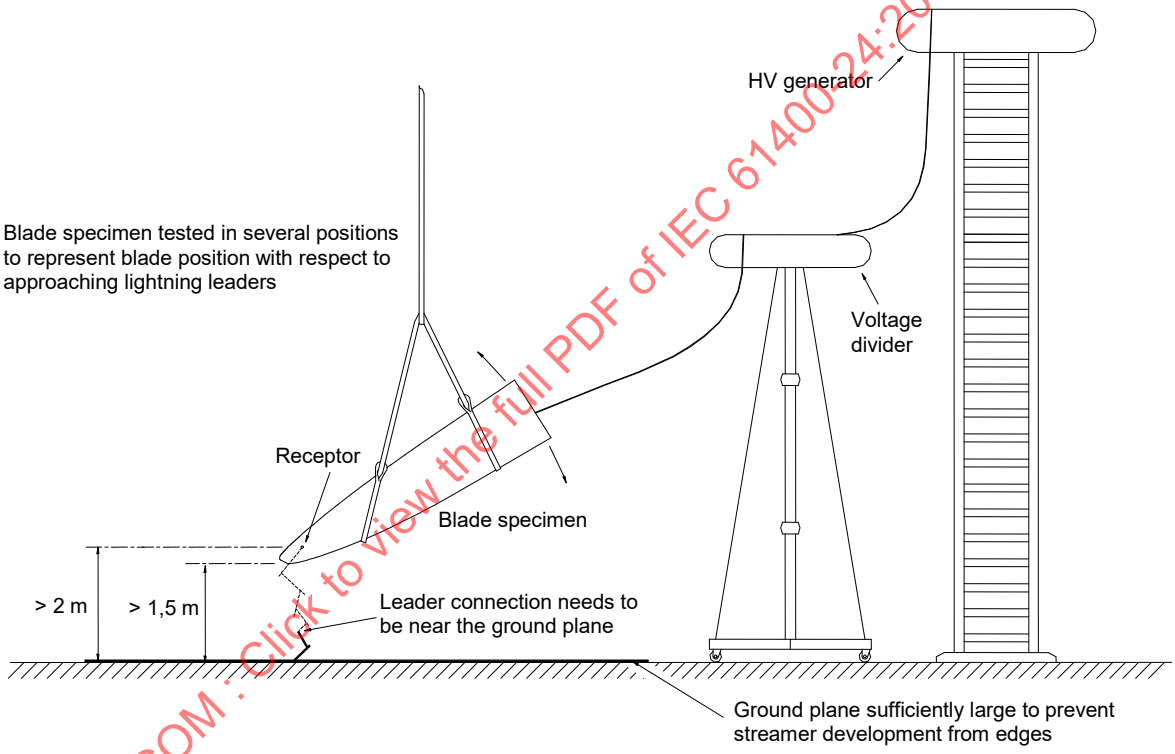

Figure D.1 – Example of initial leader attachment test setup A

The distances shown in Figure D.1 are indicative only. The minimum air-gap distance to conductive parts shall be 1,5 m.

The test specimen, having its lightning protection system connected to the output of a Marx generator, is elevated above the external electrode, a large area ground plane. The ground plane shall be of sufficient size to avoid edge effects, i.e. to avoid having flashovers terminating on the edge of the ground plane and to be regular and uniform enough to ensure that the connection point of the flashover is in the lower part of the gap. The test specimen shall be tested in the 90°, 30° and 10° orientation at all 4 blade pitch angles as defined in Figure D.2, to represent electric field directions that this part of the test specimen may experience on the turbine. The specific angles defined for the mandatory test sequence identifies likely attachment points at the most predominant blade angle relative to the field

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(90°) and also stresses inboard sections of the tip region where likely attachment points are also observed in field (30° and 10°). Additional angles may be used to investigate the blade performance during the design process.

In Figure D.2, three different angles of the blade relative to the ground plane are used (90°, 30° and 10° with horizontal, all with tolerances ±3°), and four different pitch positions. By applying three discharges of each polarity and at each orientation, the blade will experience 54 impacts.

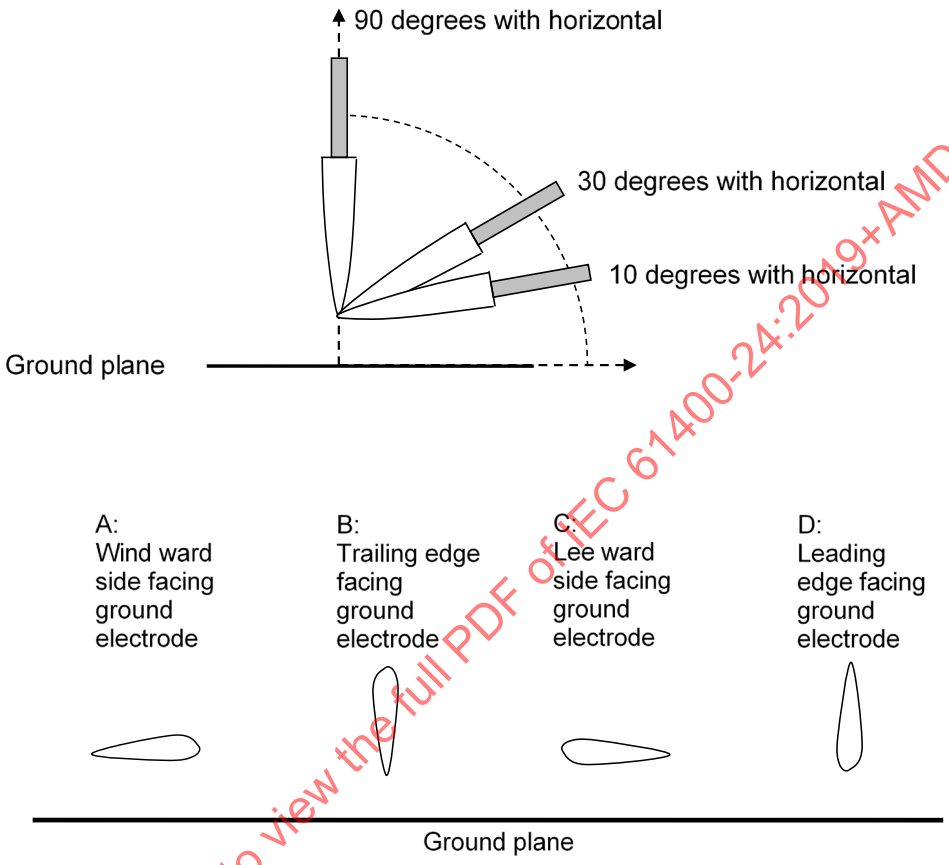

Figure D.2 – Possible orientations for the initial leader attachment test setup A

For two-bladed rotors, the attachment distribution along the blades will be different than for three-bladed rotors. Hence, the high-voltage initial leader attachment test should be conducted with even lower angles (preferably as close to 0° as possible) to demonstrate adequate interception effectiveness for the tip as well as for inboard sections of the blade. Currently, the mandatory test sequence for three-bladed rotors apply for two-bladed rotors as well, until further field experience with two-bladed rotors is published.

NOTE Tests of wet and polluted blade samples can be used to stress particular design features and emulate a naturally aged blade, but such tests are not mandatory.

The angle between the blade length axis and the external ground electrode is defined in accordance with Figure D.3. For each test configuration in Figure D.2, the blade length axis is defined as a line intersecting the closest surface (windward side (A), trailing edge (B), leeward side (C) or leading edge (D) at distances of 1 m and 5 m from the tip.

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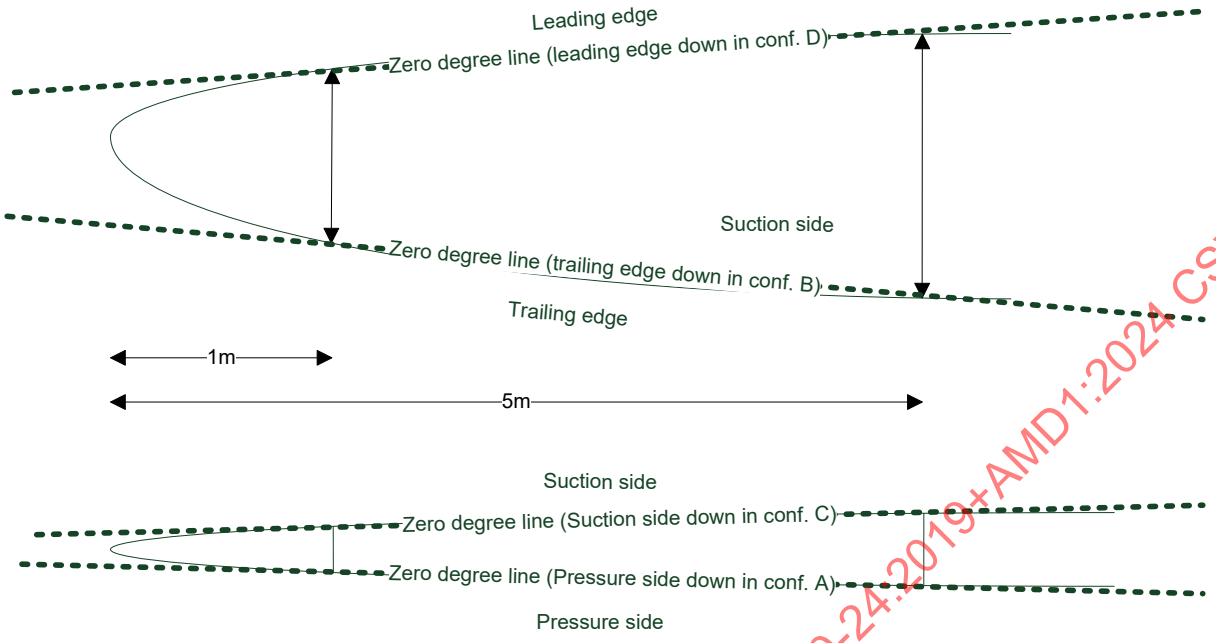

Figure D.3 – Definition of the blade length axis during strike attachment tests

For blade designs equipped with serrations, winglets, vortex generators or other aerodynamic features, the same criterion as shown in Figure D.3 applies. Sketches of the application on a blade with a winglet are shown in Figure D.4.

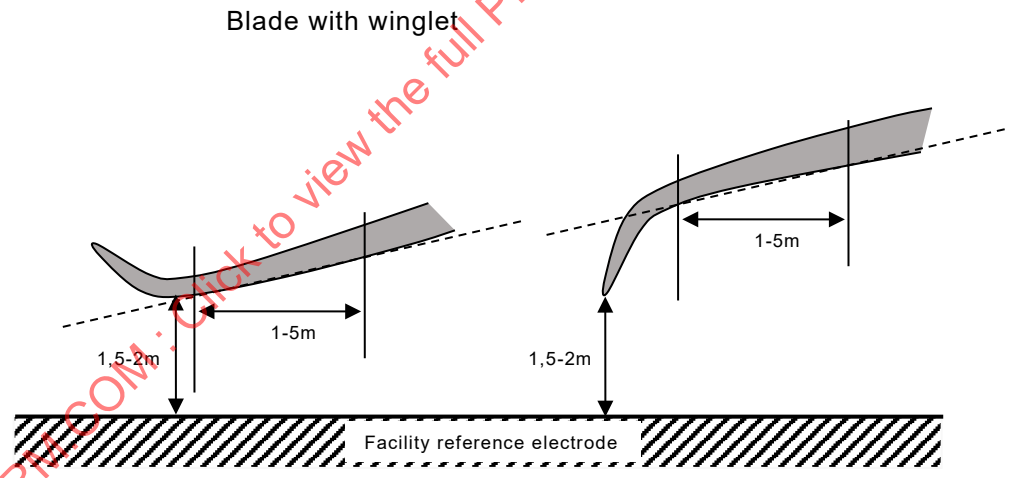

Figure D.4 – Example of the application of angles during the HV test

In the case of blades with winglets, the gap distance to non-conducting parts may be adjusted depending on the winglet design, provided the distance to the air-termination and conducting parts is minimum 1,5 m, and the minimum air-gap distance to non-conducting parts is 0,5 m.

Two conditions shall apply for a valid test when test setup A is used:

a) Connection of the streamers shall occur in the lower part of the air gap between the energised blade and the ground plane, i.e. more than half the flashover distance away from the blade specimen. This is confirmed by photographs of the flashovers. The leader connection point is shown in Figure D.5. If this is not achieved, the uniformity of the plane surface shall be improved, or the distance between blade and plane increased. If the connection has occurred closer to the blade than half way between the blade and the

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ground plane and the test has resulted in successful attachment to a designated protection device or design, the test should be considered successful. But if a puncture of the blade has occurred, the test shall not be considered successful, and the specific test is disregarded and an additional test may be applied.

b) The streamer from the ground plane shall not originate from the edge of the ground plane. In such a case, the size of the ground plane may be increased. But note that increasing the diameter of the HV electrode may not stop flashovers from originating at the edge of the HV electrode and bypassing the test specimen.

If the flashover originated at the ground plane, and the test has resulted in successful attachment to a designated protection device or design, the test should be considered successful. But if a puncture of the blade has occurred, the test shall not be considered successful, and the specific test is disregarded and an additional test may be applied.

Conditions a) and b) are typically met by keeping the following dimensions:

1) The ground plane should be at least 2 m from the closest conductive element (inside or outside the test specimen);
2) The ground plane should be at least 1,5 m from the nearest test specimen skin;
3) The smallest dimension of the ground plane should be at least 5 times the minimum gap length between the blade and the ground plane.

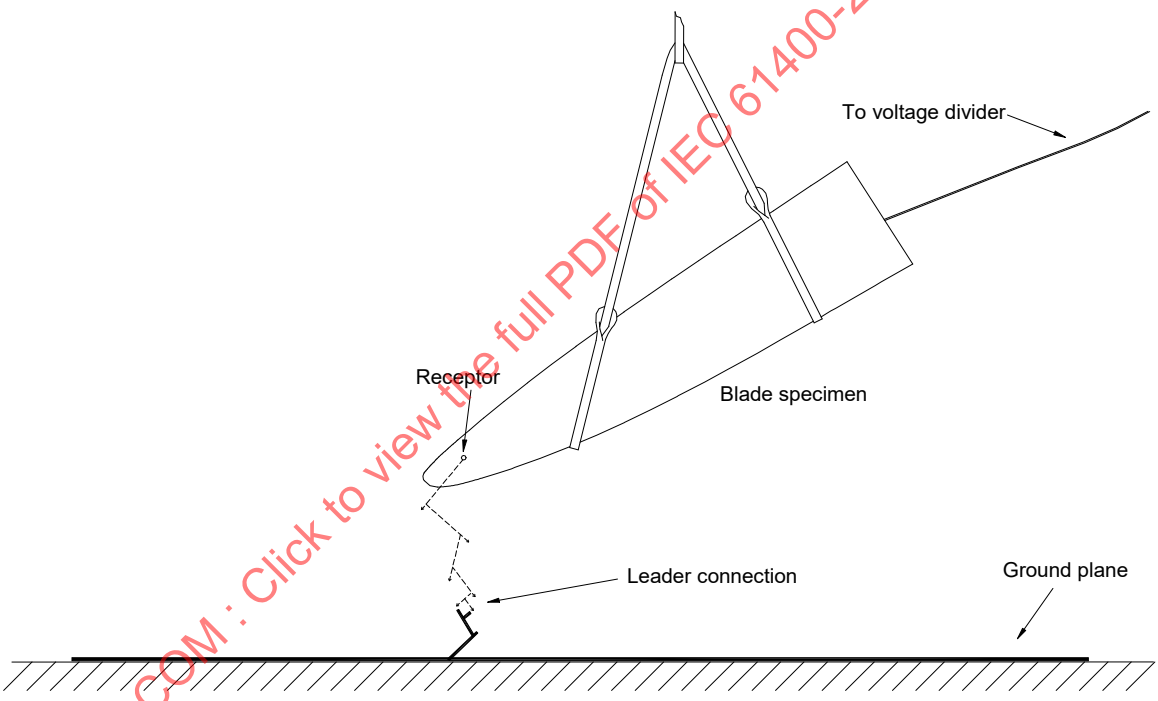

Figure D.5 – Example of leader connection point away from test specimen

Specific dimensions and test specimen orientations shall be described in the test plan.

D.2.2.3.3 Test setup B

The general test arrangement for test setup B is illustrated in Figure D.6.

The specimen should be tested in several positions representing different directions of the approaching leader, as specified in Figure D.2 for test setup A.

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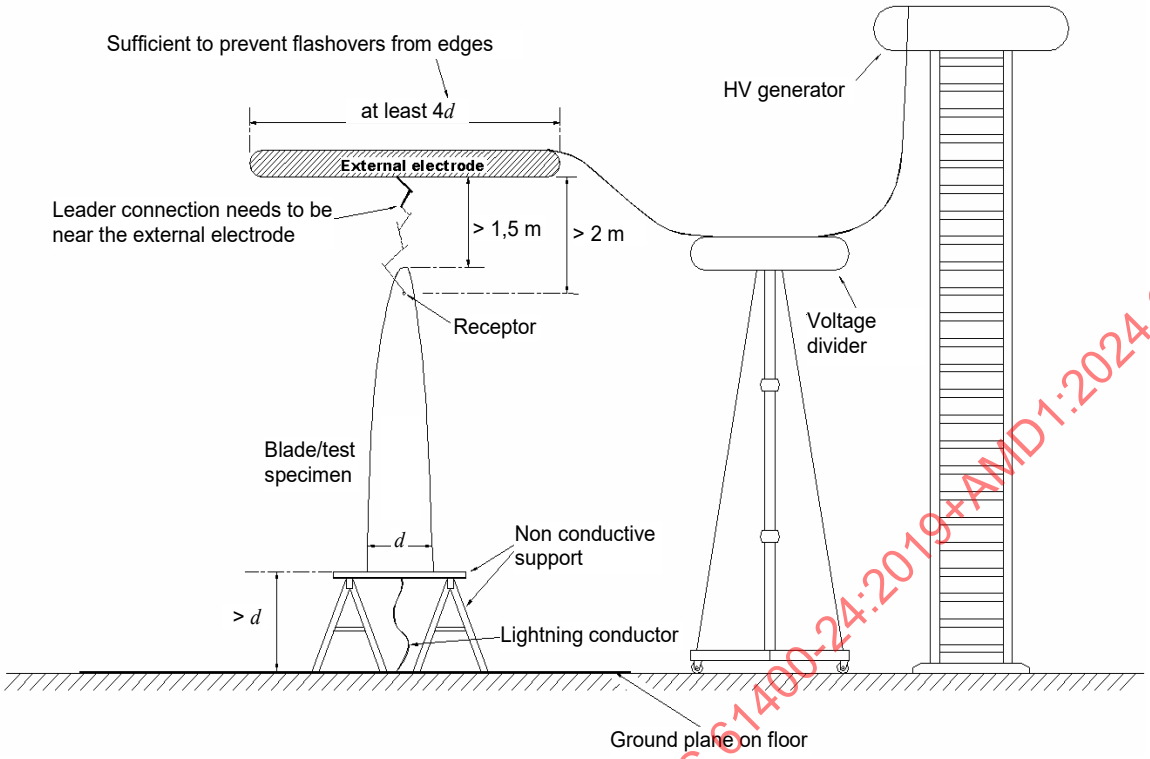

Figure D.6 – Initial leader attachment test setup B

The distances shown in Figure D.6 are indicative only. The minimum air-gap distance to conductive parts shall be 1,5 m.

Test setup B is applicable for blades as an alternative to test setup A, but also suitable for test specimens where elevation in the test facility is impractical, such as meteorological instrument booms, hubs, spinners. This arrangement has the disadvantage that the ground plane on the test facility floor may distort the electric field near the test specimen. The minimum clearance to extraneous structures is specified, in IEC 60060-1, as 1,5 times the minimum flashover distance between the two opposite electrodes. To minimise the distortion on the electric field present in the gap, the ground plane and other conductive structures shall be at least 1,5 times the gap length away, i.e. 3 m with the gap length of 2 m in Figure D.6.

The test specimen is elevated above the ground plane on supports by a distance greater than 1,5 times the distance between air termination on the test specimen and the external electrode to minimise influence of the ground plane on test results. The external electrode is suspended above the test specimen and at high potential when the test is applied. The external electrode shall be of sufficient size to avoid edge effects, i.e. to avoid having flashovers terminating on the edge of the external electrode. The test specimen should normally be tested with two or more orientations, to represent the possible electric field directions that this part of the blade or other structures may experience in service. One pitfall with Setup B is that when the external electrode is at positive polarity, flashovers can originate at the edges of this electrode and terminate on the ground plane and bypass the test specimen.

Three conditions should apply to a valid test when test setup B is used:

a) Connection of the streamers should occur in the upper part of the air gap between the energised external electrode and the test specimen, i.e. more than half the flashover distance away from the test specimen. This is confirmed by photographs of the flashovers.

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The leader connection point is shown in Figure D.6. If this is not achieved, the uniformity of the plane surface should be improved, or the distance between the blade and the plane increased.

b) The streamer from the external electrode should not originate from the edge of this electrode. In such a case, the size of the external electrode may be increased. But note that increasing the diameter of the HV electrode may not stop flashovers from originating at the edge of the HV electrode and bypassing the test specimen. In this case, the only solution is to use test setup A.

c) The end termination of the LPS or other conductive elements within the specimen should be elevated above the ground plane by a distance larger than 1,5 times the distance between air termination on the test specimen and the external electrode.

Conditions a) and b) are typically met by keeping the following dimensions:

1) The external electrode should be at least 2 m from the closest conductive element (inside or outside the test specimen).
2) The external electrode should be at least 1,5 m from the nearest test specimen skin.
3) The smallest dimension of the external electrode should be at least 5 times the minimum gap length between the blade and the ground plane.

Specific dimensions and test specimen orientations should be described in the test plan.

D.2.2.4 Test voltage waveform

The voltage waveform used is a slowly rising voltage waveform reaching flashover to the specimen before the prospective voltage peak. This voltage waveform is selected since it is the most representative of the electric field in the vicinity of a structure during an initial leader attachment.

On rare occasions, the flashover can happen after the peak of the voltage waveform. Such tests are regarded valid and are accounted for in the overall evaluation provided it does not happen in more than 10 % of all flashovers throughout the test sequence. But if a puncture of the blade has occurred, the test shall not be considered successful, and the specific test is disregarded and an additional test may be applied.

Such waveforms might be achieved by using the switching impulse voltage in IEC 60060-1 with time to peak of 250 μs ± 50 μs (i.e. 250 μs ± 20 %) and decay time to half value of 2 500 μs ± 1 500 μs (i.e. 2 500 μs ± 60 %). Since the voltage is applied as a rise to flashover, the decay time of the full waveform is not of particular interest.

A typical test voltage waveform is shown in Figure D.7.

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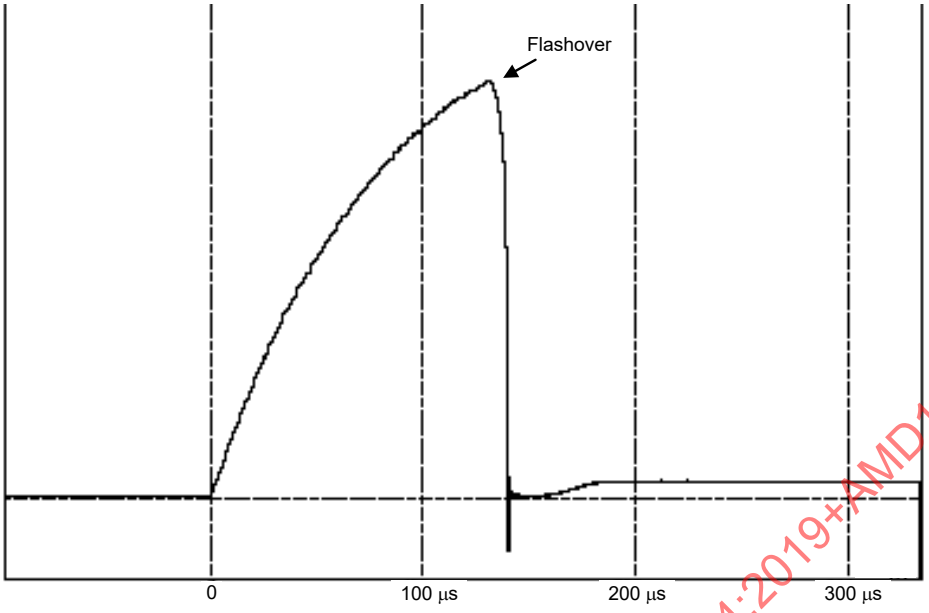

Figure D.7 – Typical switching impulse voltage rise to flashover (100 µs per division)

Three tests of each polarity and each orientation of the test specimen with respect to the opposite electrode are applied, giving an overall number of test discharges of 54.

The HV generator discharge current is typically less than 2 000 A, which encompasses most leader currents. The physical effects of this current will not, therefore, represent those of a much more severe stroke current, or of continuing currents, that may take the same path as the leader. Tests to determine the effects of lightning stroke currents on blade composite structures and lightning conductor designs shall be conducted in accordance with Clause D.3.

D.2.2.5 Measurements and data recording

The following measurements and data recordings should be made.

- Photographs and description of each test setup.
- Waveform plots of the test voltage waveforms.
- Photographic records of all tests to determine strike point and the connection point of the flashover. These should have complete coverage of the tested areas of the specimen. One or two cameras should enable immediate preliminary analysis of the test to be made so that any punctures are identified immediately. An additional camera looking into the interior of a blade specimen might be useful to monitor internal streamer/leader behaviour during tests.
- Photograph of each electrode position.
- Photographs of puncture locations or other significant effects.
- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests and test location.
- Record of any deviations from the test procedure.
- Records of the results of each test showing electrode polarity, voltage amplitude and waveforms (showing front time and duration).

D.2.2.6 Test procedure

This general test procedure is applicable to both test setups (A and B).

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Generator performance verification:

a) Measure laboratory environmental conditions.

b) Review and implement safety procedures.

c) Clean the test specimen with an appropriate technique to remove moisture, dust, debris, and other contaminants that could affect the test results. Carefully inspect the test specimen for any blemishes that might later be confused with effects of the tests, and identify these so that they are not confused with subsequent test results.

d) Wrap the leading and trailing edges of the blade in an aluminium foil and ground these foils to the tip air termination system and to the down conductor where it exits the blade for the generator performance verification tests (the wrapping of the blade is advised but not mandatory).

e) Position the specimen at the minimum angle with respect to the horizontal ground plane in setups A and B, and set the initial test specimen polarity to be positive (+), regardless of whether test setup A or test setup B is used. Experience has shown that this condition results in a lower probability of puncture of non-conducting materials since streamers originating from test specimen LPS progress further into the air gap before being joined by opposing streamers from the negative electrode.

f) Adjust the generator settings to ensure a flashover at the rising front of the waveform for the selected distance between the blade and the external electrode and initiate a test to the blade while measuring the applied voltage.

g) Apply a test to the test specimen, while measuring the applied voltage and taking photographic evidence of the path of the flashover. Ensure that the flashover occurs on the rising wave front before the crest of the voltage waveform.

h) If the waveform is not correct or the flashover did not occur on the rising wave front before the crest of the voltage waveform, adjust the generator parameters or air gap between the specimen and opposite electrode as necessary to obtain the specified waveform and flashover.

i) Once the waveform is within the described tolerances, remove the conductive foil applied in d) and proceed to the actual test sequence.

Test sequence:

1) Apply a test to the test specimen, while measuring the applied voltage and taking photographic evidence of the path of the flashover. Ensure that the flashover occurs on the rising wave front before the crest of the voltage waveform.

2) If the attachment occurred to the blade structure, outside the intended LPS, e.g. if an unexpected puncture of laminate skin has occurred, perform an assessment to determine if the test specimen has failed the test. If it has failed, then the test sequence is terminated. Attachment to insulating surfaces followed by a surface flashover to the intended air termination is not considered to be a failure.

3) Repeat steps 1) and 2) until three tests of positive polarity have been applied under the same conditions.

4) Switch the polarity of the HV generator to ensure the polarity of the test sample being negative relative to the ground plane (test setup A) or external electrode (test setup B).

5) Repeat steps 1) and 2) until three tests of negative polarity have been applied under the same conditions.

6) Reposition the test specimen (test setup A) or the external electrode (test setup B) as required by the test procedure.

7) Repeat steps 1) to 5) until all combinations of blade orientations and polarities have been tested with a total of 54 discharges as required by the test procedure.

NOTE Occasionally, there will be a withstand in which no flashover occurs, particularly having the blade charged at negative polarity. When this happens, an additional test shall be applied to ensure 54 valid discharges documented by pictures of each flashover.

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D.2.2.7 Data interpretation

Test specimens should undergo a thorough post-test evaluation to determine the adequacy of the design with respect to the pass/fail criteria.

D.2.2.8 Pass/fail criteria

To pass the initial leader attachment test, all 54 flashovers shall attach to the intended air termination system designed to intercept the strike (discrete receptors, conductive coating, metal mesh, etc.), documented by pictures of 54 individual flashovers. No punctures through the insulating structures of the blade are allowed, disruptive discharges attaching outside air terminations are regarded to be a failure.

All 54 flashovers shall appear as flashovers in the air or along the exterior blade surface from the intended air terminations on the blade to the remote ground plane (test setup A) or the external electrode (test setup B).

Following the HV initial leader attachment test, the areas subjected to direct attachment shall undergo the subsequent stroke attachment test in accordance with D.2.3 and the high-current verification test in accordance with Clause D.3 determining the design capability of handling the lightning current.

D.2.3 Subsequent stroke attachment test

D.2.3.1 Test purpose

Following the HV initial leader attachment test in accordance with D.2.2, the areas subjected to direct attachment shall undergo the subsequent stroke attachment test according to D.2.3 and the high current verification test according to Clause D.3 determining the design capability of handling the lightning current.

The purpose of this test is described in the following:

1) In both events of a downward initiated strike and an upward initiated strike, where the first interception of the lightning flash has occurred correctly at the intended air termination, the first stroke of a downward flash or initial continuous current (ICC) of an upward flash may be followed by a dark period, and subsequently a re-attachment of the dart leader to the air termination. The intention of the test is to show that the breakdown between the dart leader and the air termination happens as a surface flashover, instead of a puncture of the blade skin.
2) Experience has shown that insufficiently insulated receptor bases or other installations in conjunction with air terminations can lead to punctures and fatal damages in field. This test will investigate the design for such defects, and if the test is passed the likelihood of failures in field is therefore minimised.

In all cases, the test will determine whether the field necessary for discharge formation in proximity of air terminations (side and tip receptors) causes the flashovers to occur on the exterior surface of a blade or punctures the blade and flashes along an interior surface.

This test is applicable to surfaces of a wind turbine blade in proximity of air termination systems.

D.2.3.2 Test specimen

The test specimen should be a section of a full-scale blade, such as a blade tip or other surface that contains a likely point of lightning attachment, a discrete lightning receptor or other protection device.

Typical test specimens would be a blade tip section used also for initial leader attachment tests of D.2.2.3, setups A or B, or another specimen that is representative of a structure local

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to a likely lightning attachment point, air termination or similar. An example might be a blade section 2-m-long cut from a longer blade specimen. Any surface finishes, including surface fillers or paints should be provided to ensure realistic surface flashover characteristics.

D.2.3.3 Test setup

The test setup is as follows.

- An overview of a typical test arrangement showing a cross section view of the test specimen and typical test electrode position is illustrated in Figure D.8. The tests are conducted with one or more electrode positions, representing the possible directions of leader sweep as seen in Figure D.11.
- Support the test specimen above the ground plane at a distance of at least 1,5 times the minimum flashover distance as described in IEC 60060-1:2010, 4.2.
- The receptor(s), lightning down conductors and any other conductive components bonded to the blade LPS as part of the design should be at ground potential.
- Connect the output terminal of the HV generator to the high-voltage electrode. The electrode shall be spherical with a radius of 50 mm ± 5 mm. The surface of the HV electrode shall be placed 50 mm ± 5 mm away from the surface on the test specimen to represent the voltage applied by a lightning channel sweeping over the surface of the test specimen. Alternately, the blade lightning protection system may be connected to the HV generator and the sphere electrode may be grounded.
- Set up equipment to measure and record the applied test voltage.

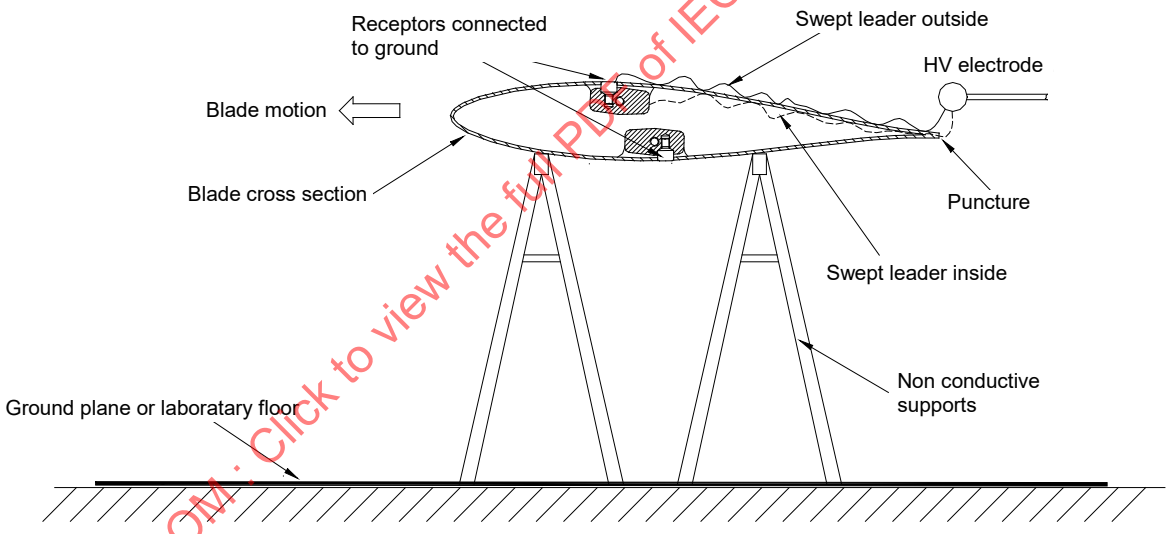

Figure D.8 – Subsequent stroke attachment test arrangement

D.2.3.4 Test voltage waveform

The electric field associated with a swept channel for downward strikes, and reattachment of the dart leader, produce rapidly increasing electric fields that are represented more appropriately by the "lightning impulse" voltage waveform defined in IEC 60060-1. The full lightning impulse voltage waveform has a rise time T_1 of 1,2 μs and a decay time to half value T_2 of 50 μs as defined in IEC 60060-1 and shown in Figure D.9.

This waveform is applied with a virtual peak voltage that is higher than required flashover to the air termination so that flashover occurs on the wave front as shown in Figure D.10.

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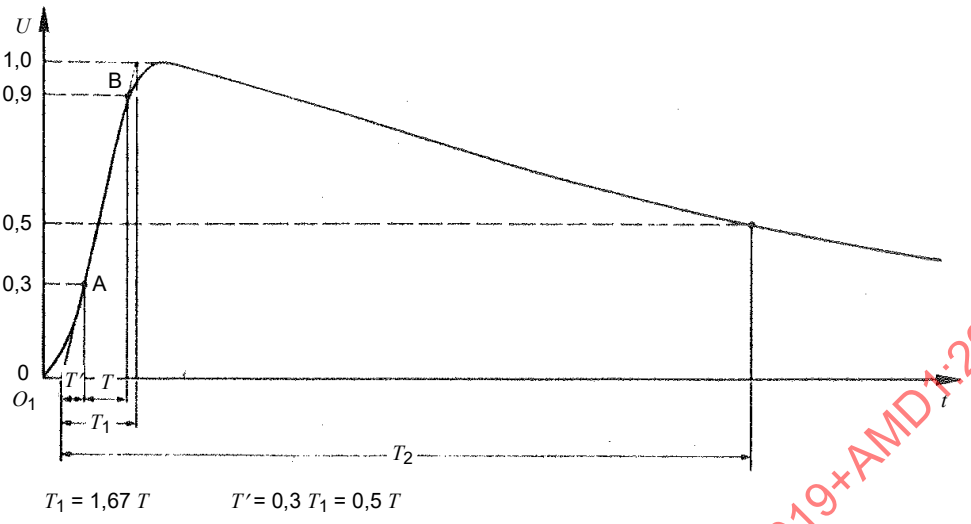
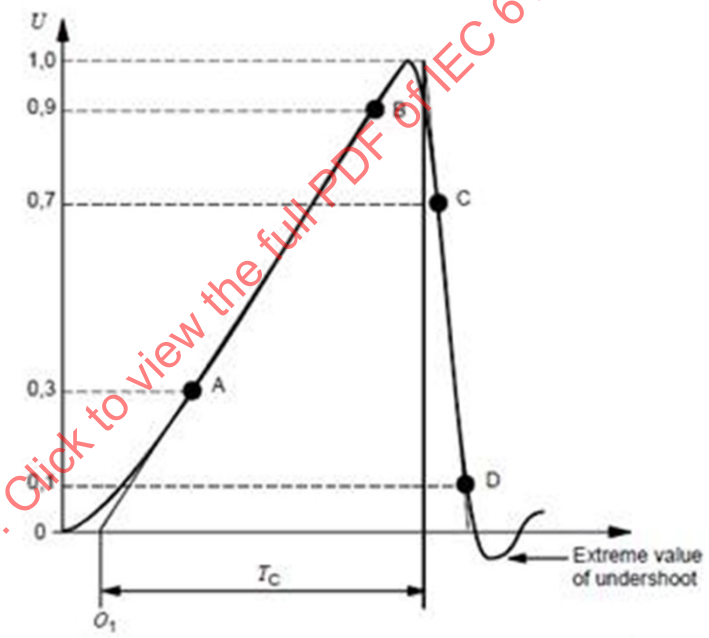


This figure is adapted from IEC 60060-1.

Figure D.9 – Lightning impulse voltage waveform



This figure is adapted from IEC 60060-1.

Figure D.10 – Lightning impulse voltage chopped on the front

The front-of-wave flashover illustrated in Figure D.10 represents the result of the rate of rise of a stroke current (dI/dt) multiplied by the inductance of a lightning leader or channel for a downward flash strike or the field associated with the re-attachment of the dart leader following the first return stroke.

NOTE For long air gaps exceeding 0,5 m, it is accepted that the flashover happens later than the crest of the 1,2/50 µs waveform.

D.2.3.5 Measurements and data recording

The following measurements and data recordings should be made:

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- Photographs and description of each test setup and electrode position.
- Photographic records of all tests. Cameras should provide 360° coverage of the test specimen. One camera should enable immediate preliminary analysis of the test shot to be made so that any punctures are identified immediately. An extra camera looking into the interior of the blade sample might be useful to monitor internal streamer/leader behaviour during tests.
- Photographs of any puncture locations or other significant effects.
- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests and test location.
- Records of any deviations from the test procedure.
- Records of the results of each test showing voltage polarity, amplitude and waveform (showing front time and duration).

D.2.3.6 Test procedure

The test procedure is as follows:

a) Measure laboratory environmental conditions.

b) Review and implement safety procedures.

c) Carefully inspect the test specimen for any blemishes that might later be confused with effects of the tests and identify these so that they are not confused with subsequent test results.

d) Calibrate the generator and instrumentation, to ensure correct waveform and a peak voltage higher than required to flashover between the test electrode and the air termination.

e) Clean test specimen with appropriate technique to remove dust, debris and other contaminants which could affect test results.

f) Apply a discharge to the test specimen while measuring the applied voltage and taking photographs of any flashover that occurs.

g) Inspect the test specimen and document the results. Mark and photograph any punctures or other effects on the test specimen.

h) If puncture has occurred, perform an assessment to determine if the test specimen has failed. If it is deemed to have failed, then the test sequence may need to be terminated.

i) Repeat steps f) to h) to accomplish three discharges at each polarity, and for the electrode positions shown in Figure D.11. The electrode positions are located at the trailing edge 50 mm above the blade skin at the same radius as the side receptor.

j) In the case of other air termination designs, including "electrically conductive elements" such as metal mesh, carbon fibre composite structure, or other electrically conductive parts of the blade design that may serve as a designated air termination, these have to be tested as shown in Figure D.11, then three discharges at each polarity shall be performed at the worst case electrode positions (identified by the manufacturer) at the trailing edge 50 mm above the blade skin.

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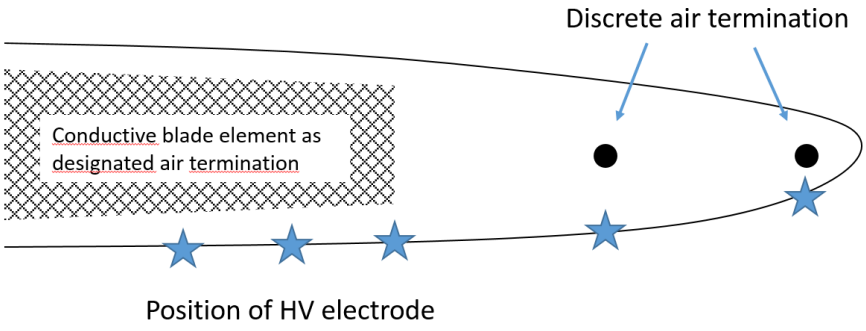

Figure D.11 – HV electrode positions for the subsequent stroke attachment test

D.2.3.7 Data interpretation

Test specimens should undergo a thorough post-test evaluation to determine the adequacy of the design against the pass/fail criteria.

D.2.3.8 Pass/fail criteria

To pass the subsequent stroke attachment test, no punctures through the insulating structures of the blade are allowed. All flashovers shall either appear as surface flashovers or in the air above the surface from the test electrode to the intended air terminations on the blade.

D.3 High-current physical damage tests

D.3.1 General

These tests are used to determine the effects of a lightning attachment to a blade or nacelle surface and the current flow away from such an attachment. These effects can be evaluated at the points of attachment and along the path(s) taken by the lightning current.

D.3.2 Arc entry test

D.3.2.1 Test purpose

Following the HV initial leader attachment test in accordance with D.2.2, the areas subjected to direct attachment shall undergo the subsequent stroke attachment test in accordance with D.2.3 and the high-current verification test in accordance with Clause D.3 determining the design capability of handling the lightning current.

This test is applicable to structures such as wind turbine blades and nacelles that are exposed to direct lightning attachment.

The test is used to determine the direct (physical damage) effects that may result at the locations of possible lightning channel attachment to a blade or where high current and energy densities may flow away from a point of entry during a lightning attachment. Examples are blade air termination systems and associated electrical conductors, metal foils, diverter strips and fittings and connectors in the lightning current path in proximity to the attachment point.

The test can be used to assess:

- arc attachment damage;
- hot spot formation;

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- metal erosion at air termination systems;
- performance of segmented and solid diverter strips;
- adequacy of protection materials and devices;
- magnetic force effects;
- blast and shock wave effects;
- behaviour of joints and hardware assemblies.

D.3.2.2 Test specimens

These tests may be performed on full-scale production items or representative prototypes. These tests may also be performed on panels, coupons or sub-sections of the blade or other wind turbine assembly. The panels, coupons or sub-sections should be fabricated with the appropriate manufacturing processes, paints and other finishes, joints and materials representing the series production. For protection devices that require a specific voltage to ionise, such as segmented diverter strips, the length of the ionisable test specimen should be short enough to ionise during the high-current test, since high-current generators usually do not apply more than 100 kV.

D.3.2.3 Test setup

The test setup is as follows.

- Mount the test specimen in a fixture that can support the specimen securely, and ensure a distance to other conductive surfaces of at least 1,5 times the minimum flashover distance as described in IEC 60060-1:2010, 4.2 (it may be relevant to place the test specimen vertically rather than horizontally e.g. in case molten metal is deposited on the blade causing risk of fire).
- Connect the generator return to the assembly so the lightning currents are conducted away from the test specimen in a manner representative of when the blade or nacelle is struck by lightning. Ensure that magnetic forces and other interactions associated with current flow within the setup are controlled so they represent the natural situation and do not unduly influence the test results.
- Orient a test electrode 50 mm above the area of the test specimen that is to be evaluated. For most arc entry tests, the electrode should be the "jet diverting" type, as shown in Figure D.12, a tungsten electrode, or another electrode configuration which minimises the amount of electrode material deposited upon the test specimen surface. This type of electrode has been shown to best represent the shockwave effects of natural lightning attachments without affecting the surface of the test sample unrealistically. The electrode position should be a minimum 50 mm chord-wise displaced from the edge of the air termination towards the trailing edge. The injection point shall represent the most likely wear points. The injection point in the test shall be defined by the position of the ignition wire as indicated in Figure D.12.
- Where the specimen is sensitive to polarity, the test electrode polarity in the long stroke current test shall be negative (i.e. specimen polarity positive) in order to produce maximum damage since arc roots are more concentrated at the anode.

  NOTE Experience has shown that physical effects of lightning attachment on air termination devices on blades are not sensitive to current polarity.
- A fine metallic wire, not exceeding 0,5 mm in diameter, may be used, if desired, to direct the arc to a specific point of interest on the test specimen. Especially if the conductive part is kept below an insulating barrier (e.g. thin layer of fibre glass above a CFRP structure), a small hole not exceeding Ø 2 mm can be drilled through the insulating layer. This approach is helpful for generators that use low voltages. Test results will not be adversely affected by the wire, which vaporizes as soon as current begins to flow.
- The arc entry testing is conducted on the trailing edge side of the air termination system (the hang-on zone).
- Set up sensing and recording equipment.

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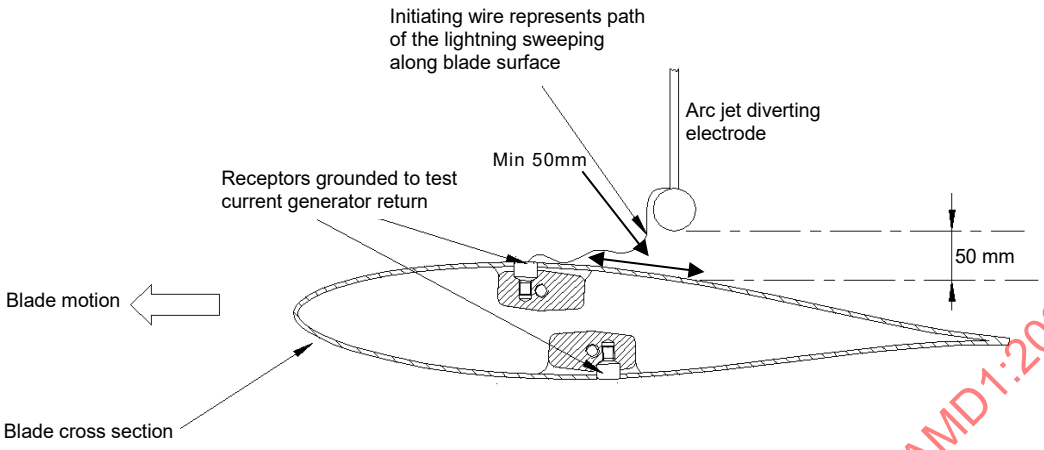

A lateral displacement of the electrode relative to the air termination enables a verification of the shockwave effect from the lightning channel.

Figure D.12 – High-current test arrangement for the arc entry test

D.3.2.4 Test current waveforms

The test currents to be applied include the first short stroke and the long stroke, with amplitudes, charge levels and specific energies as defined in Table A.1 for LPL I Zone OA1. As specified in the lightning environment defined for the actual structure (blade part) concerned, these test levels are scaled according to the actual exposure where the attachment point is placed. The two current components may be applied in one discharge if possible, or applied in individual discharges as suggested in Table A.3. The parameters of these test currents are shown in Table D.1 and Table D.2.

Supplying the current parameters within their tolerances *I* (−10 % / +10 %), *W/R* (−10 % / +45 %) and Q_{flash} (−20 % / +20 %) in the same impulse, can be achieved by an approximately exponentially decaying current with T_2 in the range of 350 μs, or an oscillating current pulse with similar specific energy accompanied by a continuous current supplying the remaining charge. The DC component supplying the remaining part of the charge exhibits a peak current in the range of 200 A to 1 200 A (−10 % / +10 %), and a discharge time of current flow = 0,5 s with a tolerance of −10 % / +10 % regulated to inject the necessary amount of charge with the tolerances in accordance with IEC 62305-1.

D.3.2.5 Measurement and data recording

The following measurements and data recordings should be made.

- Photographs and description of the test setup.
- Photographs of the test specimen before, during and after each test. Infrared video cameras to determine local hot spot areas during tests might be beneficial.
- Photographs and description of damage to the test specimen.
- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests, and test location.
- Record of any deviations from the test procedure.
- Records of the results of each test showing polarity, current amplitudes, waveforms (showing front time and duration), specific energies and charge transfers at applicable test points.

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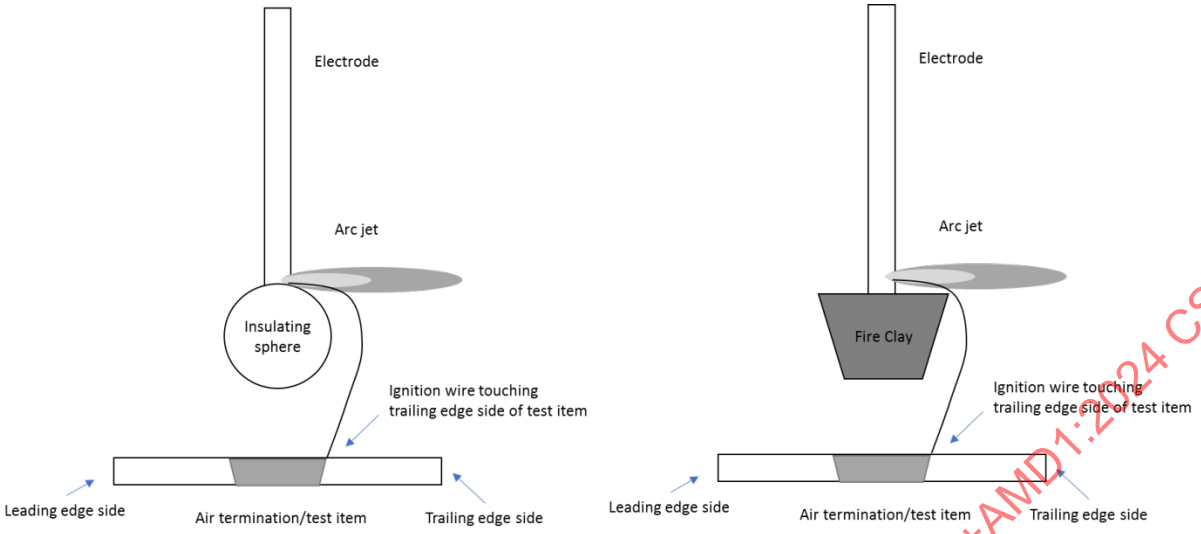

Figure D.13 – Typical jet diverting test electrodes

D.3.2.6 Test procedure

The test procedure is as follows:

a) Measure laboratory environmental conditions.

b) Review and implement safety procedures.

c) Calibrate the generator and instrumentation as follows.

   1) Insert a conductive bar or panel in place of the test specimen with material properties similar to the test specimen.

   2) Connect the bar or panel to the generator test current return.

   3) Initiate a test to the bar while measuring the applied current waveform(s).

   4) If the current level or waveform(s) are not within the tolerances (I (−10 % / +10 %), W/R (−10 % / +45 %) and Q_{flash} (−20 % / +20 %)), adjust the generator parameters.

   5) Repeat steps 3) and 4) as necessary to obtain the required waveform(s).

   6) Remove the bar or panel and install the test specimen.

d) Apply a test to the test specimen.

e) Inspect the test specimen and document the results.

f) If required, place the electrode at a new position on the test specimen and repeat steps d) to e).

In order to demonstrate compliance with LPL I, the following current pulses shall be applied to the system in step d) above. Subject to a specific lightning exposure assessment, the first return stroke pulse (test 1-3) is scaled in amplitude.

The verification plan shall include rationale for the scaling of the first return stroke pulses used in terms of the peak current, specific energy and charge levels. The charge content in the long stroke current pulse is constant throughout the blade length, and the manufacturer shall outline the pass/fail criteria in relation to the expected lifetime and maintenance intervals of the component in question.

The first three pulses (test 1-3 in Table D.1) shall be used to determine the design adequacy in relation to the selected LPL (pass/fail criteria), whereas the following pulses (test 4-6 in Table D.1) characterise the wear due to the charge content of the long stroke.

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A suitable current pulse of sufficient magnitude to trigger the arc column shall be used to establish the necessary arcing of the test gap preceding the long stroke current in test 4-6.

Table D.1 – Test current parameters corresponding to LPL I

Test Id.	Peak current [kA]	Specific energy [MJ/Ω]	Charge per test [C]
1-3 (3 tests)	200	10	100
4-6 (3 tests)		-	200
Accumulated charge content			900
NOTE Test parameters are applied with tolerances defined in IEC 62305-1, I (−10 % / +10 %), W/R (−10 % / +45 %) and Q_{flash} (−20 % / +20 %).			

Considering the surface erosion of air-termination systems due to the conducted charge, the damage is cumulative. This means that the accumulated charge conducted during testing will help determine the inspection interval/frequency of replacement, as long as a realistic total amount of charge is applied.

For inboard air terminations on blades, the peak current and hence the specific energy should be scaled in accordance with the lightning exposure as defined in 8.2.2. The charge levels are however maintained, such that even side receptors inboard the blade tip section shall be tested with the charge levels as specified in Table D.1.

For designs that make use of several air terminations, all air terminations shall be exposed to the full test programme. If a blade design consists of many air terminations manufactured similarly, only one item of each type needs to be tested as part of this type testing.

In addition, for sites with winter lightning exposure, the following pulses (test 7-X in Table D.2, X being minimum 9 [3 additional tests] for one individual protection component) shall be used to characterise the wear of the air-termination points closest to the blade tip due to the charge content of the long stroke in winter lightning. The component may need replacement after a subset of the tests in Table D.2 (that means it is allowed to interrupt the test after the minimum 9 and replace worn out components after any of the tests 10-X as long as it is duly documented in the test report), and the manufacturer shall then align the wear of the LPS found during testing and the expected exposure at the particular site, and use the information to tailor the maintenance cycles for the particular site.

A suitable current pulse of sufficient magnitude to trigger the arc column shall be used to establish the necessary arcing of the test gap preceding the long stroke current.

Table D.2 – Test current parameters for winter lightning exposure testing (duration maximum 1 s)

Test Id.	Peak current [kA]	Specific energy [MJ/Ω]	Charge per test [C]
7-X (X ≥ 9)	-	-	600
Accumulated charge content (winter lightning)			3 (minimum) times 600
NOTE Test parameters are applied with tolerances defined in IEC 62305-1, I (−10 % / +10 %), W/R (−10 % / +45 %) and Q_{flash} (−20 % / +20 %).			

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D.3.2.7 Data interpretation

Test specimens should undergo a thorough post-test evaluation to determine the adequacy of the design with respect to pass/fail criteria. In connection with air-termination systems, such criteria should encompass noise as a consequence of surface erosion, ease of replacement, etc.

D.3.2.8 Pass/fail criteria

To pass the arc entry test, the manufacturer should define the expected exposure of the turbine parts in question, align the expected service intervals with the test results, and verify that the wear parts of the structures can be replaced safely and as planned at the end of lifetime.

D.3.3 Conducted current test

D.3.3.1 Test purpose

This test is applicable to lightning down conductors, connection components and other mechanical fixed or flexible components that are in the current path(s) between the air termination system and the wind turbine earthing system.

This test can be used to assess:

- lightning current conducting abilities;
- temperature rises in conductors, conductor insulation, connection components and remaining parts of the structure;
- arcing and sparking in equipotential bondings, bearings, sliding contacts, spark gaps, brushes and general connection components;
- magnetic force effects;
- current carrying capability of carbon fibre composite materials and interfaces.

D.3.3.2 Test specimen

The test specimen should be a full-scale production item such as sections or sub-sections of lightning conductors or conducting structures installed in a representative manner that may include interfaces between structural parts (CFRP structures), adhesive bonded joints, fastened joints, bearings or brushes. The structure specimens should be large enough to allow a representative lightning current distribution to be achieved.

Connection components inside blades can be tested without being fully implemented into the blade shells. This enables a thorough evaluation of the performance during and after the test.

D.3.3.3 Test setup

The test setup is as follows.

- Mount the test specimen in a fixture that elevates the specimen to a distance from other conductive surfaces of at least 1,5 times the minimum flashover distance as described in IEC 60060-1:2010, 4.2 so that these do not influence the test results.
- Connect the generator output and return terminals to the specimen so the test currents are conducted through the specimen in a manner representative of when the blade or other structure is struck by lightning. The polarity of the generator is usually not relevant. Ensure that magnetic forces and other interactions associated with current flow within the specimen are controlled to ensure that they represent the natural situation. Figure D.14 shows a typical arrangement.
- Set up sensing and recording equipment.

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NOTE A semi-coaxial arrangement of the conductors and the test specimen can be used to minimise magnetic forces due to currents in the conductors that bring test current to and from the specimen and to achieve a realistic distribution of current through the specimen. Figure D.14 shows a typical arrangement for testing a section of a wind turbine blade. Measurements of induced voltages into electrical wiring that may be installed within a blade can also be made during the conducted current test, as described in Clause 8.

D.3.3.4 Test current waveforms

The test currents to be applied include the first short stroke, with amplitudes, charge levels and specific energies as expected for the lightning environment as defined by the manufacturer for the particular structure. The important parameters of these test currents are shown in Table D.3 and Table D.4.

The specific test currents to be applied are determined by the protection level that has been assigned to the part of the wind turbine structure that is being tested. The test current amplitudes to be applied to specimens that represent only a portion of the conductive path through the structure (e.g. two parallel down conductors within a blade, CFRP structural components in parallel with the down conductor, etc.) should be scaled in accordance with the lightning exposure as defined in 8.2.2 for blades. The manufacturer shall define the parameters of the test current affecting each current path and each interface of the structure. Often this current magnitude is increased by up to 50 % to account for possible imbalances in current distribution throughout a structure cross-section.

A detailed analysis of the current distribution and the associated current components in the different paths of the structure may reveal that waveform parameters do not scale linear with the peak magnitude of the current. In the test specification, the arguments for the scaled current parameters shall be defined.

D.3.3.5 Measurement and data recording

The following measurements and data recordings should be made.

- Photographs and description of the test setup.
- Photographs of injection points.
- Photographs of the test specimen before, during and after each test. Infrared video cameras to determine local hot spot areas during tests might be beneficial.
- Photographs and description of damage to the test specimen.
- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests and test location.
- Record of any deviations from the test procedure.
- Records of the results of each test showing polarity, current amplitudes, waveforms (showing front time and duration), specific energies and charge transfers at applicable test locations.

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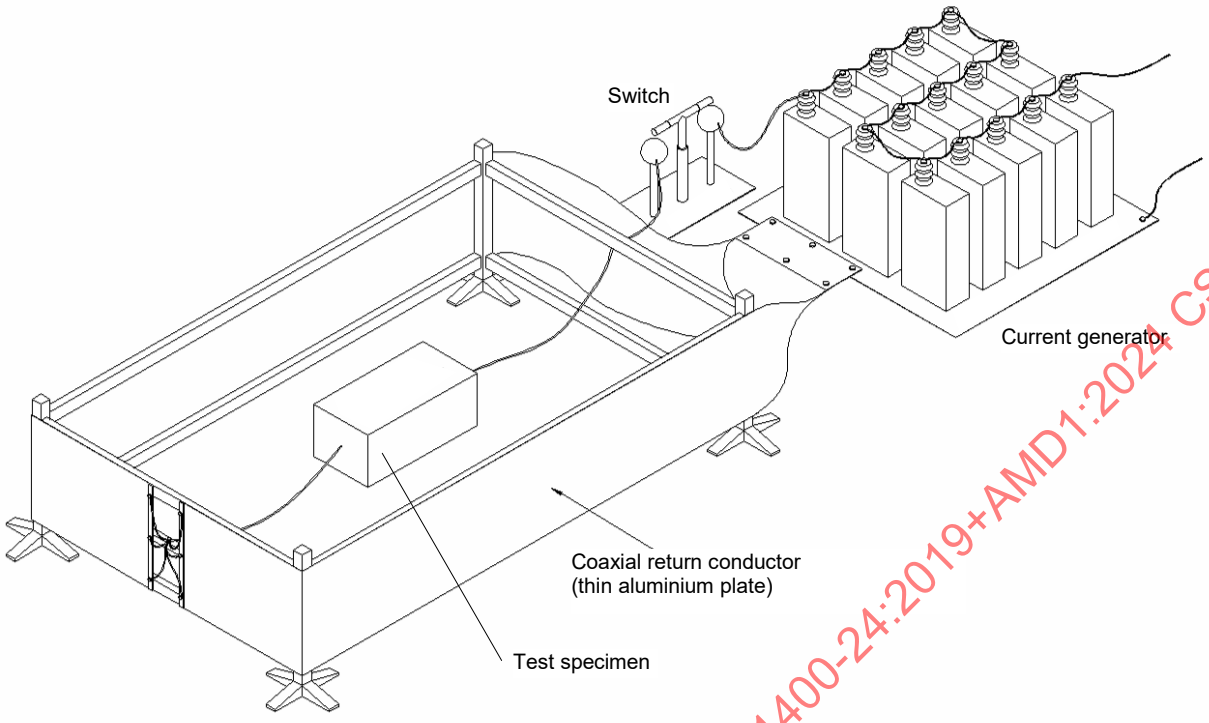

Figure D.14 – Example of an arrangement for conducted current tests

D.3.3.6 Test procedure

The test procedure is as follows.

a) Measure laboratory environmental conditions.

b) Review and implement safety procedures.

c) Calibrate the generator and instrumentation as follows.

   1) Detach the generator high and return current from the test specimen and connect them to a conductive bar near or in place of the test specimen. The bar should have material properties that are similar to the test specimen.

   2) Apply a test to the bar while measuring the applied current waveform(s).

   3) If the current level or waveform(s) are not within the tolerances (I (−10 %/+10 %), W/R (−10 %/+45 %) and Q_{flash} (−20 %/+20 %)), adjust the generator parameters.

   4) Repeat steps 2) and 3) as necessary to obtain the required waveform(s).

   5) Remove the bar and reattach the generator to the test specimen.

d) Clean test specimen using the appropriate technique to remove dust, debris and other contaminants that could affect test results.

e) Measure the series resistance of the test sample, with respect to the pass/fail criteria.

f) Apply a test to the specimen.

g) Inspect the test specimen and document the results.

h) Repeat steps f) and g) to apply additional tests as called for in the test plan.

In order to demonstrate compliance with LPL I, the following current pulses shall be applied to the system in step f) above. Subject to a specific lightning exposure assessment, the first return stroke pulse (test 1-3) is scaled in amplitude.

The verification plan shall include argumentation for the scaling of the first return stroke pulses used in terms of the peak current, specific energy and charge levels. The charge content in the long stroke current pulse is constant throughout the blade length, and the

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manufacturer shall outline the pass/fail criteria in relation to the expected lifetime and maintenance intervals of the component in question.

For fixed connection components (cable lugs, bolted connections, and other non-moving parts), the test sequence in Table D.3 shall be used. The three pulses (test 1-3 in Table D.3) shall be used determine the design adequacy in relation to the selected LPL (pass/fail criteria).

Table D.3 – Test current parameters corresponding to LPL I

Test Id.	Peak current [kA]	Specific energy [MJ/Ω]	Charge per test [C]
1-3 (3 tests)	200	10	100
NOTE Test parameters are applied with tolerances defined in IEC 62305-1, I (−10 % / +10 %), W/R (−10 % / +45 %) and Q_{flash} (−20 % / +20 %).			

For flexible paths (spark gaps, sliding contacts, brushes, bearings, etc.), the arc root erosion due to the charge impact in the long duration stroke shall be included as well, and the test sequence in Table D.4 shall be used. The charge content in the long stroke current pulse is constant throughout the blade length, and the manufacturer shall outline the pass/fail criteria in relation to the expected lifetime and maintenance intervals of the component in question.

Table D.4 – Test current parameters corresponding to LPL I (for flexible paths)

Test Id.	Peak current [kA]	Specific energy [MJ/Ω]	Charge per test [C]
1-3 (3 tests)	200	10	100
4-6 (3 tests)	-	-	200
Accumulated charge content			900
NOTE Test parameters are applied with tolerances defined in IEC 62305-1, I (−10 % / +10 %), W/R (−10 % / +45 %) and Q_{flash} (−20 % / +20 %).			

Considering the erosion of spark gaps, sliding contacts, brushes, bearings, etc. due to the conducted charge, the damage is cumulative. This means that the accumulated charge conducted during testing will help determine the inspection interval/frequency of replacement, as long as a realistic total amount of charge is applied.

In addition, for sites with winter lightning exposure, the following pulses (test 7-X in Table D.5, X being minimum 9 [3 additional tests] for one individual protection component) shall be used to characterise the wear of spark gaps, sliding contacts, brushes, bearings, etc. The component may need replacement after a subset of the tests in Table D.5 (i.e. it is allowed to interrupt the test and replace worn out components after any of the tests 7-X as long as it is duly documented in the test report), and the manufacturer shall then align the wear of the LPS found during testing and the expected exposure at the particular site, and use the information to tailor the maintenance cycles for the particular site.

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Table D.5 – Test current parameters for winter lightning exposure testing (duration maximum 1 s)

Test Id.	Peak current [kA]	Specific energy [MJ/Ω]	Charge per test [C]
7-*X* (*X*≥9)	-	-	600
Accumulated charge content (winter lightning)			3 (minimum) times 600
NOTE Test parameters are applied with tolerances defined in IEC 62305-1, *I* (−10 % / +10 %), *W/R* (−10 % / +45 %) and Q_{flash} (−20 % / +20 %).			

D.3.3.7 Data interpretation

Test specimens should undergo a thorough post-test evaluation to determine the adequacy of the design with respect to pass/fail criteria.

D.3.3.8 Pass/fail criteria

The connection component or electrical interfaces is deemed to have passed the test if the intended electro-mechanical functionality of the component is intact, including the following:

a) No arcing detrimental to the functionality occurs during the test sequence, besides the natural arcing in connection with moving parts involving open arcs as part of the design (spark gaps, brushes, sliding contacts, etc.).

b) The contact resistance for fixed metal to metal connections, measured with a laboratory grade micro ohm meter delivering 10 A on small samples and measuring using four terminal resistance measurement as close as possible to the connection component is less than 1 mΩ. In the case where the connection component or the conductor(s) are of stainless steel, a value of 2,5 mΩ is allowed.

c) No detrimental change of functionality of connections involving CFRP demonstrated by inspection, measurement, and/or testing.

d) Fixed connection does not exhibit any crack to normal or corrected vision without magnification nor does it have any loose parts or deformation impairing its normal use.

e) For bolted clamping connections the loosening torque is greater than 0,25 and less than 1,5 times the tightening torque. In the case of connectors with more than one screw, only the loosening torque of the first screw is relevant to this test.

f) For screw-less components, such as compressed connection components, each conductor of the specimen shall be subjected independently to a mechanical tensile force of 900 N ± 20 N for 1 min. Each conductor shall be tested independently for multiple conductor connectors. The connection component is deemed to have passed the test if there is less than a 1-mm movement of the conductor during the test and no damage on the connector or conductor.

g) The structural integrity of the blade or blade section is not compromised by the current injection. It is the responsibility of the manufacturer of the specific component or system to evaluate whether the damages are acceptable, and to document that the turbine can remain in operation until the next scheduled inspection.

For structures or components which are intended to be replaced during normal services, the manufacturer shall align the expected service intervals with the test results, and verify that the wear parts of the structures can be replaced safely and as planned before the end of their lifetimes.

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Annex E
(informative)

Application of lightning environment and lightning protection zones (LPZ)

E.1 Lightning environment for blades

E.1.1 Application

The objective of the blade lightning environment concept is to document how the lightning exposure can be distributed along the blade length. It does not consider a method to decide where to place air termination or to ensure lightning protection coordination. The blade lightning environment concept chosen should be based on industry experience (internal or public as presented in Clause C.8), and the blade attachment probability at different span-wise locations, resulting in a higher strike probability towards the tip region of the blade.

The specific threat requirements of peak current, specific energy and total charge (for the LPL chosen, the charge remains the same for all areas of the blade) are defined for each area of the blade surface. These threat requirements are then used to define the design and test levels for the LPS components installed in a given part of the blade. In the definition of the requirements for the different areas, consider that current from higher areas (area 1) will be conducted through lower areas, hence design requirements for the conducted current tests for lower areas are adopted from the higher areas.

The manufacturer is free to define a specific lightning exposure for a particular blade in question, provided that the exposure is documented by analysis or field data. Alternatively, the lightning environment concept presented in this annex may be adopted.

E.1.2 Examples of simplified lightning environment areas

In this subclause, two approaches of simplified lightning environment concepts are provided for guidance, although special blade features or environmental conditions may suggest different divisions of the blade surface. It is the final responsibility of the manufacturer to demonstrate the compliance of the chosen lightning environment with the LPL for the wind turbine blade. The lightning environment is achieved by splitting the blade in different areas defining the specific lightning environment for each area.

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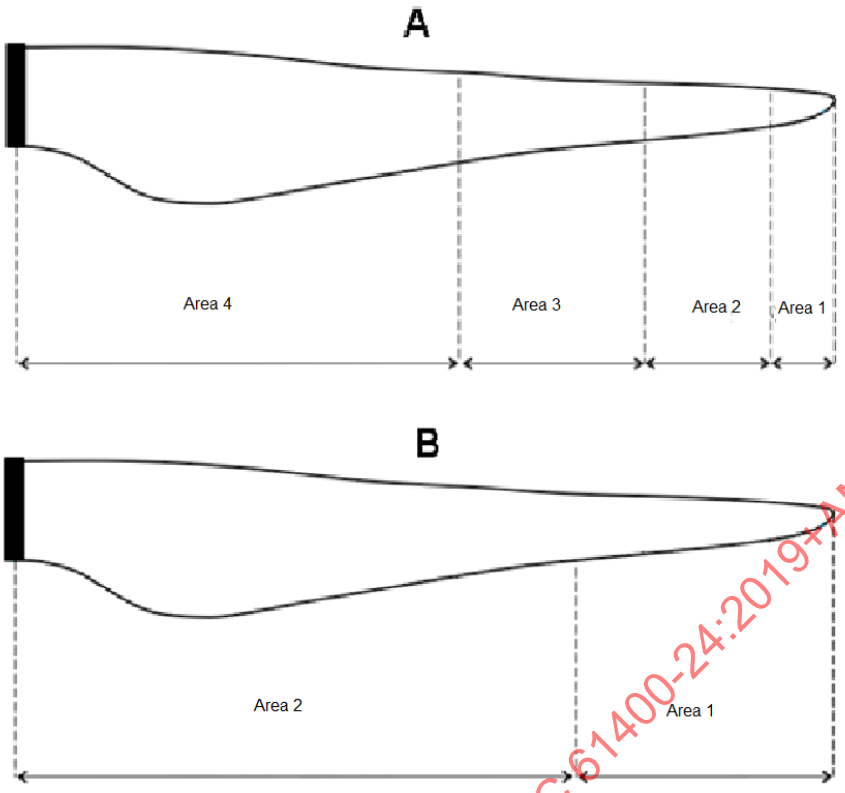

Figure E.1 – Examples of generic blade lightning environment definition

Figure E.1 shows two possible blade lightning environment definitions, type A dividing the blade into four areas with different exposure to direct strikes, type B dividing it into two areas. Based on the analysis supporting the chosen concept, and documented by the manufacturer, the areas can be defined by different LPLs. For example, in the type A concept, blade area 1 could be protected to cover LPL I lightning currents for direct strikes and the rest of the areas 2, 3 and 4 with LPL II, III and IV respectively. In a second type B, LPL I and lower could be chosen for areas 1 and 2. For any approach, it is a requirement that area 1 comprising blade tip should comply with LPL I, alternatively the overall risk assessment should show that LPL II or less is applicable for the most severe part of the blade. Disregarding the exposure chosen for each area, the manufacturer should ensure that the direct strikes intercepting area 1 can be safely conducted through the blade and the remaining areas, even if the exposure to direct strikes is less in the inboard areas.

In any case, the manufacturer should assure that as a whole component, the blade complies with the required LPL by means of combination of attachment probability of the lightning strikes attachment and severity of the lightning currents.

The lightning environment is defined for each area, examples for concept A and B in Figure E.1 are shown in Table E.1 for concept A, and Table E.2 for concept B.

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Table E.1 – Blade area definition for the example in concept A

Blade area		Typical area dimensions [m]			Current level
Area	**Length (m) or % blade length**	40 m blade	60 m blade	80 m blade	*I* [kA]
1	5 %	2	3	4	200
2	10 %	4	6	8	150
3	15 %	6	9	12	100
4	Remainder of blade	28	42	56	10

Table E.2 – Blade area definition for the example in concept B

Blade area		Typical area dimensions [m]			**Current level** (10/350 us current component)
Area	**Length (m) or % blade length**	40 m blade	60 m blade	80 m blade	*I* [kA]
1	40 %	16	24	32	200
2	60 %	24	36	48	150, 100, 50, 10, as defined for the specific blade.

The magnitude of the subsequent short stroke being intercepted by the different areas scale linearly with the scaling of the first short stroke, whereas the charge associated with the long stroke is kept constant throughout the areas.

The performance of any part of the blade LPS or conductive components partaking in the lightning protection coordination should be verified as described in 8.2.2 – with the specific exposure as defined for the lightning environment.

E.1.3 Area transitions

The lightning environment process is an example of how the lightning exposure can be described for a particular blade and site. In defining the lightning exposure of a special blade, specific attention should be applied to conductive structural elements and/or internal electrical systems if transitioning between areas in the tip region. At transitions between areas, installed sub-components should be designed to withstand the parameters of the higher-level area for a distance of 1 m from the area transition.

E.2 Definition of lightning protection zones for turbines (not blades)

E.2.1 General

In order to design a lightning protection system for a structure, it is convenient to divide it into lightning protection zones (LPZ) where the lightning electromagnetic environment is defined. Table E.3 lists the definitions of lightning protection zones according to IEC 62305-1.

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Table E.3 – Definition of lightning protection zones according to IEC 62305-1

Outer zones	
LPZ 0	Zone where the threat is due to the un-attenuated lightning electromagnetic field and where the internal systems may be subjected to full or partial lightning surge current. LPZ 0 is subdivided into:
LPZ 0_A	Zone where the threat is due to the direct lightning flash and the full lightning electromagnetic field. The internal systems may be subjected to full or partial lightning surge current.
LPZ 0_B	Zone protected against direct lightning flashes but where the threat is the full lightning electromagnetic field. The internal systems may be subjected to partial lightning surge currents.
Inner zones	
LPZ 1	Zone where the surge current is limited by current sharing and by SPDs at the boundary. Spatial shielding may attenuate the lightning electromagnetic field.
LPZ 2,…n	Zone where the surge current may be further limited by current sharing and by additional SPDs at the boundary. Additional spatial shielding may be used to further attenuate the lightning electromagnetic field.
NOTE 1 In general, the higher the number of an individual zone, the lower the electromagnetic environment parameters. NOTE 2 Current limiting by current sharing refers to reduction of the current loading of individual conductors of a lightning protection system due to distribution of the original lightning current between several conductors.	

E.2.2 LPZ 0

The boundary between LPZ 0_A and LPZ 0_B for the nacelle, hub and tower above 80 % of the hub height, as shown in Figure E.2, protection against direct lightning attachment shall be provided as needed, which can be determined by means of the rolling sphere model as shown in Figure E.2 (see also IEC 62305-1 and IEC 62305-3). Electronic equipment on the outside may require protection even below 80 % of the hub height (see IEC 60305-3 for further information). The surfaces of the wind turbine below 80 % of the hub height are LPZ 0_B. Computer models can also be used to quantify the expected magnitude of strikes to the different parts of the turbine. The internal systems of LPZ 0_B may be subjected to partial lightning surge currents.

By means of air terminations (for example lightning rods) placed at the rear edge of the nacelle cover, an LPZ 0_B may be created at the top of the nacelle, whereby meteorological instruments can be protected against direct lightning attachment.

The air-termination system positioning tools (rolling sphere, protective angle, etc.) in IEC 62305-3 do not apply to wind turbine blades. Therefore, the air-termination system design should be verified in accordance with 8.2.3.

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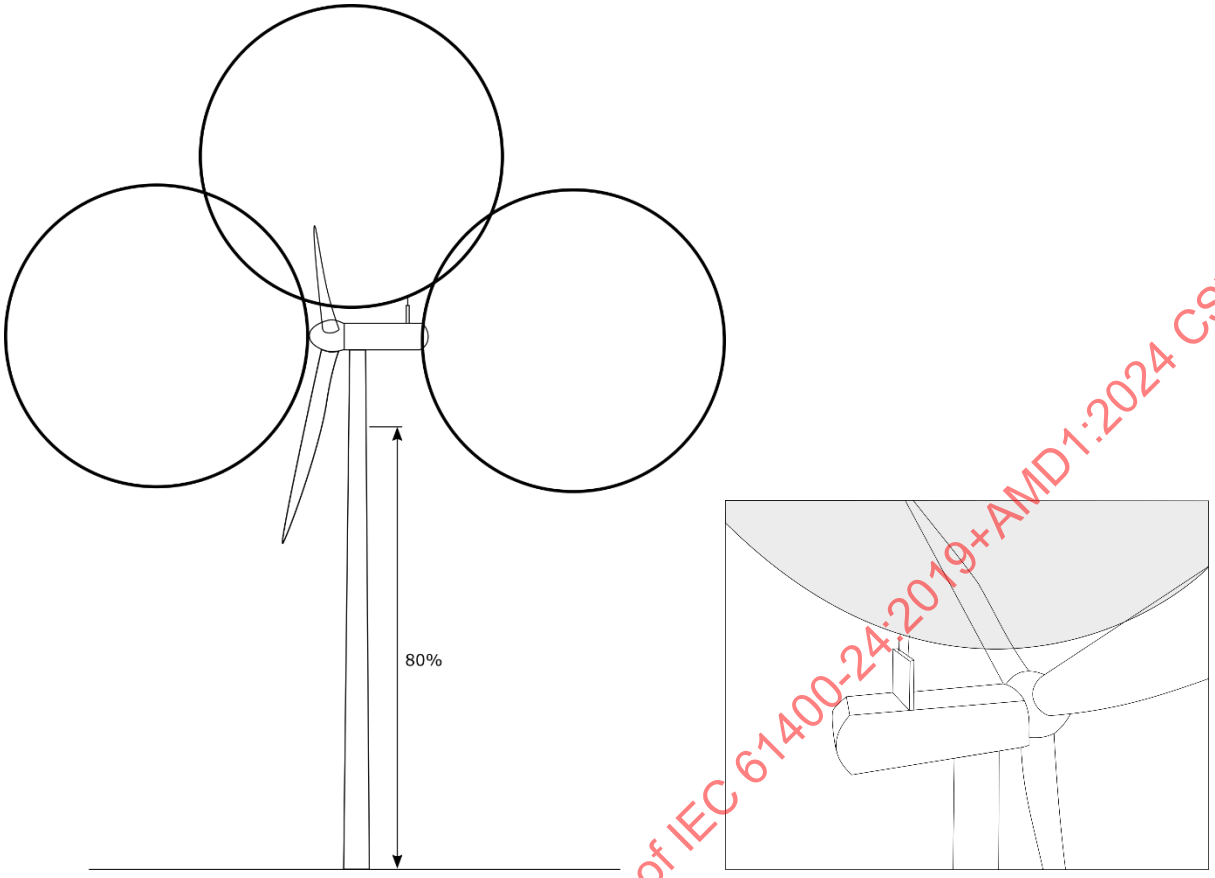

Figure E.2 – Rolling sphere method applied on wind turbine

E.2.3 Other zones

The boundary between LPZ 0_A or LPZ 0_B and LPZ 1 can be made at the tower or at the top cover of the nacelle if there is a metal cover or sufficient metal shielding mesh to protect components inside (a Faraday cage around the nacelle interior is optimum). In the case of GFRP nacelle covers, it is recommended that a metal frame or strapping be integrated into the nacelle cover to define, as a minimum, the area within as zone 0_B to protect nacelle components from direct lightning attachment or leader current without return stroke (see Figure E.3 and Figure E.4). This should be bonded thoroughly to the mechanical drive train bedplate of the nacelle. Ideally, a mesh of metal in a GFRP cover should be integrated into this frame to define the nacelle as LPZ 1. A mesh with large mesh dimension, up to a few metres in mesh size, will protect the nacelle against direct lightning attachment and leader current without return stroke. It will only have small attenuation against magnetic and electrical fields.

A mesh with small mesh size will also protect against direct lightning attachment and leader current without return stroke. Depending on the mesh size and the thickness of the mesh, the mesh can have high attenuation against magnetic and electrical fields. As a rule of thumb, attenuation will be effective at a distance from the mesh equal to the mesh size.

Figures E.6 and E.7 show how the interior of the wind turbine may be divided into protection zones LPZ 1 and LPZ 2. The nacelle (with some mesh in the cover), the tower and the trans-former kiosk are protection zone LPZ 1. The devices inside metal cabinets in LPZ 1 areas are in protection zone LPZ 2 (see Note). For instance, controls inside a cabinet inside a metal tower are in LPZ 2, but in a metal cabinet outside the tower it is LPZ 1 or LPZ 2 (see Note).

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If the tower is made of a metal tube and there is good electrical connection between the parts of the tower, the LPZ inside the tower can be defined as LPZ 2. A steel tubular tower is a very effective Faraday cage, provided it is electromagnetically closed at top and bottom.

Very sensitive equipment may be placed within a still more protected zone, LPZ 3, in another level of metal cabinets (see Note). It is the sensitivity of the components in a given zone (i.e. withstand limits) that defines the level to which the lightning influences (such as current, voltage magnetic and electrical field) should be reduced to in that zone. Therefore, no specific values of current, voltage and electromagnetic field in each zone are recommended in the IEC 62305 series.

NOTE For a metal cabinet, the attenuation against magnetic and electrical fields is dependent on the way the metal cabinet is designed. For EMC cabinets, the manufacturer can provide measurements of the attenuation of magnetic and electrical fields.

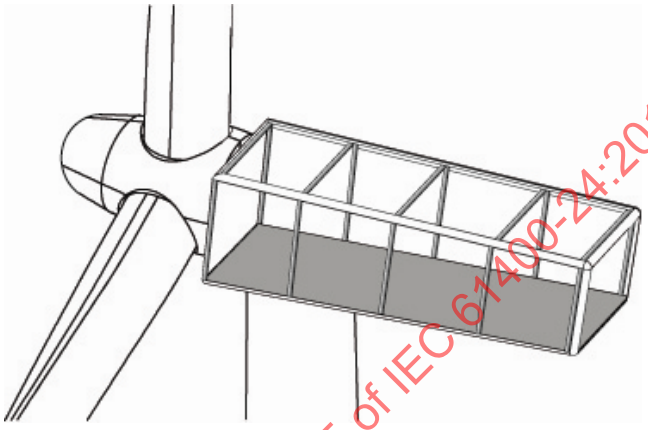

Figure E.3 – Mesh with large mesh dimension for nacelle with GFRP cover

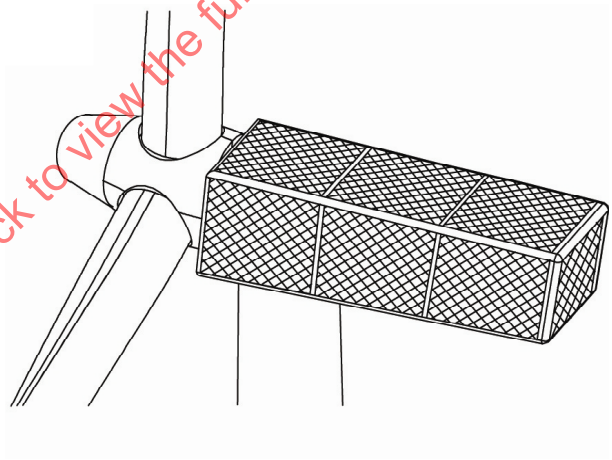

Figure E.4 – Mesh with small mesh dimension for nacelle with GFRP cover

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E.2.4 Zone boundaries

At each zone boundary, it should be ensured that cables and wires crossing the boundary do not conduct large parts of the lightning current or voltage transients into the lightning protection zone with the higher number. This is accomplished by means of proper bonding and shielding practices and overvoltage protection of cables and wires at the zone boundary. The goal is to reduce current and voltage to a level tolerable for the equipment placed in the protection zone with the higher number.

The amount of necessary components for protection against overvoltages (SPDs) can be reduced by means of appropriate division into zones, appropriate positioning of cables, use of shielded cables and use of optical fibres for transmission of signals and data.

Successive zones are characterised by significant changes in the LEMP severity. The boundary of an LPZ is defined by the protection measures employed for the attenuation against magnetic and electrical fields.

In some special situation, it can be necessary to go directly from LPZ 0_B to LPZ 2. This places higher demands on the protection components at the zone boundaries that should attenuate the influencing parameters to the necessary level.

Lightning protection zones can be connected via the shields of shielded cables or via shielding cable ducts, whereby for example two control cabinets placed some distance apart can be connected without having to use SPDs on circuit cores (see Figure E.5). Likewise, a cabinet defined as LPZ 2 can be extended with a shielded cable to include an external metal sensor housing also defined as LPZ 2.

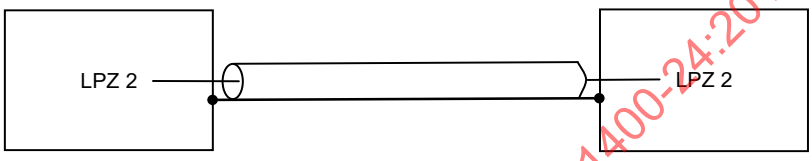

Figure E.5 – Two cabinets both defined as LPZ 2 connected via the shield of a shielded cable

E.2.5 Zone protection requirements

To avoid the occurrence of damage or unacceptable failure, it should be ensured that within a given zone, no components are exposed to parts of the lightning current, voltage differences or electromagnetic and electrical fields above their withstand levels. To fulfil these demands, tests and verifications should be carried out and documented.

Protection may be achieved by using coordinated SPDs, by using shielded cables, by using shielding cable routes, or combinations thereof as needed.

An example of how to document a surge protection measures (SPM) system is shown in Figure E.7.

When applying LPZ on turbines, some special considerations applies as defined in the following cases:

Case 1: Voltage drop along structure

A LPZ inside an enclosure ensuring the same potential of equipment inside does not need overvoltage protection of internal wiring. Equipment not placed within the same enclosure even when in the same LPZ might require surge protection if it is evaluated that the equipment during a lightning exposure does not achieve the same voltage potential. The voltage drop along the connected structure whereon the equipment is placed can be sufficient to cause a voltage difference. For example, with reference to Figure E.6, imagine a power consumer in the front end of the nacelle in LPZ 1. This consumer is connected to a power supply installed in the rear end of the nacelle in LPZ 1. During a lightning strike to the blade, the lightning current will pass through the front part on the nacelle structure, thereby causing a voltage drop along the structure. The consequence is that the power consumer and power supply will be at different potential level even though they are in the same LPZ. This has to be taken into account.

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Case 2: Dynamic LPZ environment ranges

As indicated in case 1, an LPZ can be subjected to different voltage potential depending on the current path and the exact location in the LPZ. It is therefore acceptable to specify an LPZ with a surge and electromagnetic range. E.g. surge environment: 5 kA to 10 kA, Electromagnetic environment: 2 kA/m to 10 kA/m.

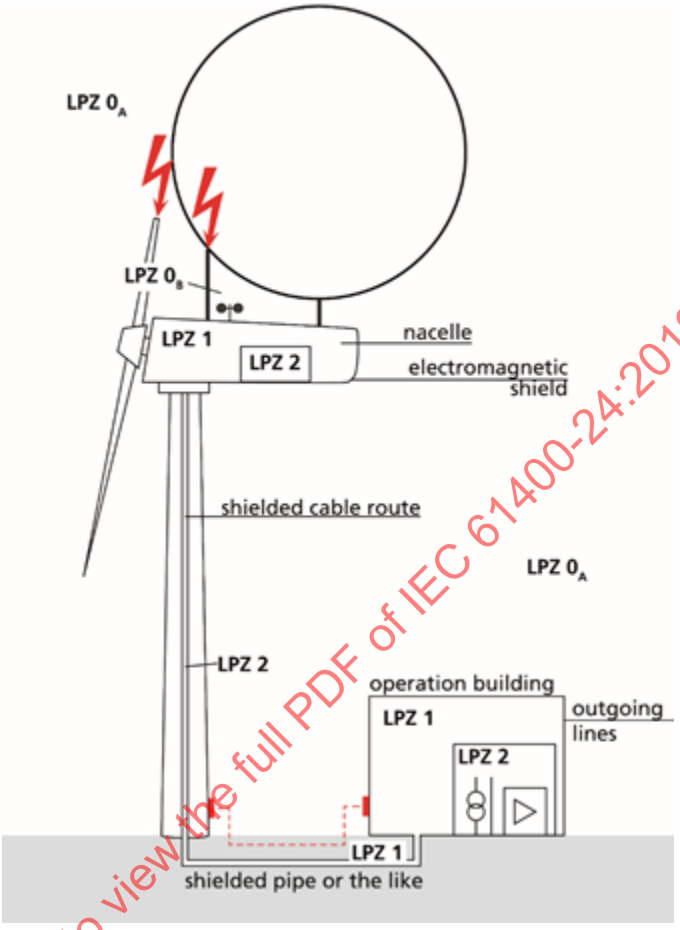

Figure E.6 – Example: division of wind turbine into different lightning protection zones

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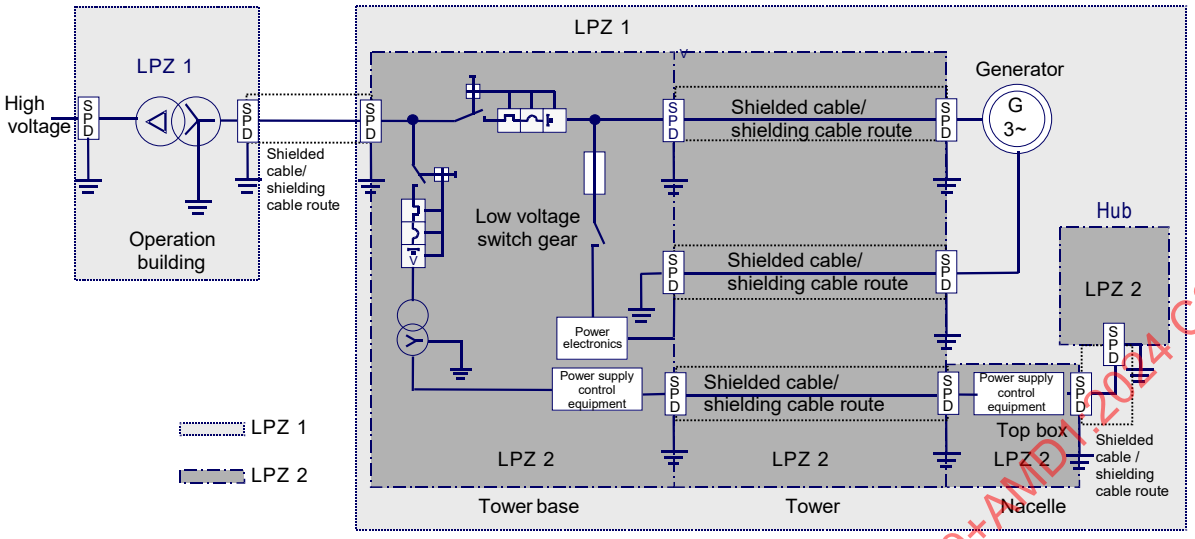

Figure E.7 – Example of how to document a surge protection measures (SPM) system by division of the electrical system into protection zones with indication of where circuits cross LPZ boundaries and showing the long cables running between tower base and nacelle

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Annex F
(informative)

Selection and installation of a coordinated SPD protection in wind turbines

F.1 Location of SPDs

IEC 62305-4 includes detailed information about the location of SPDs. It includes information on the limitations of the cable distance where an SPD provides protection owing to the oscillation phenomenon and induction effects.

IEC 61643-12 includes some further examples where additional protection may be necessary, such as where:

- very sensitive equipment is present;
- the distance between SPD located at the entrance to the LPZ and equipment to be protected is too long;
- electromagnetic fields inside the structure are created by internal interference sources.

Subclause D.3.3 of IEC 62305-4:2010 discusses the problem of oscillation phenomena. The oscillation protection distance is the maximum length of the circuit between the SPD and the equipment, for which the SPD protection is still adequate, taking into account the oscillation phenomenon and capacitive load. The oscillation phenomenon may be disregarded if the length of the circuit between the SPD and the equipment is less than 10 m or if the effective protection level is 50 % of the rated impulse withstand voltage level of the downstream equipment.

Subclause D.3.3 of IEC 62305-4:2010 discusses the problem of induction phenomena. The induction protection distance is the maximum length of the circuit between the SPD and the equipment for which the SPD protection is still adequate, taking into account the induction effect. The induction effect can be minimised by using spatial shielding and line shielding – see also Annex G.

Owing to overvoltages, which are caused for example by switching operations or fuse operation in the wind turbine electrical systems or in the electrical power system to which the wind turbine is connected, additional SPDs within an LPZ might be necessary – see also Clause F.7.

F.2 Selection of SPDs

SPDs can in general be selected based on the SPD data sheets and product information.

NOTE IEC-CB test certificate gives an independent proof that SPDs comply with the relevant standards IEC 61643-11 and IEC 61643-21.

F.3 Installation of SPDs

With increasing length of the connecting leads of SPDs, the effectivness of protection against overvoltages is reduced. To gain maximum protection, the total connection lead length should be kept as short as possible.

For the installation of SPDs in wind turbines:

- it is recommended that the total connection lead length does not exceed 0,5 m;

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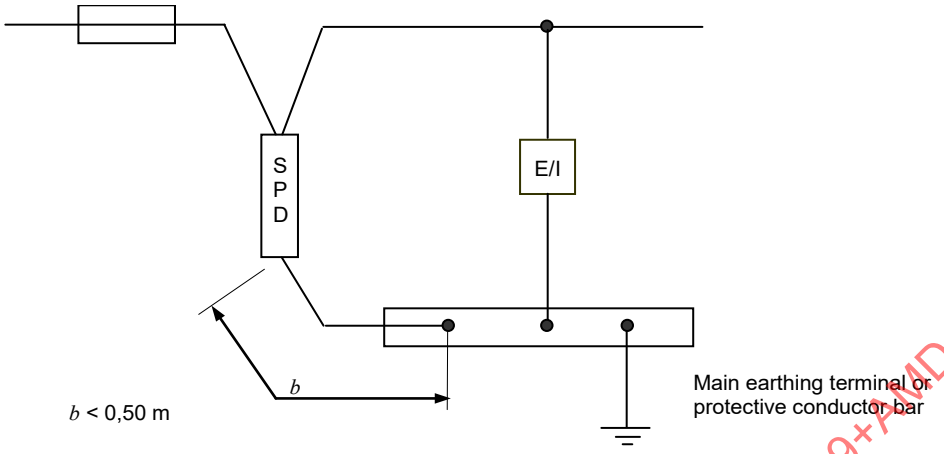
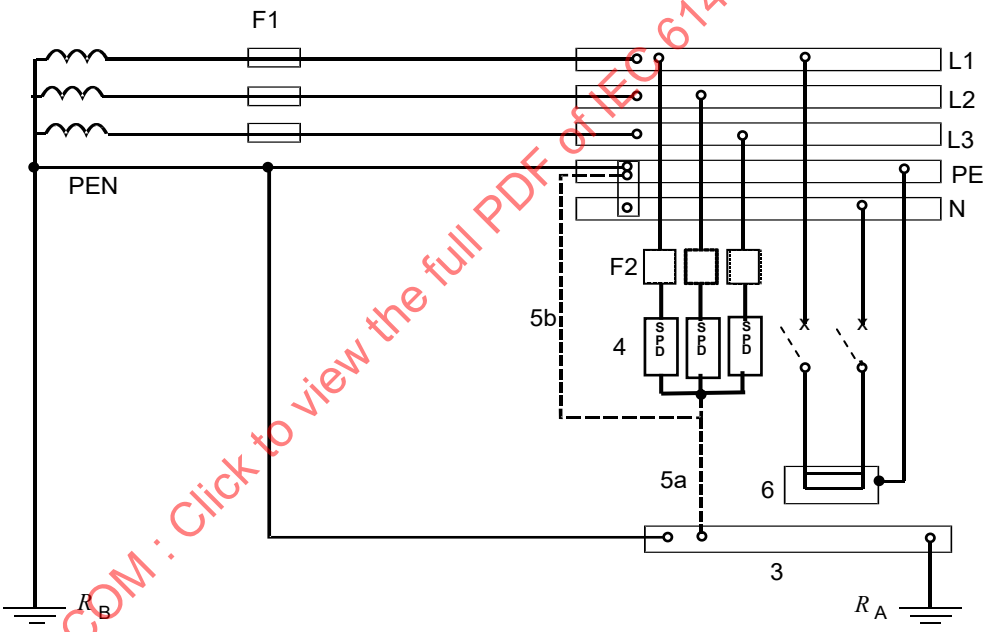
- the so-called point-to-point installation scheme should be in accordance with Figure F.1;
- earthing connections 5a and 5b should be in accordance with Figure F.2.



This figure is adapted from IEC 60364-5-53.

Figure F.1 – Point-to-point installation scheme



This figure is adapted from IEC 60364-5-53.

Figure F.2 – Earthing connection installation scheme

F.4 Environmental stresses of SPDs

IEC 61643-11 specifies:

- operating and storage temperatures of −5 °C to +40 °C (normal range) and −40 °C to +70 °C (extended range);
- relative humidity under indoor conditions should be between 30 % and 90 %;
- IEC 61643-11 does not at this time include requirements for vibration.

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If the actual environmental stress of the SPDs installed in wind turbines exceeds the values given in IEC 61643-11, appropriate test methods and stress values of the IEC 60068 series should be applied. The manufacturer of the wind turbine should specify requirements for specific points of installation, e.g. nacelle and hub.

F.5 SPD status indication and SPD monitoring in case of an SPD failure

SPDs may be overloaded owing to exceptionally high lightning currents or owing to repetitive stress. Furthermore, critical parts of the electrical and control systems of wind turbines may result in increasing requirements on the availability.

In such applications, defined by the manufacturer of the wind turbine, SPDs may provide a combination of continuity of supply and continuity of protection as described in IEC 60364-5-53.

This may, if needed, be providedfor example by:

- a system to monitor the SPDs;
- a signalling and control mechanism within the SPD to give warning against upcoming SPD failures;
- a remote signalling to be included into an overall monitoring and control system of the wind turbine.

F.6 Selection of SPDs with regard to protection level (U_p) and system level immunity

If necessary, the system level immunity can be verified by a system level immunity test. Possible methods of system level immunity testing are described in Annex H.

F.7 Selection of SPDs with regard to overvoltages created within wind turbines

Overvoltages, which are caused by switching operations in the wind turbine electrical systems or in the electrical power system to which the wind turbine is connected, have to be considered when selecting and applying overvoltage protection measures for the wind turbine.

Possible examples of such overvoltages created within wind turbines might be:

- grid short circuits;
- static converters (energy stored in the event of disconnection);
- increased capacitive discharge currents due to power inverter cycling;
- load switching by the low-voltage switchgear.

F.8 Selection of SPDs with regard to discharge current (I_n) and impulse current (I_{imp})

In general, wind turbines are erected on exposed sites of the landscape. Furthermore, due to the increasing height of wind turbines, the probability of lightning attachments increases. A possible way to increase the service lifetime of SPDs in the case of a high number of lightning attachments is to select SPDs with higher discharge current and impulse current parameters than given in IEC 60364-5-53, see Table F.1. Circuits connected to equipment located in protective zone LPZ 0_B might be regarded as particularly exposed circuits, as described in 8.5.5.10. This kind of equipment is classified as externally installed equipment, in accordance with IEC 62305-4:2010, Clause B.12.

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A typical example of externally installed equipment in wind turbines is wind measuring systems.

In such cases, it is recommended that SPDs within wind turbines fulfil the requirements of Table F.2.

Table F.1 – Discharge and impulse current levels for TN systems given in IEC 60364-5-53

SPD Class I – I_{imp} (10/350)
12,5 kA for each mode of protection
SPD Class II – I_n (8/20)
5 kA for each mode of protection

Table F.2 – Example of increased discharge and impulse current levels for TN systems

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

When a combined SPD is used for protection purposes in accordance with both SPD Class I and SPD Class II, the ratings of I_n and of I_{imp} should agree with the values in Table F.1 and Table F.2.

When conducted to earth from the wind turbine structure, the lightning current is divided between the earth termination system, the external conductive parts (if any) and the service lines, directly or via SPDs connected to the lines. The level of current diverted via the individual SPDs depends on the number of parallel paths between which the current is shared and the impedances of the individual paths – IEC 62305-1:2010, Annex E provides guidance on how to do the calculation.

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Annex G
(informative)

Information on bonding and shielding and installation technique

G.1 Additional information on bonding

Due to the transient nature of the lightning current, the peak voltage drop along a conductor can be approximated as

$$V = L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{G.1}$$

where

L is the inductance of the conductor [H/m];

$\mathrm{d}i/\mathrm{d}t$ is the maximum rate of change of lightning current [A/s].

The inductance of a conductor can normally be considered to be in the order of 1μH/m and the maximum $\mathrm{d}i/\mathrm{d}t$ can vary from 0,2 kA/μs to 200 kA/μs depending on the lightning stroke and the level of current sharing between individual conductors. The voltage difference along a bonding strap can therefore be up to 200 kV/m.

Consider the system shown in Figure G.1 with two control cabinets located on different metallic planes inside a wind turbine nacelle. A lightning current flows into the upper plane and is transferred to the lower plane via a bond strap. When a lightning current flows through the bond strap, the potential of cabinet 1 is raised with respect to cabinet 2. The possible result of this change in potential could damage components located in cabinet 1 or 2. The situation can be improved by good bonding practice, proper cable installation practice and either SPD protection of the signal wire or by using a shielded signal cable with shield bonded at both ends.

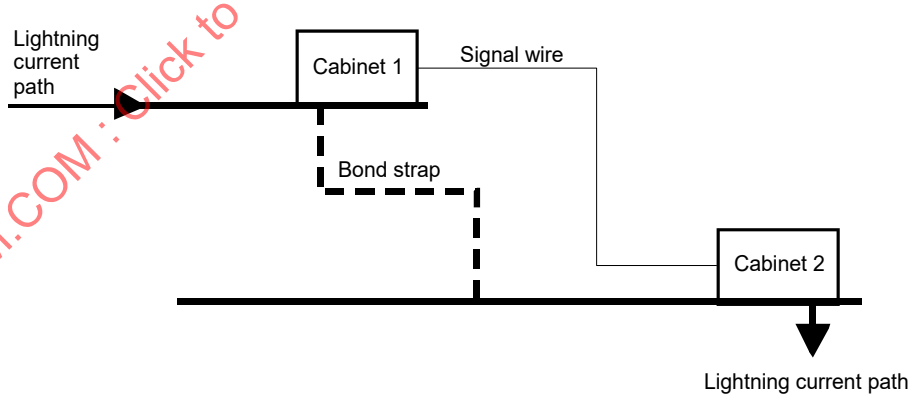

Figure G.1 – Two control cabinets located on different metallic planes inside a nacelle

The use of multiple bond straps and minimisation of the bond strap length will result in the lowest possible voltage difference between the two metal planes.

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Bonding within a wind turbine should therefore use multiple conductors that are:

- capable of carrying the predicted fraction of lightning current to pass through the path in question;
- as short and straight as possible.

Wiring can also be protected by routing wires in conduits/raceways or by using shielded cable as discussed in IEC TR 61000-5-2.

G.2 Additional information on shielding and installation technique

When lightning currents flow through a wind turbine, large magnetic fields are produced. If these changing magnetic fields pass through a loop, they will induce voltages within that loop. The magnitude of the voltage is proportional to the rate of change of the magnetic field and the area of the loop in question. The constructor should consider the magnitude of induced voltages and make sure that such voltages do not exceed the withstand level of the cabling and attached equipment.

The diagram below shows a loop of wire running next to a current-carrying conductor. The voltage U will be proportional to the rate of change of the magnetic field (see Figure G.2).

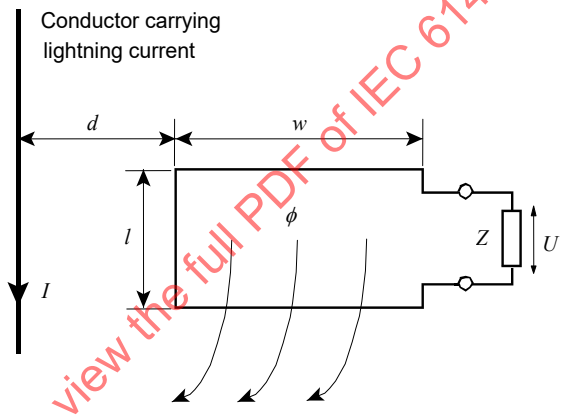

Figure G.2 – Magnetic coupling mechanism

This can be expressed in the following formula:

$$U = -\frac{\mathrm{d}\varphi}{\mathrm{d}t} \tag{G.2}$$

where

ϕ is flux linkage [Wb];

U is the voltage induced in the loop [V].

It can be shown that the total flux passing through the loop is:

$$\varphi = \frac{\mu_0 l \cdot I}{2\pi}\left[ln\left(\frac{d+w}{d}\right)\right] \tag{G.3}$$

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Therefore, the voltage induced in the loop is:

$$U = \frac{\mu_0 l}{2\pi} ln\left(\frac{d+w}{d}\right) \cdot \frac{\mathrm{d}i}{\mathrm{d}t} = M \cdot \frac{\mathrm{d}i}{\mathrm{d}t} \tag{G.4}$$

where

μ_0 is the permeability of air and the other dimensions are as given on the diagram;

M is the mutual inductance between the loop and the current-carrying conductor [H/m].

When loops are closed, the current induced in the loop is:

$$I = \frac{\int u \mathrm{d}t}{L} \tag{G.5}$$

where

L is the self-inductance of the loop;

u is the open loop voltage.

See IEC 62305-4 for a detailed discussion of induced voltages and currents.

This voltage would be an example of a differential voltage, i.e. one induced between two wires in a system. To prevent voltages being induced into the electrical wiring, it is obvious that the reduction of the peak change of magnetic field passing through a loop and the reduction of loop area will result in lower induced voltages. This can be achieved in a number of ways:

- increased separation between the current-carrying conductor and the electrical circuit: this method of reducing induced voltages would work, but is not normally possible within the confines of a wind turbine. However, if a preferred lightning current path can be established, for example within the nacelle, then it is possible to reconsider the placement of wind turbine wiring;
- use of twisted pair cable: the use of twisted pair cable will, as has been discussed, reduce the induced voltage level. It will do this by effectively reducing the area – through which the magnetic field passes – to zero. Twisted pair systems will therefore reduce differential mode voltages, but common mode voltages may still exist;
- use of shielding: the practice of routing the wiring inside steel pipes or metal conduits is good as these very effectively shield cables from magnetic fields. The use of shielded cables also provides the same effect for the conductors located within the shields. It is important to note though that protection is only possible when both ends of the shield/pipe/conduit are solidly bonded. If this is not the case, in other words if only one end of a conductor shield is bonded, there will be no protection from inductive/magnetic coupling.

Shielding of cables will in most cases give a good protection against LEMP.

Bonding the shield correctly at both ends (i.e. 360° connection to the equipment chassis) ensures correct functionality and provides the best protection.

If the cables are long or the current impulses are high, calculations will show that the induced voltage between the shield and the wire will be high. If the equipment connected to the cable cannot withstand these high voltage impulses, shielding should be combined with SPD. This could be a situation between the tower bottom and the nacelle.

The lightning current will run in the shield of shielded cables. The current will induce voltage between the wires and the shield. The value of this voltage can be calculated according to the transfer impedance.

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If the signal in the shielded cables is too sensitive, it can be necessary to protect the wire with an SPD.

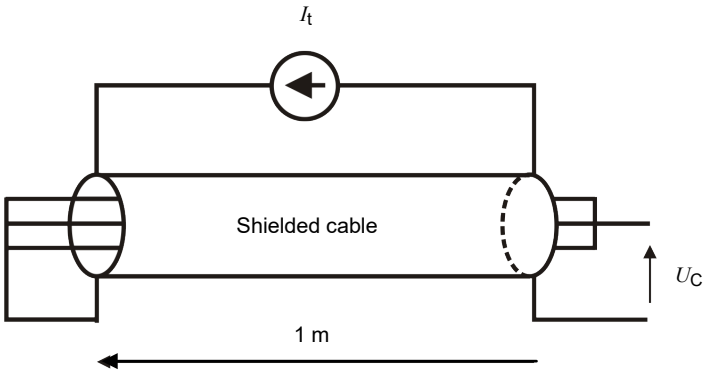

Figure G.3 – Measuring of transfer impedance

Measuring of the transfer impedance can be done in accordance with IEC 62153-4-3 if a current is supplied to the shield, if the cable length is known and if the wire and shield is short-circuited in one of the ends of the cable, the voltage can then be measured in the other end of the cable (see Figure G.3).

With the known test current I_t and voltage U_c, the transfer impedance can be calculated as:

$$Z_T = \frac{U_c}{I_t} \tag{G.6}$$

which can then be used for calculation of the voltage between shield and wire as:

$$U_c = l \cdot I_t \cdot Z_T \tag{G.7}$$

where

U_c is the voltage between shield and wires [V];

l is the length of cable [m];

I_t is the current in the shield [A];

Z_T is the transfer impedance [Ω].

When the cable is installed, the voltage drop will be divided between the matching impedances at two ends of the cable, and thereby affect the terminals of the connected equipment. A rough estimate is that the calculated voltage will be divided by two between the two ends of the cable.

If shielded power cables have low impedance connections between the phase conductors and the shield/ground, the lightning current will be shared between the shield and the phase conductors. Such low impedance connections could be SPDs for protection against overvoltages between phase conductors and shield/ground at the ends of the cable. This situation would for example need to be considered for the power cable connecting the wind turbine to the grid.

IEC 62305-2:2010, Annex D gives guidance on how to assess the failure current for shielded cables (i.e. the level of lightning current flowing in a cable shield that will cause failure due to breakdown of cable insulation).

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Annex H
(informative)

Testing methods for system level immunity tests

The following testing methods apply for system level immunity tests.

a) SPD discharge current test under service conditions:

   1) Prior to the system level immunity test:
   The equipment to be protected, the immunity of which has to be determined by applying the methods in accordance with IEC 61000-4-5.
   The protective effect of the SPDs has to be determined with test procedures in accordance with IEC 61643-11.

   2) In a common system test, the equipment to be protected is tested here under service conditions, i.e. 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. The impulse current or the partial lightning current at the point of installation of the SPDs needs to be analysed. In case of shielded cabling the current injected to inner conductors needs to be evaluated in accordance with G.2. If no specific analysis is done, the current parameters of Clause F.8 should be applied for low voltage power systems. Default values for data and signalling circuits can be found in IEC 62305-1. For the relevant test categories, see Table 2 of IEC 61643-22:2015. Where applicable, additional circuits, such as communication lines, sensors, motors should be connected.

   3) Figure H.1 gives an example circuit of an SPD discharge current test under service conditions including SPDs class II and a pitch control system of a wind turbine. Figures H.2a to H.2e show various examples for the injection of test current in the case of shielded and unshielded lines or cables.

b) Induction test for lightning currents:

   1) Impulse currents should be injected into a defined metal, mounting plate in order to examine the behaviour of the complete system within an electromagnetic field generated by lightning currents.

   2) The system under test should be installed as realistically as possible.
   This simulated installation should include individual equipment, all installed SPDs and the real length and type of the interconnection lines.

   3) The resulting induced impulse currents within the cabling of the complete system should be monitored.

   4) The characteristic and applicable values of the primary lightning currents should be derived from IEC 62305-1:2010, Table C.3.

   5) Figure H.3 gives an example circuit of an induction test due to lightning currents including SPDs class II for the power supply and SPDs for the control equipment of a pitch control system of a wind turbine.

c) Recommended test classification of system level immunity test (following IEC 61000-4-5):

   1) Normal performance within limits specified by the manufacturers.

   2) Temporary loss of function or degradation of performance which ceases after the disturbance ceases and from which the equipment under test recovers its normal performance without operator intervention.

   3) Temporary loss of function or degradation of performance, the correction of which requires operator intervention.

   4) Loss of function or degradation of performance which is not recoverable owing to damage to hardware or software or loss of data.

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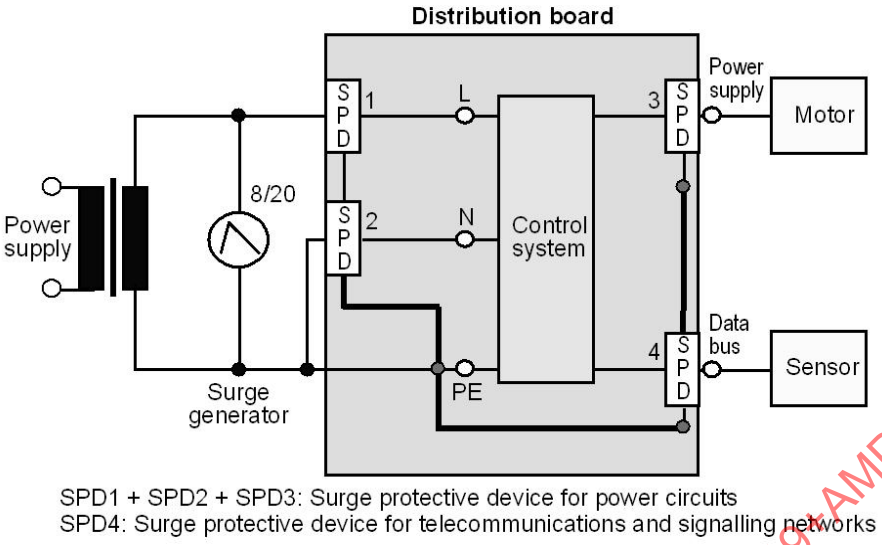
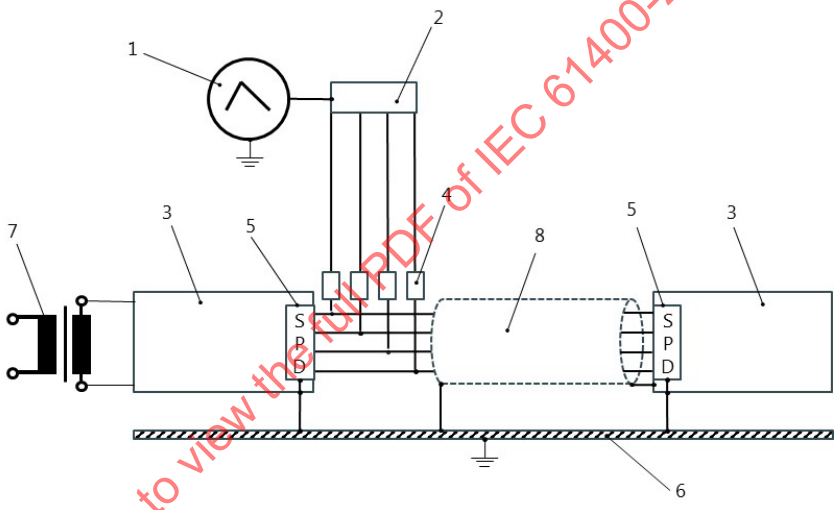


Figure H.1 – Example circuit of a SPD discharge current test under service conditions



Key

1 Impulse current generator
2 Balancing unit for equal impulse current distribution of the (see 8.7.1 of IEC 61643-11)
3 Equipment to be protected
4 Decoupling unit, e.g. spark gap, gas discharge tube
5 SPD: Surge Protective Device
6 Ground plate
7 Power source: for nominal supply voltage
8 Shielded cable

a) Typical test set-up for shielded lines/cables and injection of test current in wire bundle

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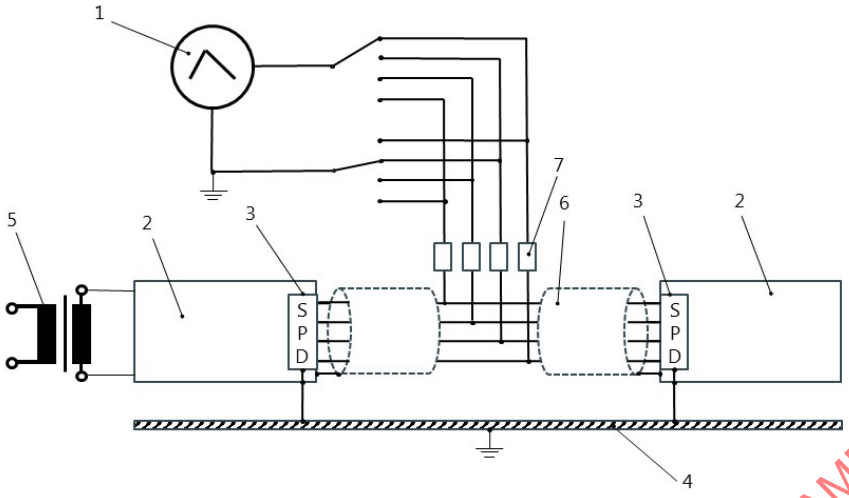
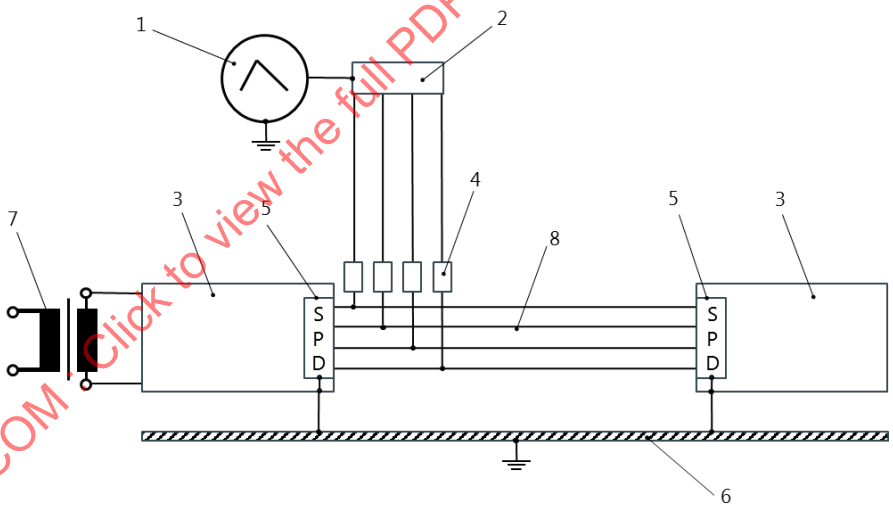


Key

1 Impulse current generator
2 Equipment to be protected
3 SPD: Surge Protective Device
4 Ground plate
5 Power source: for nominal supply voltage
6 Shielded cable
7 Decoupling unit, e.g. spark gap, gas discharge tube

b) Typical test set-up for shielded lines/cables and injection of test current in single wire



Key

1 Impulse current generator
2 Balancing unit for equal impulse current distribution of the (see 8.7.1 of IEC 61643-11)
3 Equipment to be protected
4 Decoupling unit, e.g. spark gap, gas discharge tube
5 SPD: Surge Protective Device
6 Ground plate
7 Power source: for nominal supply voltage
8 Unshielded cable

c) Typical test set-up for unshielded lines/cables and injection of test current in wire bundle

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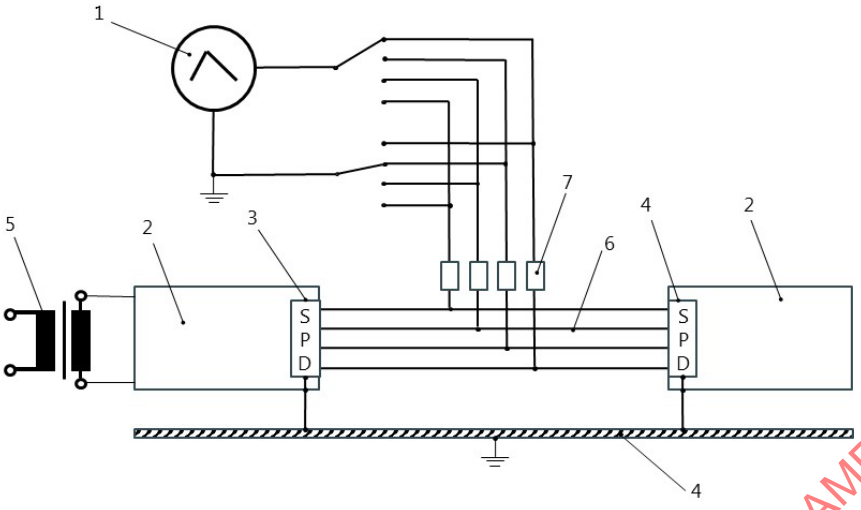
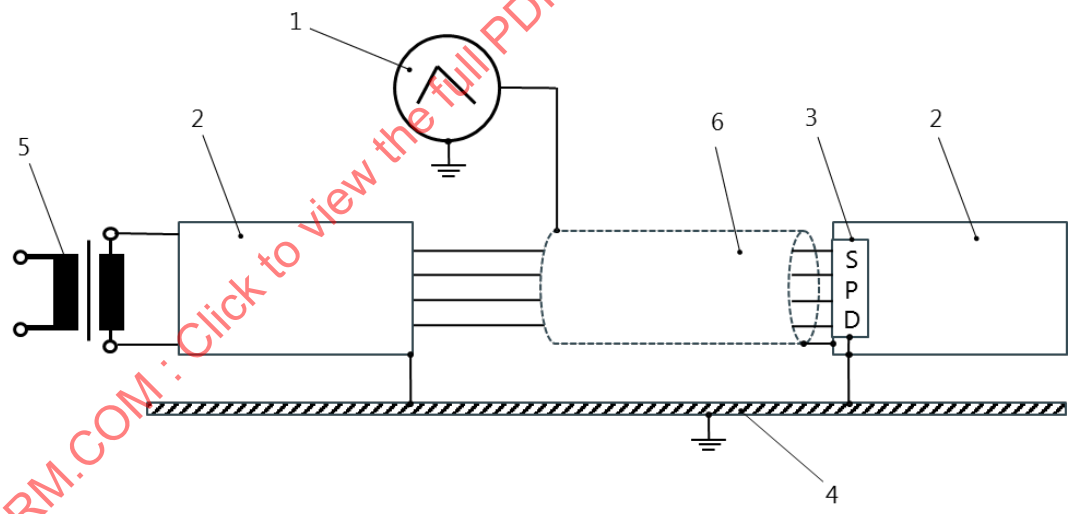


Key

1 Impulse current generator
2 Equipment to be protected
3 SPD: Surge Protective Device
4 Ground plate
5 Power source: for nominal supply voltage
6 Unshielded cable
7 Decoupling unit, e.g. spark gap, gas discharge tube

d) Typical test set-up for unshielded lines/cables and injection of test current in single wire



Key

1 Impulse current generator
2 Equipment to be protected
3 SPD: Surge Protective Device
4 Ground plate
5 Power source: for nominal supply voltage
6 shielded cable

e) Typical test set-up for shielded lines/cables and injection of test current in shield

Figure H.2 – Typical test set-up for injection of test current

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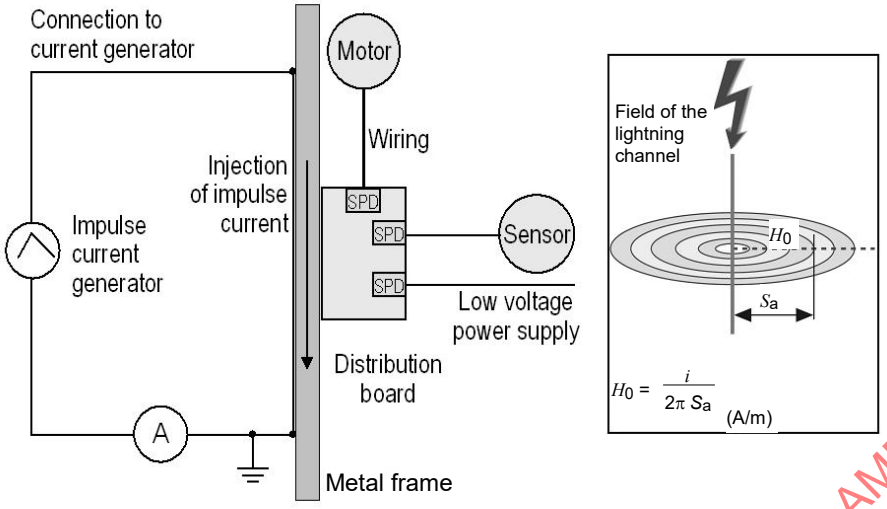

Figure H.3 – Example circuit of an induction test for lightning currents

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Annex I
(informative)

Earth termination system

I.1 General

I.1.1 Types of earthing systems

For large wind turbines, there will always be an extensive foundation structure that incorporates large amounts of steel in large dimensions. The steel in the foundation structure should generally be used for earthing purposes as a foundation earthing system, because doing so will result in the lowest possible earthing resistance.

In case the LPS designer chooses to install a separate earthing system with earth electrodes, it is still necessary to ensure proper bonding to the foundation steel, as keeping the lightning current from flowing into the foundation steel will be very difficult, and as potential differences between a separate earthing system and the foundation steel may be hazardous to, for example, the concrete covering steel reinforcement of a foundation.

The LPS designer and the LPS installer should select suitable types of earth electrodes. The LPS designer and the LPS installer should consider protection against dangerous step voltages in the vicinity of the earth termination networks if they are installed in areas accessible to the public.

Deep-driven earth electrodes can be effective in special cases where soil resistivity decreases with depth and where substrata of low resistivity exist at depths greater than those to which rod electrodes are normally driven.

In the case of pre-stressed concrete, consideration should be given to the consequences of the passage of lightning discharge currents, which may produce unacceptable mechanical stresses.

Two basic types of earth electrode arrangements are considered in IEC 62305-3.

Type A arrangement: horizontal or vertical electrodes connected to not less than two down conductors. Type A can be used for minor buildings (for example measurement or office sheds in connection to a wind farm).

NOTE 1 For further information on type A arrangements, see IEC 62305-3:2010, 5.4.2.1 and E.5.4.2.1.

Type B arrangement: one or more external ring conductors or natural earth electrodes built into the structure. This type of arrangement comprises either an external ring earth electrode in contact with the soil for at least 80 % of its total length or a foundation earth electrode.

Type B arrangements should be used for wind turbines.

NOTE 2 For further information on type B arrangements, see IEC 62305-3:2010, 5.4.2.2 and E.5.4.2.2.

I.1.2 Construction

I.1.2.1 Foundation earthing electrodes

A foundation earth electrode comprises conductors that are installed in the foundation of the structure below ground level. They have the advantage that they are adequately protected against corrosion if the concrete is of good homogenous quality and covers the foundation earth electrode by at least 50 mm.

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Metals used for earth electrodes should conform to the materials listed in IEC 62305-3, and the behaviour of the metal with respect to corrosion in the soil should always be taken into account. Some guidance is given in IEC 62305-3. When guidance for particular soils is not available, the experience with earth termination systems in neighbouring plants with soil exhibiting similar properties should be ascertained. When the trenches for earth electrodes are refilled, care should be taken that no fly ash, lumps of coal or building rubble is in direct contact with the earth electrode. If the soil resistivity is very high, measures should be taken to reduce the earthing resistance. It is suggested to use electrodes with larger surface area, for example by using meshes of conductors in trenches instead of single electrodes or by using conductive refill material to improve the electrode contact to earth in trenches and drilled holes. Corrosion should be considered when using earth improving material.

Steel embedded in concrete has approximately the same galvanic potential in the electrochemical series as copper in soil. Therefore, when steel in concrete is connected to steel in soil, a driving galvanic voltage of approximately 1 V causes a corroding current to flow through the soil and the wet concrete and dissolve steel in soil.

Copper or stainless steel conductors should therefore be used for earth electrodes in soil where these are connected to steel embedded in concrete.

At the perimeter of a structure, a metal conductor in accordance with IEC 62305-3 should be installed connecting the tower to the metal of the foundation in the shortest possible path.

During installation, it is advantageous to measure the earthing resistance regularly. The driving of electrodes may be interrupted as soon as the earthing resistance stops decreasing. Additional electrodes can then be installed at other positions where the effect on the earthing resistance is better. It is recommended to keep track of the measurements of each electrode in the QA system.

The earth electrode should be sufficiently separated from existing cables, metal pipes, etc. in the earth, and due allowance should be made for the earth electrode departing from its intended position during driving. The separation distance depends on the electrical impulse strength and resistivity of the soil and the current in the electrode.

If there is danger of an increase of resistance near to the surface (e.g. through drying out), it is often necessary to use deep driven earth electrodes of greater length.

Radial earth electrodes should be installed at a depth of 0,5 m or deeper. An increase in burial depth of the electrode ensures that in countries with low temperatures during the winter, the earth electrode is not situated in frozen soil (which has extremely low conductivity). Vertical electrodes are preferred to achieve a seasonally stable earthing resistance. An additional benefit is that deeper earth electrodes result in a reduction of the potential differences at the earth's surface and thus lower step voltages reducing the danger to living beings on the earth's surface.

I.1.2.2 Type B – ring earth electrodes

In order to reduce the conventional earthing resistance, the type B earthing arrangement may be improved, if necessary, by adding vertical earth electrodes or radial earth electrodes. Figure I.1 gives the requirements regarding the minimum length of earth electrodes.

The clearance and depth for a type B earth electrode are optimal in normal soil conditions for the protection of persons in the vicinity of the wind turbines. In countries with low winter temperatures, the appropriate depth of earth electrodes should be considered.

Where large numbers of people frequently assemble in an area adjacent to the wind turbine to be protected, extended potential control for such areas should be provided. More ring earth electrodes should be installed at reasonable distances from the first and subsequent ring

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conductors. These ring earth electrodes should be connected to the first ring conductor by means of radial conductors.

I.1.2.3 Earth electrodes in rocky soil

During construction, a foundation earth electrode should be built into the concrete foundation.

Even in rocky soil where a foundation earth electrode has a reduced earthing effect, it still acts as an equipotential plane coupling lightning current to ground.

Radial earth electrodes lying on or near the earth surface may have to be covered by stone, gravel or embedded in concrete for mechanical protection.

When the wind turbine is situated close to a road, a ring earth electrode should, if possible, be laid beneath the road. However, where this is not possible over the whole length of the exposed road segment, such equipotential control should be provided at least in the vicinity of the earth electrodes.

For potential control in certain special cases, a decision should be made whether to install an additional partial ring in the vicinity of the wind turbine entrance, or to artificially increase the resistivity of the surface layer of the soil (e.g. by adding a layer of gravel).

I.2 Electrode shape dimensions

I.2.1 Type of arrangement

A type A arrangement comprises horizontal or vertical earth electrodes installed outside the structure to be protected and connected to each down conductor. The total number of earth electrodes should be not less than two.

The minimum length of each electrode at the base of each down conductor is:

– l_1 for horizontal electrodes, or
– 0,5 l_1 for vertical (or inclined) electrodes.

where l_1 is the minimum length of horizontal electrodes shown in Figure I.1.

The minimum length (l_1) of earth electrode depends on the lightning protection level (I-IV) and on the soil resistivity.

For combined (vertical or horizontal) electrodes, the total electrode length should be considered.

The stated minimum length l_1 can be disregarded if the earthing resistance of the earthing system is less than 10 Ω measured at a frequency different from power frequency (50 Hz to 60 Hz) and low order harmonics of this.

For a type A arrangement in soil with resistivity less than 500 Ωm, the minimum length is 5 m for two horizontal electrodes or 2,5 m for two vertical electrodes.

For soil resistivities higher than 500 Ωm, the minimum length (l_1) increases linearly up to 80 m at a soil resistivity of 3 000 Ωm.

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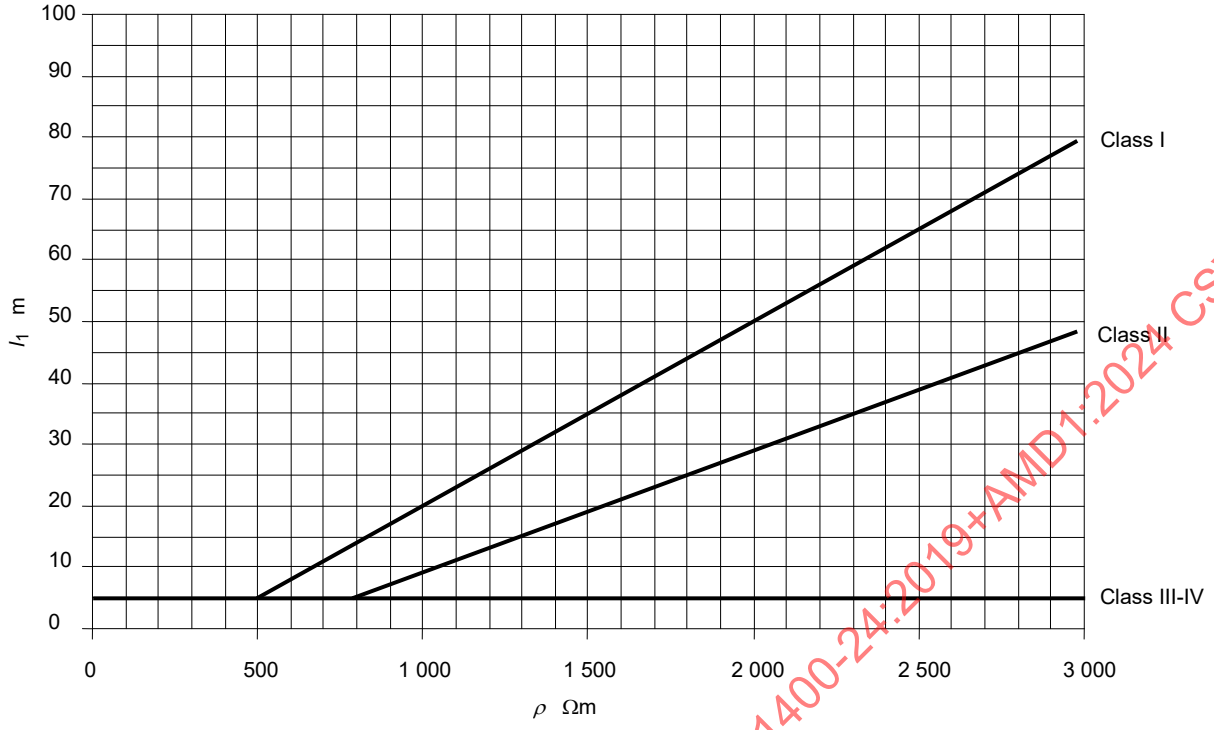

This figure is adapted from IEC 62305-3.

Figure I.1 – Minimum length (l_1) of each earth electrode according to the class of LPS

Owing to the high-frequency components of the lightning current, a length of more than 80 m, independent of the soil resistivity, does not decrease the total impedance further.

A type B arrangement comprises either a ring conductor external to the structure to be protected, in contact with the soil for at least 80 % of its total length, or a foundation earth electrode. Such earth electrodes may also be meshed.

For the ring earth electrode (or foundation earth electrode), the mean radius (r_e) of the area enclosed by the ring earth electrode (or foundation earth electrode) should be not less than the value l_1:

$$r_e \geq l_1 \tag{I.1}$$

where l_1 is represented in Figure I.1 according to LPS levels I, II, III and IV.

When the required value of l_1 is larger than the convenient value of r_e, additional horizontal or vertical (or inclined) electrodes should be added with individual lengths l_r (horizontal) and l_v (vertical) given by the following equations:

$$l_r = l_1 - r_e \tag{I.2}$$

$$l_v = (\ l_1 - r_e\ ) / 2 \tag{I.3}$$

The number of electrodes should be not less than two.

The additional electrodes should be connected as equidistantly as possible.

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Information about the soil resistivity, prospective earth fault current and clearance time is of utmost importance for planning the correct design and installation of the earthing system.

The soil resistivity will differ very much depending on the character of the soil.

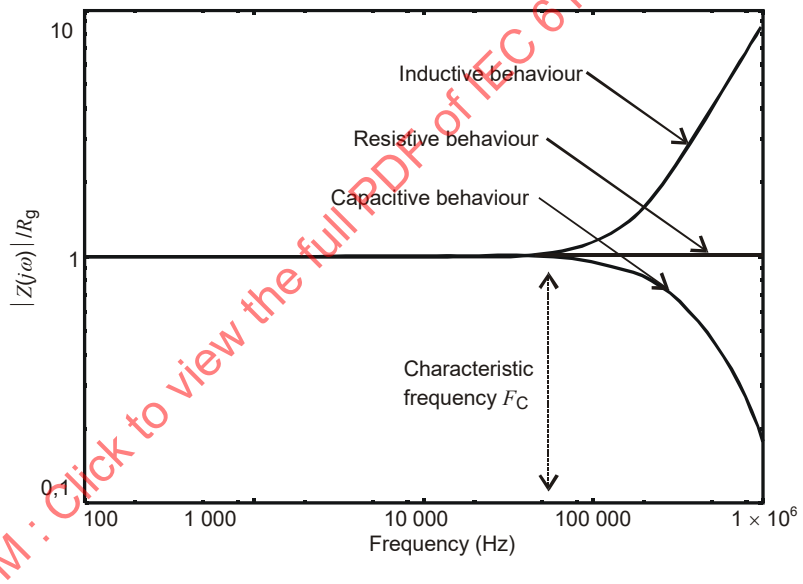
Examples:

For LPL I and ρ = 1 500 Ωm, Figure I.1 gives a minimum earth electrode length l_1 = 35 m.

In the case of a ring earth electrode with radius r_e = 10 m, two horizontal electrodes with individual length l_r = 35 m – 10 m = 25 m or two vertical electrodes l_v = (35 m − 10 m) / 2 = 12,5 m should be added.

I.2.2 Frequency dependence on earthing impedance

As earthing system measurements are usually made with low frequency, the result is obtained as a resistance, but the earthing system designer should realise that, owing to the high frequency of the lightning (up to 1 MHz), the electrode impedance impulse response may be higher or lower than the value measured at a low frequency. The electrode behaviour (capacitive, inductive or resistive) depends on the electrode shape, soil resistivity and the point where lightning current is injected.



This figure is adapted from Cigré WG C.4.4.02 July 2005 [7].

Figure I.2 – Frequency dependence on the impedance to earth

Figure I.2 shows typical dependence on the impedance to earth, the ratio of the impedance modulus ($Z(j\omega)$) and the low frequency resistance to earth (R_g). There are two frequency ranges: low frequency (LF) range up to about 50 kHz, where the impedance is nearly constant and equal to the resistance, and high frequency (HF) range above 50 kHz, where the impedance is changing with the frequency and may be higher or lower than the measured resistance value. The dynamic behaviour of earthing electrodes subjected to lightning current impulses is an important issue (i.e. the ratio between maximum values of voltage and current injected).

Resistive and capacitive behaviour are advantageous since the HF is equal to or smaller than LF resistance to earth. Usually, capacitive behaviour is typical for earthing systems with meshed electrodes branching out to cover an area whereas earthing systems with few long electrodes have mostly inductive behaviour. The use of multiple earthing arrangements

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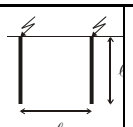
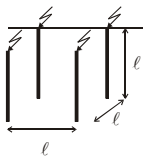
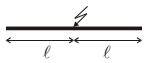
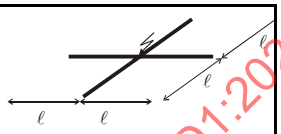
improves the impulse efficiency as indicated in Table I.1. However, in practice, it is not always possible to use small electrodes for fulfilling requirements in standards of low values of resistance.

Horizontal rods are slightly less effective at power frequency in comparison to vertical rods, but have better impulse efficiency.

Table I.1 – Impulse efficiency of several ground rod arrangements relative to a 12 m vertical ground rod (100 %)

Ground rod arrangement						
Percentage	100	95	85	85	80	70
This table is adapted from Cigré WG C.4.4.02 July 2005 [7].						

I.3 Earthing resistance expressions for different electrode configurations

It is standard practice for most earthing system designs to be produced using some form of computer software since these are capable of accurately analysing the interaction between multiple elements usually used in such systems. Some of these systems are capable of analysing the response of the earthing system to transient currents, such as those that result from lightning. Such tools will usually give the most accurate results. In the case such tools are not available, the formulae for simple earthing electrode configurations and combinations listed in the following Table I.2 to Table I.6 may be used.

Table I.2 – Symbols used in Tables I.3 to I.6

ρ [Ωm]	is soil resistivity	a_{12} [m]	is the distance between rods
n	is the number of radial wires	d [m]	is the buried depth
L [m]	is the length of every radial wire	R [Ω]	is the electrode resistance
a [m]	is the radius of radial wire	D [m]	is the diameter of ring electrode
s [m]	is the spacing between rods	e	2,718
		π	3,141 6

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Table I.3 – Formulae for different earthing electrode configurations

Buried straight horizontal electrode $$R = \frac{\rho}{\pi L}\left(\ln\frac{2L}{\sqrt{2ad}} - 1\right) \quad \text{(I.4)}$$ when $d << L$	Two rod electrodes of equal length separated by the distance a_{12} $$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} - 1 + \frac{L}{a_{12}}\right) \quad \text{(I.8)}$$ when $a_{12} >> L$
n buried electrodes radiating symmetrically from a common point $$R = \frac{\rho}{n\pi L}\left(\ln\frac{2L}{\sqrt{2ad}} - 1 + \sum_{m=1}^{n-1}\ln\frac{1+\sin\left(\frac{\pi m}{n}\right)}{\sin\left(\frac{\pi m}{n}\right)}\right) \quad \text{(I.5)}$$ NOTE In the above formula, it is assumed that the angle between any two adjacent electrodes is the same, so in the case n = 2, the electrodes extend in opposite directions from a common point. All the conductors carry the same current.	n grounds rods of equal length arranged at equal space on a circle of diameter D smaller than the length of the rods $$R = \frac{\rho}{2\pi L}\left(\ln\frac{4L}{\sqrt[n]{na\left(\frac{D}{2}\right)^{n-1}}} - 1\right) \quad \text{(I.9)}$$ when $D << L$ NOTE The n ground rods are connected through an isolated cable.
Vertical rod electrode $$R = \frac{\rho}{2\pi L}\left(\ln\frac{4L}{a} - 1\right) \quad \text{(I.6)}$$ when $L >> a$	n equal grounds rods arranged at equal space on a circle of diameter D with spacing between adjacent rods equal to or greater than the length of a rod $$R = \frac{\rho}{2n\pi L}\left(\ln\frac{4L}{a} - 1 + \frac{L}{D}\sum_{m=1}^{n-1}\frac{1}{\sin\left(\frac{\pi m}{n}\right)}\right) \quad \text{(I.10)}$$
Two rod electrodes of equal length separated by the distance a_{12} $$R = \frac{\rho}{2\pi L}\left(\ln\frac{4L}{\sqrt{a a_{12}}} - 1\right) \quad \text{(I.7)}$$ when $a_{12} << L$	Buried ring electrode $$R = \frac{\rho}{\pi^2 D}\ln\frac{4D}{\sqrt{2ad}} \quad \text{(I.11)}$$

Table I.4 – Formulae for buried ring electrode combined with vertical rods

Bare buried ring electrode	$$R_1 = \frac{\rho}{\pi^2 D}\ln\frac{4D}{\sqrt{2ad}} \quad \text{(I.12)}$$
n ground rods of equal length arranged on a circle of diameter D with spacing between adjacent rods equal to or greater than the length of a rod	$$R_2 = \frac{\rho}{2n\,\pi L}\left(\ln\frac{4L}{a} - 1 + \frac{L}{D}\sum_{m=1}^{n-1}\frac{1}{\sin\left(\frac{\pi m}{n}\right)}\right) \quad \text{(I.13)}$$
Mutual earthing resistance between the ring electrode and the n of ground rods arranged on a circle of diameter D	$$R_3 = \frac{\rho}{\pi^2 D}\ln\frac{4D}{\sqrt{2\frac{L}{e}d}} \quad \text{(I.14)}$$
Combined resistance	$$R = \frac{R_1 R_2 - R_3^2}{R_1 + R_2 - 2R_3} \quad \text{(I.15)}$$

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Table I.5 – Formulae for buried ring electrode combined with radial electrodes

Bare buried ring electrode	$R_1 = \frac{\rho}{\pi^2 D} \ln \frac{4D}{\sqrt{2ad}}$	(I.16)
n buried radial electrodes radiating horizontally and symmetrically from a common point	$R_2 = \frac{\rho}{n\,\pi L}\left(\ln \frac{2L}{\sqrt{2ad}} - 1 + \sum_{m=1}^{n-1} \ln \frac{1+\sin\left(\frac{\pi m}{n}\right)}{\sin\left(\frac{\pi m}{n}\right)} \right)$	(I.17)
Mutual earthing resistance between the ring electrode and the n buried radial electrodes radiating symmetrically from a common point	$R_3 = \frac{\rho}{\pi^2 D} \ln \frac{4D}{\sqrt{2\frac{L}{e}d}}$	(I.18)
Combined resistance	$R = \frac{R_1 R_2 - R_3^2}{R_1 + R_2 - 2R_3}$	(I.19)

Table I.6 – Formulae for buried straight horizontal electrode combined with vertical rods

Bare buried straight horizontal electrode	$R_1 = \frac{\rho}{\pi L_c}\left(\ln \frac{2L_c}{\sqrt{2ad}} - 1 \right)$ when $d << L_c$	(I.20)
Vertical rod electrode	$R_r = \frac{\rho}{2\pi L_p}\left(\ln \frac{4L_p}{a} - 1 \right)$ when $L_p >> a$	(I.21)
n vertical rod electrodes connected with an isolated cable	$R_2 = \frac{R_r}{n} + \frac{\rho}{n\,\pi\,s} \sum_{m=2}^{n} \frac{1}{m}$	(I.22)
Mutual earthing resistance between the straight horizontal electrode and the n vertical rods	$R_3 = \frac{\rho}{\pi L_c}\left(\ln \frac{2L_c}{\sqrt{2\frac{L_p}{e}d}} - 1 \right)$	(I.23)
Combined resistance	$R = \frac{R_1 R_2 - R_3^2}{R_1 + R_2 - 2R_3}$	(I.24)

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Annex J
(informative)

Example of defined measuring points

An example of the definition of measuring points is given in Figure J.1.

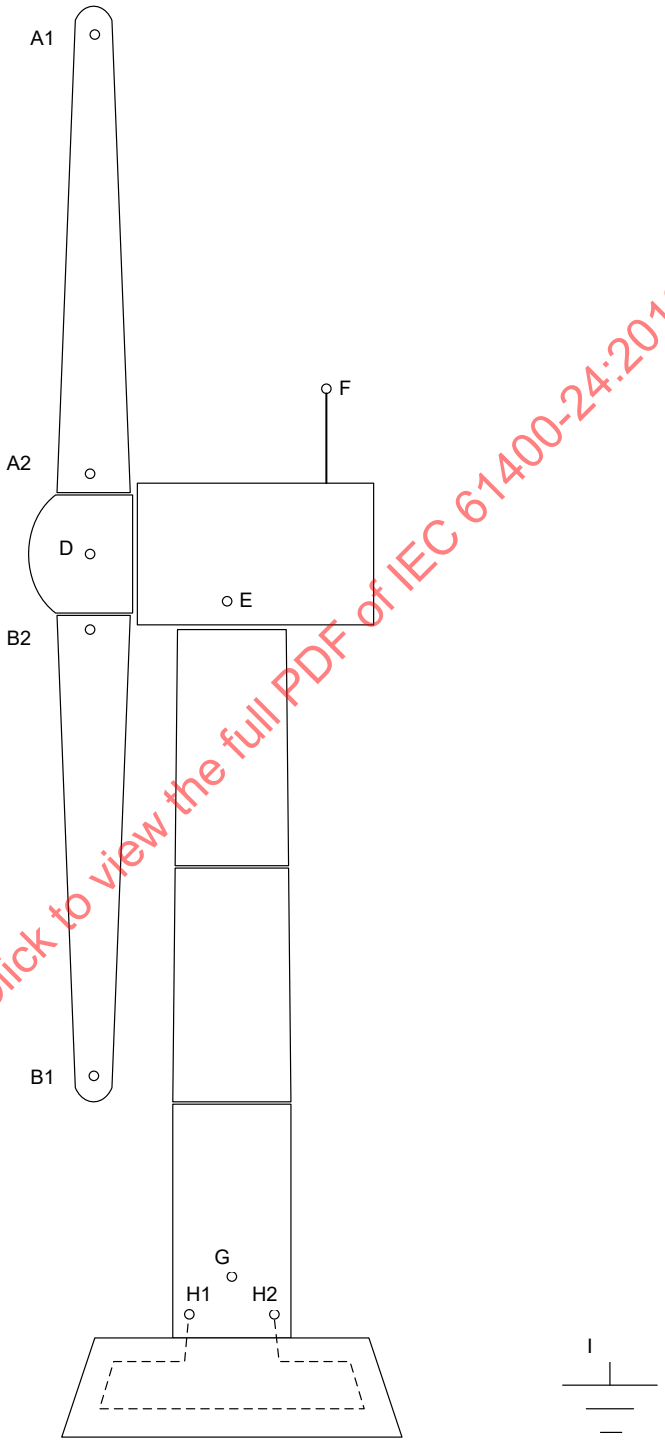

Figure J.1 – Example of measuring points

Following this example, the following measurements can be performed (see Table J.1):

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Table J.1 – Measuring points and resistances to be recorded

Measuring point	Description	Measuring point	Description	Resistance Ω
A1	Air termination point in tip of blade A	A2	Down conductor in root of blade A	
B1	Air termination point in tip of blade B	B2	Down conductor in root of blade B	
A2	Down conductor in root of blade A	D	Rotor hub chassis	
B2	Down conductor in root of blade B	D	Rotor hub chassis	
D	Rotor hub chassis	E	Nacelle chassis – or earthing bar	
F	Air termination protecting wind instruments	E	Nacelle chassis – or earthing bar	
E	Nacelle chassis – or earthing bar	G	Earthing bar in bottom of tower	
H1	Earth connection 1 to foundation electrode	H2	Earth connection 2 to foundation electrode	
G	Earthing bar in bottom of tower	I	Remote earth	

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Annex K
(informative)

Classification of lightning damage based on risk management

K.1 General

Lightning protection of wind turbine including design by manufactures and maintenance by operators should be done from the viewpoint of risk management. It is not reasonable to take a single countermeasure to protect all kind of lightning damage because the levels and aspects of lightning damages range from catastrophic to minor. It is important to understand damage aspects, possible causes and corresponding countermeasures to satisfy both safety and economic requirements.

A wind turbine is made of a large number of components but, for several reasons, the blades are the most critical components with regards to lightning damage:

- the blades are installed at the highest point of the turbine;
- the blades are made of relatively fragile material such as glued and fibre-reinforced plastics;
- blades are some of the most expensive single components in a wind turbine and may be one of the most expensive components to replace; and
- in the case of lightning strikes to the blades, there may be public safety issues with regards to falling debris.

Therefore, considering blade damages is very important for risk management of wind turbines.

In contrast, other components inside a nacelle or tower may be of less concern in relation to public safety, unless mechanical control is lost due to lightning. Countermeasures to protect these components can be treated in a cost-benefit scheme.

K.2 Lightning damage in blade

K.2.1 Classification of blade damage due to lightning

The damage should be categorised into four levels, numbering from the lowest to highest, according to damage and wearing aspects. The highest level of the blade damage is (IV), catastrophic incident, that may cause human injury and/or death, while level (III), serious incident, that requires immediate repair in order to prevent the damage from worsening to level (IV). Level (II) is categorized as a moderate event, that requires repair as soon as possible and the lowest level is level (I), minor event, that does not need repair before the next scheduled maintenance.

Table K.1 shows a classification of damage to wind turbine blades due to lightning with detail aspects of blade damages. In this table the detail aspects of damages is described as follows:

- rupturing – a sudden or immediate separation of a blade into two or more parts, like exfoliation of bond weld between two blade shells and/or large cracks in blade shells,
- falling – a drop of any components of blade onto ground including a whole blade, a part of blade shell, the blade tip, air terminations and so on,
- burnout – loss of the whole or part of the blade due to fire caused by lightning,
- air brake control wire melting – melting and breaking of a control wire for a tip air brake (see C.1.1) owing to large joule energy of lightning current passing through it.

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- down conductor melting – melting and breaking of a down conductor owing to large joule energy of lightning current passing through it,
- sparking between broken wire end – electric discharge owing to lightning between a gap of broken wires,
- cracking – a crack along a bond weld that glue two blade shells together, where the partial bonding remaining keeping the parts together,
- tearing – a part of a blade shell is torn but remains together with the healthy part.
- surface stripping – a small break of fibres on the surface of blade,
- loss of a small part of air terminal (e.g. of a receptor) – a break of part of an air terminal in pieces. If the broken part is substantial and falls onto ground, the event should be categorized as category (IV-d) depending upon the circumstances around the turbine,
- melting – erosion of air terminal due to melting after being attached by lightning with large energy,
- scorching – a change of colour into back of the blade surface.

Table K.1 – Classification of blade damage due to lightning

(IV) **Catastrophic incident** causing possible injury and/or death	
	(IV-a) Blade rupturing and falling
	(IV-b) Blade burnout and falling
	(IV-c) Melting and/or breaking of control wire
	(IV-d) Falling of air terminal or other blade component [a]
(III) **Serious incident** requiring immediate repair	
	(III-a) Cracking along bond weld
	(III-b) Tearing at blade edge
	(III-c) Melting and/or breaking of down conductor
(II) **Moderate event** requiring repair as soon as possible	
	(II-a) Surface stripping
	(II-b) Loss of a small part of air terminal
(I) **Minor event** not requiring immediate repair	
	(I-a) Air terminal melting
	(I-b) Surface scorching
	(I-c) Other minor damages
[a] This event can be considered as (II-b) in case neither residents nor passers-by are likely to be around the wind turbine.	

In the case of offshore turbines and turbines installed in uninhabited areas, the category (IV-d) "Falling or air terminal or other blade component" can be demoted to (II-b) because it may not create a public safety risk. Otherwise, it should be categorized into the highest damage level (IV), catastrophic incident, even if the dropped component is small.

K.2.2 Possible cause of blade damage due to lightning

Possible causes of damages to wind turbine blades due to lightning have been clarified by investigations on past turbine incidents. Most of the incidents classified as (IV), catastrophic incident, have occurred on poor blades such as in case of:

- old blade designs that have tip air brake control wires,
- poor blade designs, such as those with insufficient mechanical bonding of air terminals/receptors to the main body of the blade,

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- blades of poor manufacturing quality, such as with imperfect glue bonding between blade shells,
- poorly maintained blades, such as oversight, neglect or underestimation of past damages.

The cause of blade rupturing and cracking is normally considered to be an overpressure damage owing to the hot lightning arc expanding as a shockwave inside blade cavities or within the blade laminate structures.

K.2.3 Countermeasures against blade damage due to lightning

Corresponding to the possible causes of blade damages, appropriate counter measures are needed. To avoid the level (IV) incidents, that may affect public safety, all involved parties should pay attention to imperfect conditions; for the blade manufacturer, imperfect design and/or installation should be improved and tested in accordance with this document; wind turbine manufacturers should define adequate inspection and maintenance procedures and techniques, for the wind power plant operators to implement.

Figure K.1 shows the recommended countermeasures according to the classification of blade damage due to lightning. Scheme A in this figure denotes the above-mentioned appropriate countermeasures to avoid the level (IV) incidents. Even after implementation of the appropriate countermeasures, incidents cannot be avoided completely, but can be limited to a defined tolerable level. Elimination of all levels of incidents/events should not be aimed at because the effort may not be reasonable and would not be proper risk management.

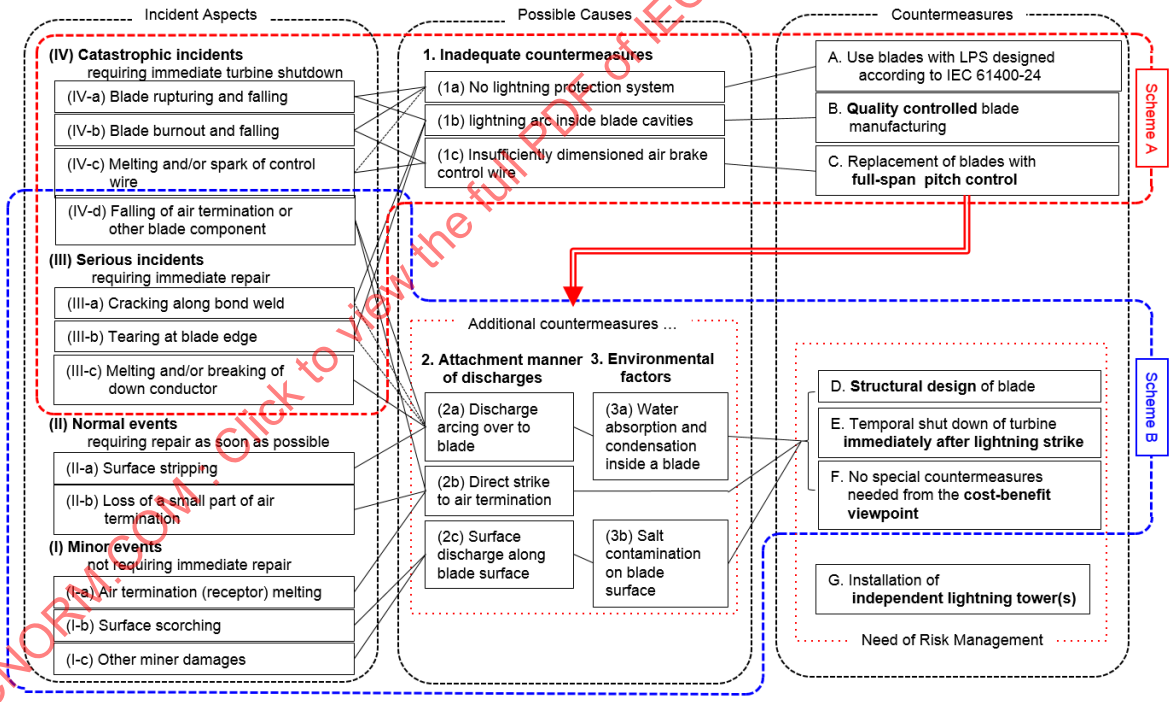

Figure K.1 – Recommended countermeasures schemes according to the incident classification

Temporal shut down of a damaged turbine as shown in Figure K.1 can be the most realistic countermeasure to reduce the total risk of lightning damage. Immediate inspection by skilled service team, or automatic and remote inspection if possible, is recommended before restarting the wind turbine.

Table K.2 also shows a matrix of risks and corresponding countermeasures against blade damage due to lightning, taking risk management into account. This table does not only show risks of damage of blades but also describes the risks of lost profit caused by the stop of

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turbine operation. Note that the length of stoppage does not always depend upon the level of damage, but also depends on maintenance scheme issues such as:

- availability of service personnel who are specialists in wind turbine maintenance,
- availability of spare parts,
- availability of relevant vehicles, lifts, cranes, jack-up vessels etc. as needed to repair or replace damaged parts.

Service and maintenance agreements with suppliers and/or maintenance service providers.

Table K.2 – Matrix of blade damages due to lightning, taking account of risk management

Level		(IV) Catastrophic incident				(III) Serious incident			(II) Moderate event		(I) Minor event		
Damage aspect		(a) Blade rupturing and falling parts	(b) Blade burnout and falling parts	(c) Melting and/or breaking of air brake control wire	(d) Falling of air termination or other blade component	(a) Cracking along bond weld	(b) Tearing at blade edge	(c) Melting and/or breaking of down conductor	(a) Surface stripping	(b) Loss of a small part of an air termination	(a) Air termination melting	(b) Surface scorching	(c) Other minor damages
Risk management (qualitative suggestion)	Possibility of human injury	high				medium			almost none		none		
	Social impact	very high				low			almost none		none		
	Need of blade replacement	yes			none	sometimes yes			almost none		none		
	Assumed repairing method	special crane for blade replacement			crane	gondola or crane			high-place work vehicle		service lift, scaffold or rope work		
	Party responsible for repair	depends on insurance / service / contract / age of blade							qualified service & maintenance provider		qualified service & maintenance provider		
	Estimated repairing cost	very high			low to high	high			medium		low		
	Time to repair	several months			seve-ral days	several weeks			several days		almost no (repaired at periodic maintenance)		
	Lost profits	very high			low to high	high			low		almost none		
	Probability	very low (depends on the area)			low	relatively low			relatively high		high		
	Counter-measure cost	very high			me-dium	medium to high			low to medium		none to medium		

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K.3 Lightning damage to other components

K.3.1 Classification of damage in other components due to lightning

The damage classification of wind turbine components excluding blades can also be categorised in the same manner as the blades. Table K.3 shows the damages classified into four levels with examples of damage aspects.

K.3.2 Countermeasures against lightning damage to other components

Countermeasure against lightning damage to other components can also be done in the same way as that for blades. However, it should be noted that the level (I), minor event, for other components does not always mean that the event does not require immediate repair like in the classification for blades, where the viewpoint of public safety is needed. Neglecting even minor events for monitoring, communication and control devices may represent a risk of a catastrophic incident if the damage causes loss of control of the turbine.

To reduce stoppage time and thereby loss of profit, it is also recommended to use an appropriate maintenance scheme with adequate preparation for unexpected events.

Table K.3 – Classification of damage to other components due to lightning

(IV) **Catastrophic incident**	
e.g.	injury and/or death of people inside/near turbine burnout of nacelle
(III) **Serious incident**	
e.g.	insulation breakdown of generator or transformer break down of bearings
(II) **Moderate event**	
e.g.	breakdown of earthing system insulation breakdown of converter and other power-electronics devices
(I) **Minor event**	
e.g.	insulation breakdown of monitoring, control or communication device

K.4 Typical lightning damage questionnaire

K.4.1 General

The example below is a typical lightning damage questionnaire that may help collect damage data for wind turbines due to lightning. It is important to accumulate statistical data according to the same manner for a long period. It may be also useful to keep communication and share the data with domestic regulators and/or industry associations.

K.4.2 Sample of questionnaire

1. Wind turbine manufacturer:

   Wind turbine operator:

2. Wind turbine type (general description):

3. Specific wind turbine data:

❍ Rating: ..... kW ❍ Hub height: ..... m ❍ Rotor diameter: ..... m
❍ Installation date: .....❍ Other comments:

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4. Turbine location:

❍ Exact position (for example GPS coordinates):
❍ Single wind turbine ❍ Wind turbine in wind farm with ..... no. of wind turbines
❍ Coastal site ❍ Near coastal site ❍ Off shore ❍ Land-based
❍ Raised land (height above the sea): ..... m
❍ Other comments:

5. Weather conditions:

❍ Thunderstorm ❍ Wind: ..... m/s
❍ Temperature: ..... °C ❍ Other:
❍ Rain (severity if known): ..... ❍ Other comments:

6. Time of incident:

❍ Date: ..... ❍ Time: ..... ❍ Approximate accuracy of time:
❍ Other comments:

7. Level of damage due to lightning (in case of blade damage, also check in sub-category)

❍ (IV) Catastrophic incident
  ❍ (IV-a) Blade rupturing and falling
  ❍ (IV-b) Blade burnout and falling
  ❍ (IV-c) Melting and/or breaking of control wire
  ❍ (IV-d) Falling of air termination (receptor) or other blade component (see also footnote in Table K.1)
❍ (III) Serious incident
  ❍ (III-a) Cracking along bond weld
  ❍ (III-b) Tearing at blade edge
  ❍ (III-c) Melting and/or breaking of down conductor
❍ (II) Moderate event
  ❍ (II-a) Surface stripping
  ❍ (II-b) Loss of a small part of air termination (see also footnote in Table K.1)
❍ (I) Minor event
  ❍ (I-a) Air termination (receptor) melting
  ❍ (I-b) Surface scorching
  ❍ (I-c) Other minor damages

8. Suspected lightning attachment point(s):

❍ Blades ❍ Nacelle ❍ Meteorological equipment ❍ Tower
❍ Nacelle lightning conductor
❍ Other:
❍ Other comments:

9. Damaged components:

❍ Hub	❍ Rotor	❍ Main shaft bearing	❍ Pitch bearing
❍ Yaw bearing	❍ Generator bearing	❍ Gear shaft bearing	❍ Gears
❍ Generator	❍ Control system	❍ SCADA system	❍ Power system
❍ Other:		❍ Other comments:	

10. Consequences of lightning damage:

❍ Lost production time: ..... hours ❍ Repair costs (USD/EUR):
❍ Cost of lost electrical production (USD/EUR): .....
❍ Other comments:

11. Turbine lightning protection system details (except blades):

❍ None ❍ Ring earth electrode ❍ Foundation earth electrode
❍ Air termination system (type/location):
❍ Down conductors (type/location):

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Overvoltage/surge protection:
❍ None ❍ Incoming power connection
❍ Generator ❍ External data lines
❍ Internal control lines ❍ Telephone lines
❍ Other comments:

12. Blades and blade lightning protection:

❍ Blade manufacturer: ..... ❍ Blade type (pitch/stall):
❍ One blade ❍ Two blades ❍ Three blades ❍ Other:
❍ Tip brakes fitted

Rotor movement at time of stroke:
❍ Standstill ❍ Rotating ❍ Unknown

Rotor blade material:
❍ GFRP ❍ CFRP ❍ GFRP/CFRP ❍ Wood laminate
❍ Solid wood ❍ Other:
(GFRP = glass fibre reinforced plastic. CFRP = Carbon fibre reinforced plastic)

Lightning protection type:
❍ Receptor at tip (material): ..... ❍ Tip cap (material):
❍ No lightning protection ❍ Other:

Blade down conductor:
❍ External ❍ Internal
❍ Cross-sectional area: ..... mm ❍ Material: .....
❍ Other comments:

Observed damage:
❍ No blade damage ❍ Hole in blade: ∅ ..... mm
❍ Crack in blade face (length): ..... ❍ Crack in blade edge (length):
❍ Other: .....
❍ Other comments:

13. Downtime and repairing cost:

❍ Downtime: ..... days
❍ Estimated repairing cost: USD/EUR .....
❍ Reason for long downtime and/and high repair cost (if applicable):

Please mark the locations where damage has been observed on the blade (see Figure K.2):

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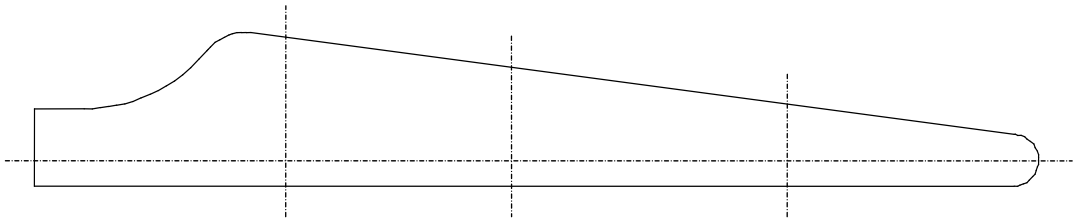
❍ Windward side:



❍ Leeward side:

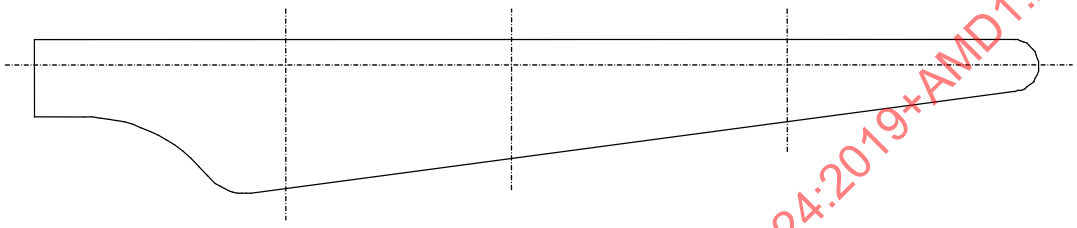


Figure K.2 – Blade outlines for marking locations of damage

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Annex L
(informative)

~~Monitoring systems~~ Lightning detection and measurement systems

~~It is recommended that wind turbines be equipped with equipment to detect lightning strikes/monitor the current levels of such lightning strikes. The purpose of such systems is to:~~

- ~~provide information to the operator on the level of lightning strikes that have affected the wind turbine and to give input to operation and maintenance regimes;~~
- ~~provide valuable data on lightning strikes to wind turbines and to assess the lightning magnitude/characteristics, contributing to risk assessment processes.~~

~~Various options for monitoring systems exist. A brief description of these options follows below.~~

~~a) Wide area lightning detection systems~~

~~Many commercial systems allow the detection of lightning using antennae that detect the electromagnetic impulse produced by a lightning flash. Such systems use multiple antennae to locate lightning flashes based on direction finding, time of arrival or interferometric techniques. Data from these systems is generally available in real time.~~

~~It is important for the user of data from a wide area lightning detection system to know several parameters that affect the performance of the system. Considerations relevant for wide area lightning detection systems are listed in Table L.1.~~

~~Table L.1 – Considerations relevant for wide area lightning detection systems~~

~~Parameter~~	~~Considerations~~
~~Detection efficiency (DE)~~	~~One of the parameters is the detection efficiency (DE). Flash DE and stroke DE are differentiated. Since a lightning flash is composed by one or several strokes, flash DE (DE_f) is typically higher than stroke DE (DE_s). It is important to note that lightning detection systems detect strokes and the grouping of strokes into flashes is done according to some criteria. These criteria should be known or defined by the user. DE depends on several parameters such as the number of sensors available, the distances between sensors and the geometry of the sensor positions around the point of interest; the performance of the sensors (e.g. noise level at each sensor site, availability, etc.); the number of sensors required and used for detection; and several other parameters. Relative DE of a network can be obtained by analyzing the current distribution at the point of interest and at a reference location (e.g. center of the network).~~
~~Location accuracy~~	~~The location accuracy of such systems can be limited to from a few hundred metres to a few kilometres. Location accuracy for an individual stroke depends, among some other factors, on the current parameters of that particular stroke and the network performance at the point of interest. Hence location accuracy is not constant for all the strokes and at all the locations of the point of interest.~~
~~Information about the data~~	~~Location accuracy and DE also depend on the settings of the data process used for determining a solution (stroke location and parameters). Since lightning data can be used for several purposes, the user of lightning data should agree with the lightning data provider about the type of data to receive depending on the purpose. As an example, very high location accuracy is not necessary for lightning warning purposes but a good DE_s or capability of detecting intra cloud lightning can be convenient.~~ ~~Some lightning data providers apply different filters to the data. This information should be provided to the user.~~

~~b) Local active lightning detection systems~~

~~Special systems, e.g. with sensors mounted on the tower of a wind turbine to trigger a lightning alarm based on electromagnetic or optical criteria. The sensor prevents remote lightning flashes from triggering a false alarm. Such systems can be connected to a SCADA system giving a useful indication of lightning strikes in real time. The systems may or may not give an indication of current waveform or magnitude, and if placed on the tower, the system would not give an indication of the location of the lightning attachment on the wind turbine. It is, however, a good option for an operator who wishes to be proactive in monitoring wind turbines after a lightning storm. Considerations relevant for local active lightning detection systems are listed in Table L.2.~~

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Table L.2 – Considerations relevant for local active lightning detection systems

Types	Considerations
Systems intended for alarm	Systems designed according to IEC 62561-6 might not be suitable for wind turbines because they are designed for standardized lightning impulses. These systems should be sensitive enough with a suitable low frequency response. The manufacturer should provide the frequency response of the sensitivity.
Current measurement systems: shunts	Current shunts typically provide the best frequency response from DC to several MHz. In wind turbines the size of the current shunt limits its use. Since current shunts are part of the down conductor system they should be tested as part of the down conductor at LPL I. The manufacturer should provide calibration information.
Current measurement systems: Rogowski and optic	Sensors based on Rogowski coils or optics (e.g. Faraday rotation principle) should have an appropriate bandwidth. The manufacturer should provide the frequency response of the system. The system should be designed to measure as much as possible of the continuing currents. Manufacturer should provide calibration information.

c) Local passive lightning detection systems

Lightning counters and peak current sensor cards (PCS) provide a minimal information about lightning events to a wind turbine. The most simple lightning counters (e.g. electromechanical) just provide the number of strikes. Electronic lightning counters also provide time stamp and estimation of lightning parameters. Peak current sensor cards provide an estimation of the maximum peak current for the time period since the sensor was installed.

Table L.3 – Considerations relevant for local passive lightning detection systems

Types	Considerations
Lightning strike counters	Lightning counters designed in accordance with IEC 62561-6 are not suitable for wind turbines because they are intended for standardized lightning impulses. Some lightning counters also estimate one or several current parameters: peak current, charge, specific energy. Devices designed for the standard lightning currents (e.g. IEC 62561-1) will not provide realistic data for all the strikes. The manufacturer should define test waveforms including continuing currents. The manufacturer should provide the reference waveforms and the uncertainties. The manufacturer should provide information about the frequency response of the sensitivity and uncertainty of the estimated parameters. Lightning counters for wind turbines should be as sensitive as possible at low frequencies in order to detect upward lightning. Manufacturer should provide the sensitivity versus frequency curve.
Peak current sensors	This type of sensors designed and calibrated only with the standard lightning current waveforms might not be suitable for the registration of real lightning currents. The manufacturer should provide information about the performance of the sensor at typical lightning currents of wind turbines. The manufacturer should provide information about the minimum detectable current and the tested waveforms. This type of sensors might not be suitable for detecting continuing currents. The manufacturer should provide the frequency response of the sensitivity and its uncertainty.

Users should be careful interpreting the information provided by the manufacturers of these types of devices. The user should know the frequency response of the device in order to obtain a conclusive result, otherwise the data might not be realistic.

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L.1 General

L.1.1 Purpose

It is recommended that wind turbines are equipped with systems capable of detecting lightning, measuring its current components, and processing the parameters of the lightning strikes. The purpose of such systems is to:

- provide information to the operator on the occurrence of lightning strikes to the wind turbine and to give input to operation and maintenance regimes;
- provide valuable data on lightning strikes to wind turbines thus allowing post-assessment of the lightning magnitude/characteristics and contribution to the operator's risk assessment processes;
- enable the operator to compare the measured current parameters of lightning strikes to the lightning protection level, LPL, used for designing the wind turbine lightning protection system (e.g. for assessing if the lightning current intercepted by the LPS is below or above the values defined in Table 1);
- avoid hazardous activities such as maintenance when there is a risk of lightning strike.

L.1.2 Nomenclature

The following nomenclature applies to this annex.

a) Thunderstorm warning systems (TWS), composed of thunderstorm detector(s) able to monitor the lightning or upcoming lightning activity and tools for processing the acquired data to provide a valid alarm (warning). They are based on local sensors (either based on electrostatic or electromagnetic fields), a group of local sensors or lightning location systems (LLS).

b) Lightning measurement systems (LMS) measuring lightning events and their features with devices installed on the turbine. These systems range from a combination of simple electromechanical event counters to complex systems measuring and analyzing lightning parameters.

L.2 Benefits of lightning detection and measurement systems

There are many benefits of measuring actual lightning exposure. Depending on the specific stakeholder, a non-exhaustive list is included in Table L.1, Table L.2 and Table L.3. The industry is encouraged to share lightning data across all stakeholders (OEM/Owner/Insurance), to ensure benefits across the entire value chain.

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Table L.1 – Considerations and benefits for the OEM (original equipment manufacturer)

Statement	Value aspect
For turbines delivered with long service contracts, the OEM (Original Equipment Manufacturer) with a service contract would like to know when the receptor/LPS has reached the design lifetime and needs to be replaced. This can be achieved by monitoring the accumulated charge and specific energy for each blade and correlating with test performance of the receptor/LPS.	This enables condition-based maintenance or repair, lowering downtime and unexpected damage costs significantly. Maintenance is cheaper than repair.
The OEM would like to know all information of strikes, to determine the efficiency of the receptors/LPS (the observed number of strikes intercepted correctly divided by the total number of strikes to the turbine/blade observed – see 3.12).	This information is used to market the OEM products, *"with a field efficiency of XX%, our turbines comply fully with YY".*
Every strike will be different, and cross correlating strike information with other sensor signals can provide valuable information to the OEM to fully understand the turbine operation and design performance.	Get more information on the lightning susceptibility of the turbines, to enable stronger and cheaper designs for future turbines.
Turbine LPS have developed intensively during the past 10 years to 20 years, and OEMs are still following different paradigms for the design and verification air terminations, down conductors and lightning coordination with additional conductive components like CFRP. If a blade design, known from verification tests or modelling, is challenged by certain features of the lightning current, an active monitoring of the lightning exposure will allow targeted maintenance. Not all lightning strikes exhibit the same strike parameters, hence the consequence of strikes will differ.	By measuring all strikes in field, evaluating the strike parameters, and comparing them to design performance from laboratory tests and/or modelling verification, the consequence of specific strikes can be assessed. By evaluating the consequence of each lightning event, maintenance and inspections can be tailored and optimized.
In case lightning damages occur, the detailed measurements of the lightning parameters can be used to assign and split the cost of repair between OEM and owner/operator.	Enable the discussion on splitting costs of blade damages based on lightning impact.

Table L.2 – Considerations and benefits for owner and/or operator

Statement	Value aspect
The operator would like to know if a lightning flash exceeded IEC LPL current parameters to which the turbine has been certified as this is useful information in relation to warranty and insurance.	Lightning damage is paid by the responsible party.
The owner and/or operator would like to know if a lightning flash was potentially dangerous to the turbine.	In case the measurement can be used to identify a strike as representing a risk, the turbine could be checked (online or on site) before it is restarted. This could prevent further damage on the turbine.
The owner and/or operator would like to know when the receptor and/or LPS has reached the design lifetime and needs to be replaced. This is performed by monitoring the accumulated charge and/or specific energy in each blade and correlating it with the receptor and/or LPS performance as proven by testing according to Annex D. Additionally, the collection of lightning exposure will enable a determination of potential LPS performance degradation.	This enables condition-based maintenance/repair, lower downtime and unexpected damage cost significantly. Maintenance is cheaper than repair.
A correlation of lightning performance across large fleets with LMS will provide knowledge on the performance of a specific design and enable customisation of the LPS design to specific site conditions (altitude, lightning regime, number of WTs in the WF, etc.).	Enable the owner to select turbines with documented good experience on the lightning performance, as required by the specific site.
Every strike will be different, and cross correlating strike information with other sensor signals can provide valuable information to the owner and/or operator to fully understand the turbine operation and design performance.	Get more information to support condition-based maintenance strategies.
In case lightning damages occur, the detailed measurements of the lightning parameters can be used to assign and split the cost of repair between OEM and owner/operator.	Enable the discussion on splitting costs of blade damages based on lightning impact.

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Table L.3 – Considerations and benefits for the Insurance company

Statement	Value aspect
Sites with severe lightning exposure will potentially have more downtime to allow for extra service and maintenance, and the damage rate in terms of failures per year could also be larger. The insurance company could customize the insurance tariff according to site conditions in terms of challenging lightning activity, such that sites experiencing significant lightning activity could be priced higher than sites with limited lightning activity.	Utilizing a dynamic insurance premium, where that insurance premiums scale with documented lightning activity, would allow the insurance company to target the premiums more correctly to the risk.
A correlation of lightning performance across large fleets will provide knowledge of which designs work well and which designs don't for similar lightning environments. Since the lightning environment is documented by LMS, a correlation between insurance claims and LMS data will provide the needed information (e.g. protection efficiency of the LPS).	Optimize insurance premiums and exclude designs with poor performance, to eventually optimise the insurance business.
A blade certified according to IEC/RE OD-501 (referencing to IEC 61400-24 for lightning matters) eventually means that the turbine should be able to continue operation without the need of repair until next scheduled maintenance; see 8.2.2. An additional perception is that strikes outside the range of the LPL are disregarded. In both cases, knowledge on the actual strike data is useful for deciding the insurance coverage.	Qualify discussion of insurance coverage by providing actual lightning strike data.
In the event that blades suffer damages due to lightning, a discussion on insurance coverage can be assisted by accurate measurements. The insurance companies could require the installation of proper LMS to quantify the lightning exposure (current magnitude, specific energy, flash charge, accumulated charge, di/dt, etc.).	Discussions on lightning exposure can be eliminated once suitable LMS complying to industry standards are used efficiently.

L.3 Lightning detection and measurement systems

L.3.1 General

Lightning detection and measurement systems are devices that provide information about lightning affecting wind turbines. By detecting the presence of lightning strikes on and/or around the wind turbine, different strategies for optimized operation or maintenance of the turbines can be implemented.

Brief descriptions of the different options are given below.

L.3.2 Lightning detection systems

IEC 62793 describes sensors and networks of sensors (including LLS) able to provide real-time information on the risk of lightning strikes. Sensors measuring electrostatic field detect lightning related conditions and are usually employed as local detectors since they measure the formation, approach or dissipation of the thunderstorm in the area where they are installed.

Sensors measuring electromagnetic field produced by lightning strokes can be used as standalone detectors or used in networks. LLS use multiple antennae to locate lightning strokes based on direction-finding, time of arrival, or interferometric techniques. Data from these systems are generally available in real-time according to IEC 62793 requirements.

It is important for the user of data from TWS to know several parameters that affect the performance of the system. Considerations relevant to lightning detection systems should be compliant in full with IEC 62793.

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L.3.3 Lightning measurement systems (LMS)

L.3.3.1 General

Lightning measurement systems are devices that provide information about lightning strikes on a wind turbine by measuring various parameters caused by that lightning strike (e.g., current magnitude, specific energy, flash charge, accumulated charge, di/dt, transient magnetic fields generated by lightning currents flowing through down conductors including the tower).

L.3.3.2 Lightning event counters and peak current sensors

Lightning counters and peak current sensor cards (PCS) provide minimal information about lightning events to a wind turbine. The simplest lightning counters (e.g. electromechanical) just provide the number of strikes. Electronic lightning counters can also provide time stamp and estimation of lightning parameters. Peak current sensor cards provide an estimation of the maximum peak current for the time period since the sensor was installed. Considerations relevant for lightning event counters and peak current sensors are listed in Table L.4.

Table L.4 – Considerations relevant for lightning event counters and peak current sensors

Types	Considerations
Lightning strike counters	Lightning counters designed in accordance with IEC 62561-6 could not be suitable for wind turbines exposed to large fractions of upward lightning. Some lightning counters also estimate one or several current parameters: peak current, charge, specific energy. Devices designed for the standard lightning currents (e.g. in IEC 62561-6) will not provide realistic data for all the strikes. The manufacturer should define test waveforms including continuing currents. The manufacturer should provide the reference waveforms and the uncertainties. The manufacturer should provide information about the frequency response of the sensitivity and uncertainty of the estimated parameters. The measurement capability of lightning counters used in wind turbines should demonstrate sensitivity to upward lightning. Manufacturer should provide the sensitivity versus frequency curve.
Peak current sensors	This type of sensors designed and calibrated only with the standard lightning current waveforms is not suitable for the registration of real lightning currents. The manufacturer should provide information about the performance of the sensor at typical lightning currents of wind turbines. The manufacturer should provide information about the minimum detectable current and the tested waveforms. This type of sensors is not suitable for detecting continuing currents. The manufacturer should provide the frequency response of the sensitivity and its uncertainty.

Users should be careful interpreting the information provided by the manufacturers of these types of devices.

L.3.3.3 Local lightning current measurement systems

Special systems, e.g. with sensors mounted on the tower and/or in the blades of a wind turbine to trigger a lightning alarm based on electromagnetic or optical criteria are called local lightning current measurement systems. The sensor measures what actually strikes the turbines and prevents remote lightning flashes from triggering a false alarm. Such systems can be connected to a SCADA system giving a useful indication of lightning strikes in real-time. The systems could give an indication of current waveform and strike severity and can hence be used by operators to evaluate the degree of wear and damage, and to prepare maintenance for the relevant turbines after a lightning storm.

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The lightning parameters which individually or in combination are closely related to the wear of the lightning protection system and/or damages of the wind turbine are the current magnitude, total charge transfer, specific energy and front time of the lightning current, etc. Whether these parameters can be measured accurately depends largely on the frequency response and resolution of the system.

The subclauses below highlight important features of local lightning current measurement system to effectively capture the desired outcome of the lightning strikes.

L.3.3.4 Classifications

The characteristics of lightning current such as the current magnitude, charge, specific energy and front time, etc. vary and could depend on the installation areas. Therefore, it is recommended to investigate available information about characteristics of lightning currents for the installation area when selecting the lightning measurement system to actually meet the expected performance. To aid the selection, local lightning current measurement systems are classified into four types according to the measurement performance and hence the adequacy of measuring the different lightning characteristics. The classification is shown in Table L.5.

Table L.5 – Requirement for each class of lightning measurement systems

Category	Range	Class I	Class II-PC	Class II-EC	Class III
Frequency bandwidth[a]	0,1 Hz to 1 MHz or wider	×			
	1 Hz to 1 MHz or wider		×		
	0,1 Hz to 100 kHz or wider			×	
	1 Hz to 100 kHz or wider				×
Maximum measurable current value[b]	200 kA or higher	×	×		
	100 kA or higher			×	×
Maximum measurable electric charge value[c]	1 000 C or higher	×		×	
	600 C or higher		×		×
Minimum detectable current value[d]	1 kA or lower	×		×	
	2 kA or lower		×		×
Digital resolution[e]	16 bit or higher	x			
	12 bit or better		x	x	
	8 bit or higher				x
Observation period[f]	0,5 s or longer		×		×
	1 s or longer	×		×	

[a] A high upper cut off frequency allows measurement of short stroke pulses, a low lower cut off frequency ensures measurement of long strokes.

[b] Upper boundary for current detection, only Class I and Class II-PC ensures measurement of LPL1 current magnitude.

[c] Sites exposed to winter lightning should consider the risk of large charge transfer.

[d] ICC strokes could transfer significant amount of charge at current magnitudes less than 1 kA. This charge transfer will add to the erosion of air terminations, which is why a minimum measurable current should consider this.

[e] Digital resolution is important when measuring small current signals with a system having a large dynamic range.

[f] Especially UW lightning and/or bipolar events are known to persist for up to 1 s and above.

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A guidance on the suitable classes of measurement systems is provided below:

Class I: Suitable for measuring all quantities of a lightning strike

Class II-PC: Focus on measuring the peak current (PC) of the lightning strike

Class II-EC: Focus on measuring the electric charge (EC) of the lightning strike

Class III: Limited measurement performance

Class IV: Any lightning measurement systems not complying with Class I-III

The classification of a lightning measurement system follows the lowest classification in any of the categories, i.e. a LMS complying with class I in five out of six categories, but only to Class II-PC in one category, is classified as Class II-PC.

L.3.3.5 Properties of lightning measurement systems

L.3.3.5.1 General

Several properties of a lightning measurement system for a wind turbine are important for ensuring that expectations are met, including the electrical properties of the front-end measuring system, the quantities which are recorded and stored by the system, and the ability to interface to the turbine or operator SCADA system. The following is a non-exhaustive informative list of topics to consider. The following subclauses of L.3.3.5 are a non-exhaustive informative list of topics to consider.

L.3.3.5.2 Electrical performances

L.3.3.5.2.1 Detection method

The front end of the lightning measurement system defines the detection method. Several principles exist ranging from full current measurements in individual blades, full current in the tower, or partial current measurement in earthing systems. When measuring lightning current in wind turbines, it is important to consider that the structure itself could affect the current measurement. This appears due to impedance mismatch at interfaces between blade and nacelle, and/or tower and ground. The result can be reflections in the measured lightning current, which are still part of the actual current component affecting the turbine but would not be present if the lightning current could be measured without the turbine.

Most of the systems that measure the lightning current flowing through the LPS (air termination, down conductor, tower and earthing system, etc.) and hence detect lightning strikes on wind turbines use various current sensors (Rogowski coil, CT, solenoid coil, resistive shunt, etc.) to measure the above-mentioned lightning parameters.

The manufacturer should specify the detection method used, the applicability of the chosen detection method for the frequency range considered, and for systems measuring partial current in the earthing system, the manufacturer should ensure that the current share is well defined across the frequency range stated.

L.3.3.5.2.2 Current detection frequency bandwidth

The current detection frequency bandwidth (the frequency bandwidth with a gain characteristic between –3 dB and +3 dB) should be defined by the manufacturer. Since lightning current is known to exhibit a wide range of frequencies from short strokes at downward lightning to long strokes experienced as ICC or winter lightning, the frequency range should be chosen for the application.

L.3.3.5.2.3 Observation period

The observation period, or total time of recording and processing, should ensure that the entire duration of the expected lightning flashes is covered.

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L.3.3.5.2.4 Minimum detectable current value

The minimum detectable current magnitude is the magnitude that the LMS can measure reliably relative to noise floor, DC offset, dynamic range, etc. ICC strokes are known to transfer significant amount of charge at low current magnitude; hence a small minimum detectable current is desirable at sites experiencing upward lightning and lightning during cold seasons, and in particular when the turbine design is prone to damages resulting from excessive charge transfer.

L.3.3.5.2.5 Maximum measurable current value

The maximum measurable current magnitude should reflect the risk of observing such strikes in field. For areas exposed to mainly low magnitude strikes (cold season winter lightning), 100 kA for the full lightning current could be sufficient [2], whereas the general ability of justifying exposure within the LPL I range as specified in Clause 8 requires a LMS capable of measuring the full lightning current of at least 200 kA.

L.3.3.5.2.6 Resolution

The resolution of the current measurement within the dynamic range is a measure of how well the current waveform is digitized in discrete steps. A high resolution means that the current magnitude is discretized in small steps, such that even small magnitude events like ICC can be measured and the associate charge transfer can be accurately calculated.

L.3.3.5.2.7 Measurement of electric charge

The charge transfer of the entire lightning flash is associated with the erosion of metal surfaces at the arc root, and damages of sliding rail interfaces, bearings and other moving parts along the lightning path. The charge is calculated by the time integral of the current, and its accuracy and minimum/maximum parameters will therefore depend on both the dynamic range (maximum and minimum detectable current magnitude), the resolution, the observation time and the sampling rate. For areas exposed to long strokes transferring significant amounts of charge (winter lightning during cold seasons), the LMS should be capable of measuring the extensive charge levels.

L.3.3.5.2.8 Trigger process

The trigger process is the mechanism in a lightning detection system at which the recording of the lightning current is triggered. The trigger process can be defined by the current magnitude, certain waveform features, magnetic fields, or a combination thereof. The overall goal of the trigger process is to ensure a reliable discrimination of lightning events over false positives.

Some LMS have a fixed and high trigger level chosen to ensure a reliable triggering in the event of what is perceived as real lightning strikes and to avoid too many false alarms, which could result in low current amplitude lightning events being neglected, whereas other systems provide a customizable trigger level enabling the user to also measure small magnitude lightning events. Small trigger levels will provide a high number of events, since also induced current and aborted leaders are measured, whereas higher trigger levels could miss the recordings of ICC potentially transferring significant amount of charge.

The manufacturer should specify the fixed trigger levels or the options of customized trigger levels.

L.3.3.5.2.9 Measurement accuracy and tolerances

The manufacturer should specify the measurement accuracy for the current measurement system, and the measurement tolerances with regards to the different key parameters as peak current, specific energy, charge, and current gradient. The accuracy should be specified and

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verified within the relevant range of the different parameters, potentially by executing lightning current tests using principles from Annex D.

Information on calibration intervals and procedure should be provided.

L.3.3.5.2.10 Electromagnetic compliance

The LMS should be compliant with the lightning environment and remain operational during the event. The performance should be documented by demonstrating compliance with relevant EMC standards and tests, as described in the IEC 61000 series.

L.3.3.5.3 Recording of lightning information

L.3.3.5.3.1 General

The important information of the lightning strike should be recorded and stored for tailoring maintenance and inspection intervals or aiding the discussion of liability in the event of damages.

L.3.3.5.3.2 Time of lightning strike

The time of the lightning strike is recorded, and if a correlation with other sensor systems is desired, the accuracy should in general be within 0,1 s. The method of reading the time should be specified by the manufacturer, and could range between ground positioning system (GPS) synchronized time stamps, network time protocol (NTP) synchronized time stamps, internal clock with manual synchronization, etc.

The manufacturer should specify the time zone used.

L.3.3.5.3.3 Lightning key parameters

The important lightning key parameters for the intended application should be recorded and stored, potentially including maximum current value, electric charge transfer, specific energy, strike polarity, strike direction of initiation, di/dt, etc.

For sites exposed to a lightning environment with charge transfer during long strokes, the accumulated charge transfer could also be very important to evaluate lifetime of air terminations, etc.

L.3.3.5.3.4 Current waveform

For additional analysis of the lightning impact to the blade, or for validation of the calculated key parameters, the current waveform itself can be valuable to record. The manufacturer should specify whether the current waveform is recorded as well as the resolution and the sampling rate of the recording.

L.3.3.5.4 Interface properties

L.3.3.5.4.1 General

Besides the measurement properties of the active lightning detection systems, another important feature is how it interfaces to the turbine, to turbine SCADA systems, operator SCADA systems, customer cloud solutions, etc.

L.3.3.5.4.2 Alarm output

Many systems feature the option of an alarm output to notify the operator when a lightning event has occurred. For some systems, the alarm output is set to trigger at a lightning event whereas other systems enable a trigger output when one or more of the key parameters exceed a predefined threshold level.

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The manufacturer should specify the alarm output options, whether it triggers on the lightning event or a key data trigger threshold, or a combination of trigger thresholds (current magnitude, charge, accumulated charge, specific energy, etc.) has been exceeded.

The alarm output may be electrical, optical, wireless, etc.

L.3.3.5.4.3 Communication interface

Several options for communicating the measurements exist:

– online system where data is transferred to an external cloud solution;
– online system where data is transferred to the operator SCADA system;
– online system where the data is transferred to the local turbine SCADA system;
– offline system, where lightning recordings are only accessible at the turbine;
– other systems not covered by the above.

The manufacturer should specify the options for communication with the lightning measurement system.

L.3.3.6 Installation and commissioning

The method of installation and commissioning should be provided by the manufacturer, to ensure a durable installation with respect to the location within the turbine and specific site conditions. If the LMS utilizes conductive elements in the blade, the designer/installer should ensure that it doesn't compromise the lightning protection coordination.

Working instructions and maintenance manuals should be part of the manufacturer's documentation.

L.3.3.7 Operation flow chart

The operation flowchart should be developed by the user in collaboration with the blade designer, to ensure that actionable information is provided by the LMS. A simple example is shown in Figure L.1, where the evaluation of current magnitude and secondly charge transfer decides if an alarm is raised.

Depending on the LMS capabilities and measurement accuracy provided, other combinations of insight providing actionable information can be defined: measurement of accumulated charge correlated with results from verification tests of the present LPS will identify the expected wear of air terminations, current magnitude and di/dt provide insight on induced voltages and differential voltage distribution, specific energy provides insight on electrical loading of connection components and equipotential bonding, the number of lightning events attaching to one turbine relative to others could affect inspection plans, etc.

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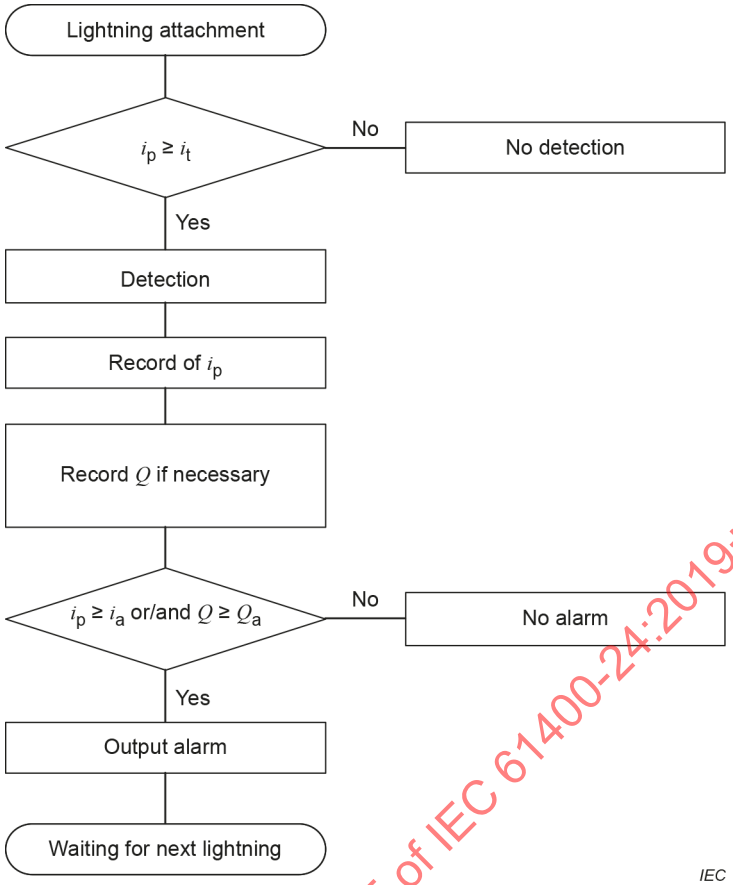

Key

i_p maximum value of detected lightning current

Q electric charge value of detected lightning

i_t trigger current value

i_a alarm current value

Q_a alarm electric charge value

Figure L.1 – Example of flow chart for lightning detection and alarm output for LPS designs sensitive to charge transfer

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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 1 000 V AD or 1 500 V DC for both on-grid and off-grid application. This class of wind turbine is known as small-scale or microgeneration. These are typically designed for domestic or light industrial applications where the power will primarily be intended for use on-site. Although there may be an ability to export excess power to the local electrical grid, these wind turbines only generate at LV and never at the MV levels which industry-scale turbines generate.

The lightning exposure and environments for small wind turbines are very different from larger wind turbines and therefore the requirements and guidelines for lightning protection will also be quite different.

The issue of lightning protection should still be considered for small wind turbines. The main issue is to provide transient protection of grid connection and communication and control system connections (if any), in order to ensure that the systems can continue to operate after being exposed to the high transient voltages and currents associated with lightning transients originating within the wind turbine. Direct lightning strikes to small wind turbines will be relatively rare, unless placed very high and exposed. However, the systems need to remain safe, both in terms of maintaining physical integrity and not causing injury to people or damage property if structures break off and also in terms of avoiding the fire hazard or damage to the electrical system to which the turbine is connected.

Even though this document 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.

Direct testing using high voltage and high current will be very instructive in helping to design the lightning protection system (see Annex D regarding test methods). Components such as blades, anemometers and the generator housing can be tested, and the electrical circuitry and control system can be tested for resistance to effects of transient current surges. The ultimate lightning protection solution may incorporate a lightning rod reaching above the rotor and equipotential electrical bonding and some form of surge protection device (SPD), which should again be validated for effectiveness by testing.

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Annex N
(informative)

Guidelines for verification of blade similarity

N.1 General

As described in 8.2.3, the lightning performance of wind turbine blades should be verified. The first item in 8.2.3 describes the use of high voltage and high current tests, conducted as described in Annex D, and once these tests have been passed for a specific blade design, the requirements of the document are fulfilled. Often, the combination of numerical methods to assess current and voltage distribution are used in combinations with laboratory testing in different stages of the design, but the full scale experimental verification is the final proof of compliance.

For alternative blade designs – or new revisions of existing designs – which differ by the blade 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 the same. The specific issues to evaluate when claiming similarity is an agreement between the blade manufacturer, the customer and/or the certifying body, hence the following list presents examples of topics to consider in the evaluation.

N.2 Similarity constraints

The comparison assumes that the original blade, 'blade 1' has previously been successfully verified following the guidelines in the present document, i.e. by passing all HV and HC tests described in Annex D. The comparison then describes how the new but similar blade, 'blade 2', is designed and dimensioned relative to blade 1.

The comparison only covers blades without additional electrical installations, i.e. blades utilising structural materials of GFRP and CFRP, and an LPS consisting of an air termination system and a down conductor layout. Blades containing additional electrical installations (sensors, heating, active flow control, etc.) cannot be verified by claiming similarity, and the design evaluation and lightning performance should therefore rely on a thorough analysis and test sequence.

To claim similarity of two different blade designs concerning the lightning protection coordination, the following items should be checked and verified (Table N.1). Refer to Figure N.1 for definition of blade aerofoil nomenclature.

Testing is required in the case of changes that will significantly affect the susceptibility of the design to lightning damages.

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Table N.1 – Items to be checked and verified when evaluating similarity

Statement		Yes	No
1. Design			
1.1	Does the laminate thickness in the outermost 5 m of Blade 2 vary by more than 30 % relative to Blade 1?		
1.2	Does the spanwise layup (radius where the layers end) of laminate and core materials on Blade 2 vary more than 10 % relative to Blade 1 for the outermost 5 m?		
1.3	Is the chord length of Blade 2 within 20 % of the chord length of Blade 1 for the outermost 5 m of the blade?		
1.4	Is the aerofoil thickness of Blade 2 within 25 % of the aerofoil thickness of Blade 1 for the outermost 5 m of the blade?		
1.5	Is the LPS concept (type of air terminations, down conductors, connection components, equipotential bondings, quantity of LPS components, dielectric strength of insulation materials, insulation thicknesses) the same for Blade 2 as for Blade 1?		
1.6	Is the number of air terminations the same on Blade 2 as for Blade 1 concerning the outermost 15 % of the blade length?		
1.7	Is the position of air terminations measured from the tip of the blade within 10 % on Blade 2 as for Blade 1 concerning the outermost 15 % of the blade length?		
1.8	Is the insulation coordination concerning the insulation of down conductors made similarly for Blade 2 as for Blade 1 (insulation thickness does not vary more than 10 %)?		
1.9	Is the blade area definition in accordance with Annex E.1 the same for Blade 2 and Blade 1?		
2. Materials			
2.1	Is Blade 2 made of the same materials as Blade 1 concerning the main structural geometry, GFRP or CFRP?		
2.2	Is the resin system used in Blade 2 the same as the resin system used for Blade 1?		
2.3	Is the material of the of tip air termination(s) on Blade 2 the same as that of Blade 1 (same metal base materials in alloys)?		
2.4	Is the material of the of side air termination(s) on Blade 2 the same as that of Blade 1 (same metal base materials in alloys)?		
2.5	Is equipotential bonding between parallel conductive paths made in the same blade radii for Blade 2 as for Blade 1, relative to the total blade length of the specific blade ± 10 %?		

If all questions are replied with a 'Yes', the lightning protection system in the two blades may be claimed to be similar and the verification of Blade 2 can be based on a successful evaluation of Blade 1. If single or a few points deviate, the differences should be assessed in detail to ascertain functional similarity is fulfilled anyway.

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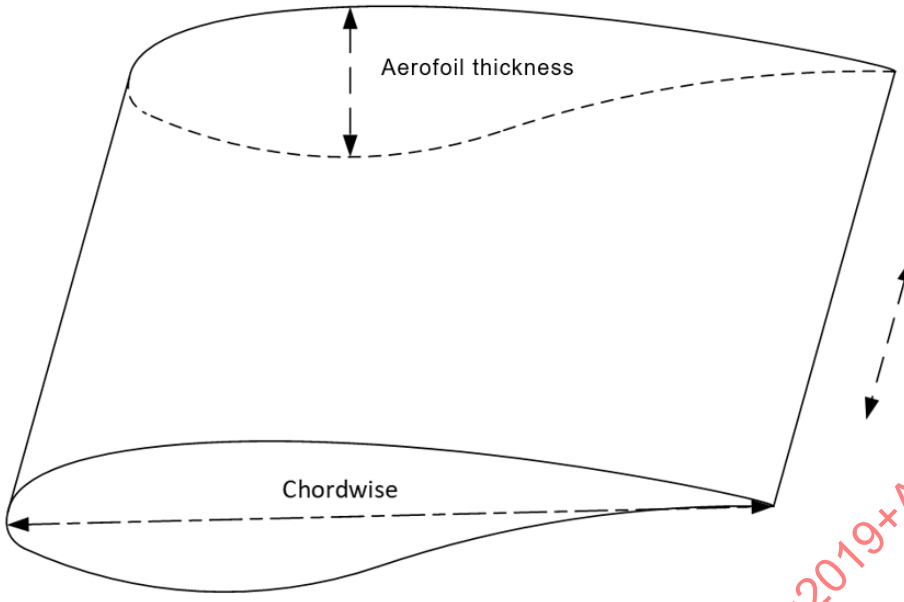

Figure N.1 – Definitions of blade aerofoil nomenclature

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Annex O
(informative)

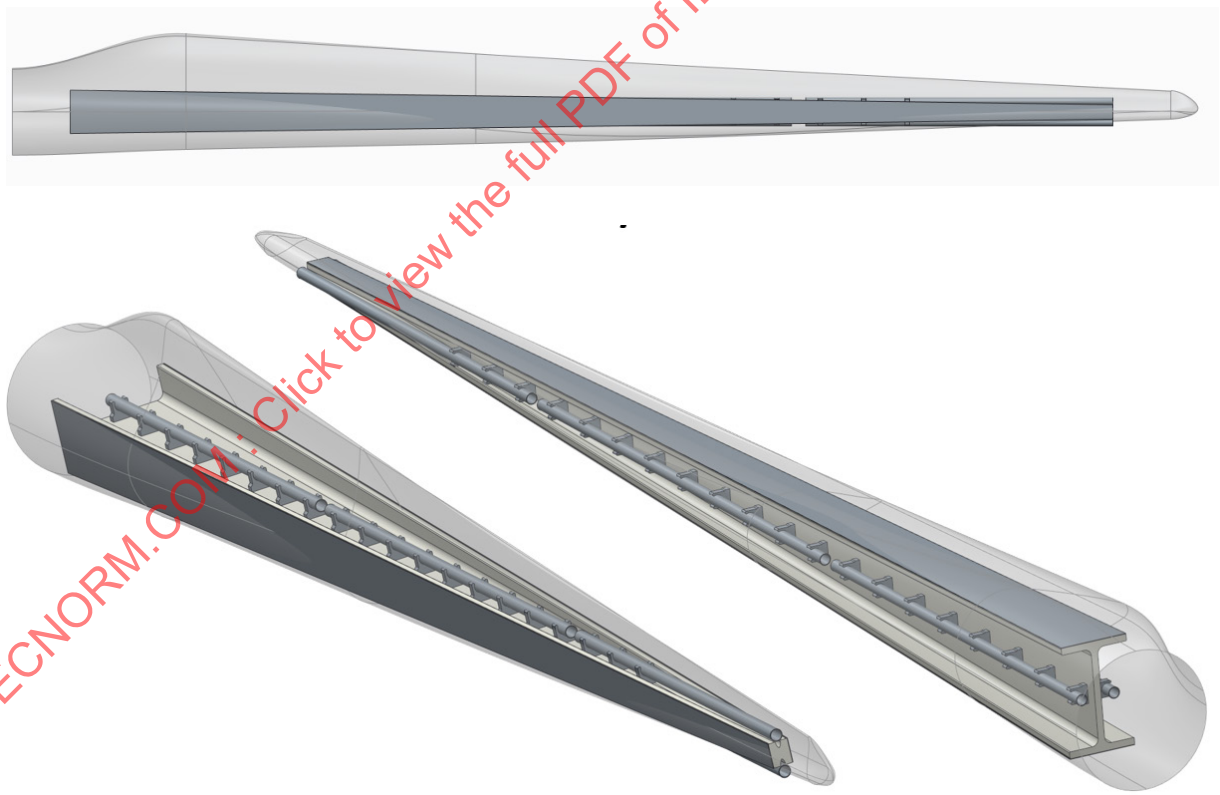
Guidelines for validation of numerical analysis methods

O.1 General

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 simple guidelines on how such verification can be achieved, using the generic geometries provided. The provider of 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.

O.2 Blade voltage and current distribution

Once the lightning strike has been intercepted by the blade air terminations, the lightning current will flow through the blade towards the root end termination to the hub or the nacelle. For blades containing conductive components besides the LPS, lightning protection coordination should be done to ensure either sufficient insulation, separation distance or adequately positioned and dimensioned equipotential bonding. For this purpose, numerical analysis is often used, and the methodologies are verified by comparing the outcome of such models with test results of geometries replicating the blade design details.



The blade skin is added on the drawing for ease of understanding.

Figure O.1 – Example geometry for blade voltage and current distribution simulations

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The geometry on Figure O.1 features the following:

– a simple scaled down blade with 5-m to 10-m-long girders (replicating both inductance and resistance of actual blade materials),
– a down conductor on one side of the web, shorted in each end,
– a signal cable on the other side of the web, everything shorted in the root, and terminated at an impedance half way out.

The test sequence conducted should reflect the entire range of rise times for naturally occurring lightning current waveforms, and the tolerances when comparing simulated and measured peak currents should be within ±20 %. The tests may be conducted in accordance with D.3.3.

O.3 Indirect effects analysis

For lightning current flowing in the hub, nacelle or tower, it may be beneficial to assess the indirect effects using an analysis or numerical modelling. In such a case, the following geometry could apply, where the approach is to inject lightning current featuring the various characteristics (peak current, frequency content, etc.) and compare the test results with simulated values. The following geometries could apply:

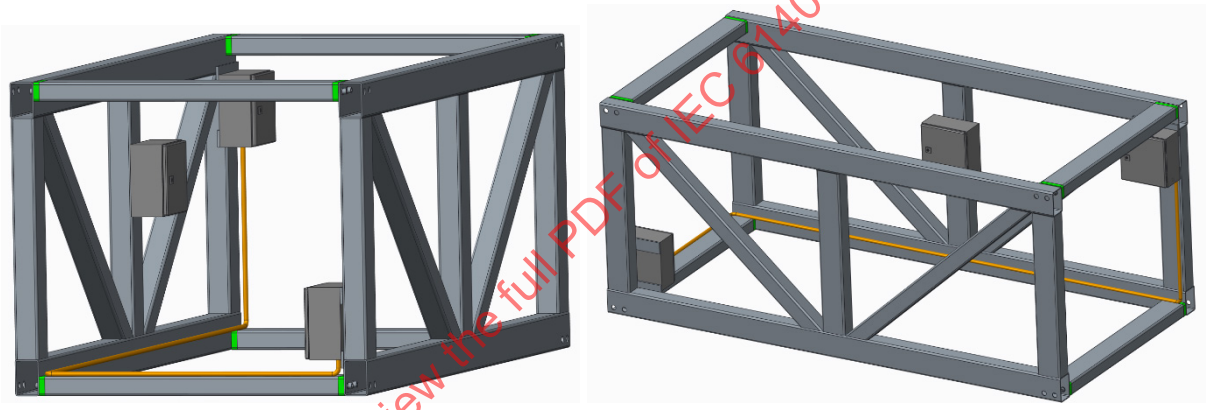

Figure O.2 – Example geometry for nacelle indirect effects simulations

The geometry on Figure O.2 features the following:

– Simplified 'nacelle' structure (3 m × 1,5 m × 1,5 m) defined in standard steel profiles, two side frames welded together, and four beams connecting the two frames.
– Two panels are mounted on the structure, and a cable conduit is traced between the two panels.
– Inside the conduit, a signal cable can be traced, terminated to earth in one end, and across an impedance in the other.
– Inject current, and measure current in the different paths, and voltage across pins of signal cables.

The test sequence conducted should reflect the entire range of rise times for naturally occurring lightning current waveforms, and the tolerances when comparing simulated and measured peak currents should be within ±20 %. The tests may be conducted in accordance with D.3.3.

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Annex P
(informative)

Testing of rotating components

P.1 General

The test is applicable to bearings for wind turbine rotor blades. The main objective of the test is to determine the current-carrying capability 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 that might be considered as rotating also in the event of a lightning strike, such as main bearings.

The test of a non-rotating and non-load bearing may present a worst-case scenario, which might be applied if no further information is given by the manufacturer.

P.2 Test specimen

P.2.1 Test specimen representing a stationary / quasi stationary bearing

The specimen might be a full-scale pitch bearing of the wind turbine, which is used in series turbines. The bearing should be specified by the manufacturer of the turbine.

P.2.2 Test specimen representing a rotating bearing

The specimen might be a full-scale bearing of the wind turbine, which is used in series turbines. The bearing should be specified by the manufacturer of the turbine. Alternative tests can be carried out on subsets of the entire, but calculations needs to be provided to demonstrate the scaling factors and effects. In the test specification, the arguments for the scaled parameters need to be defined.

P.3 Test setup

P.3.1 Test set-up representing a stationary/quasi-stationary bearing

During tests, the bearing should lie (diameter plane is faced to the floor) on isolating materials as shown in Figure P.1. The stroke current should be injected on the ring of the bearing that is connected to the rotor blade. The other ring should be grounded to the generator.

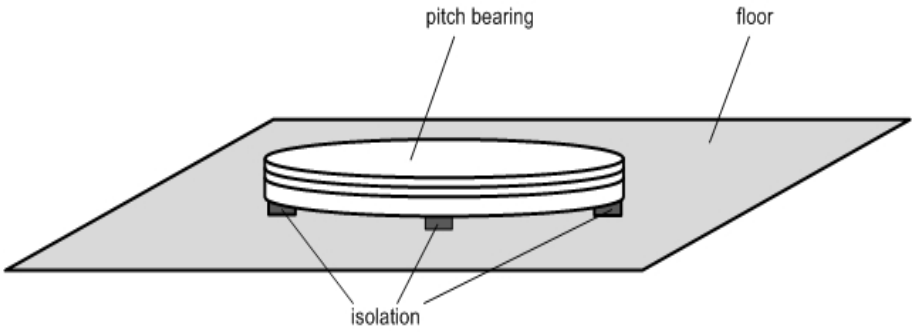

Figure P.1 – Possible test setup for a pitch bearing

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The injection of stroke current should be realized in at least one injection point. Alternatively, the injection should be defined in the same way as the bearing is connected to the LPS in the wind turbine. The injection joints should be dimensioned to carry the short stroke current as well as the long stroke current.

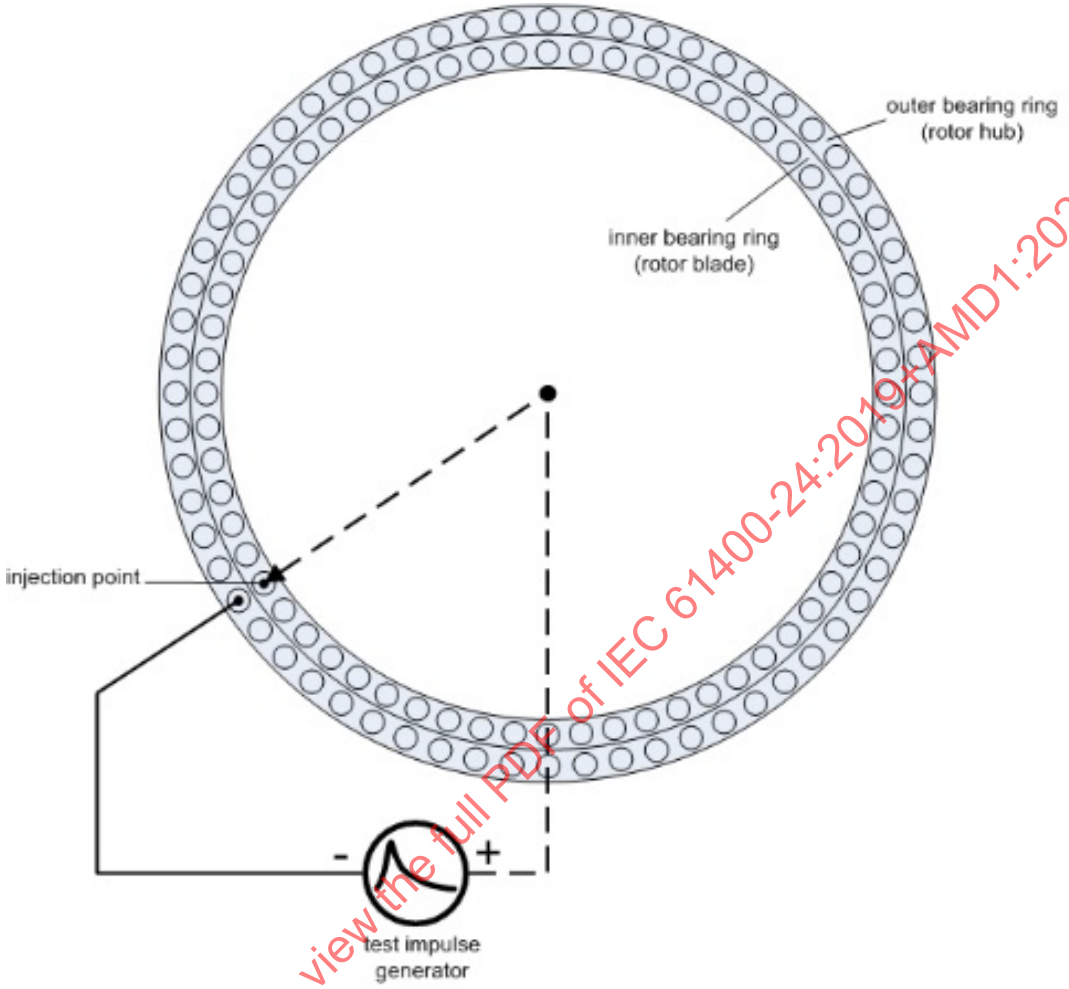

Figure P.2 – Possible injection of test current into a pitch bearing

P.3.2 Test set-up representing a rotating bearing

The test generator should be connected to the rotor shaft (replica) and the section of rotor bearing housing where it is specified for the earthing connection in the turbine (see Figure P.3). The final test setup shall be specified in detail by the manufacturer. All injection points should be designed to carry the full lightning current.

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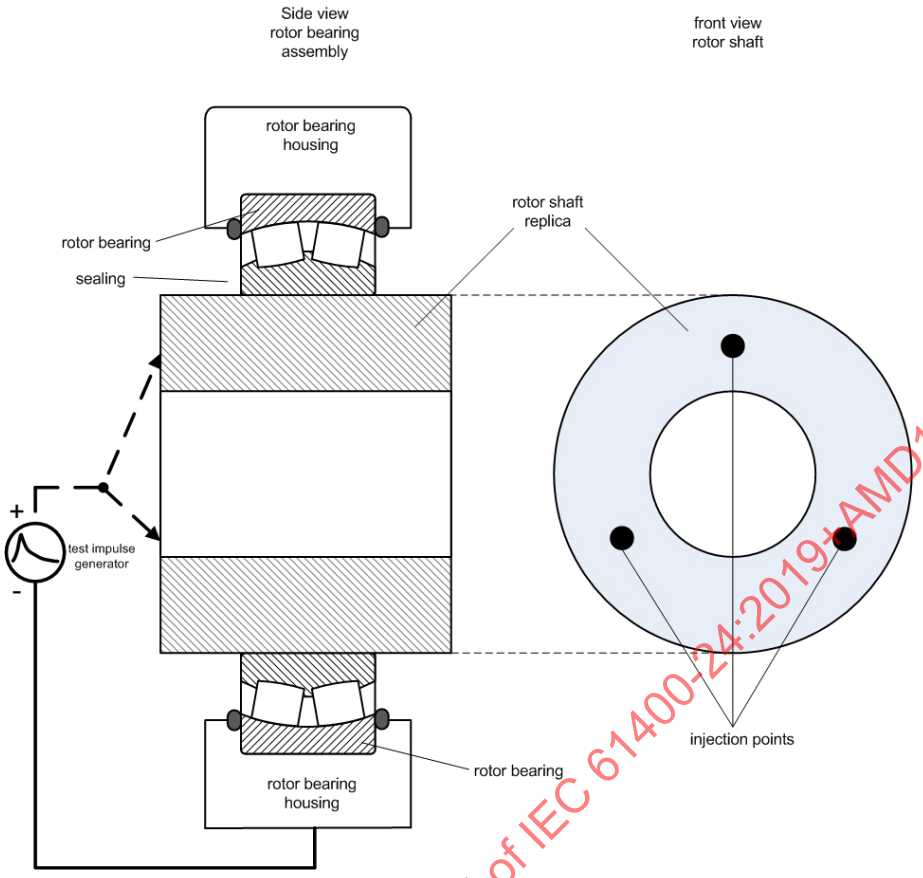

Figure P.3 – Possible test setup for a main bearing

P.4 Test procedure

Testing of rotating components should follow the general rules of conducted current tests in accordance with D.3.3. The following additional requirements apply for testing of rotating components.

The testing of pitch bearing should use the parameters of lightning protection level chosen from risk analysis or declared by the manufacturer and minimum 3 lightning impulses should be applied.

Tests should be made with the first short stroke and the long stroke in a combined impulse or also in separate impulses. For separate impulses, the testing with long current load should be done after every first short stroke impulse. After testing with short and long current, the bearing should be tested for low impedance between the inner and outer bearing ring by use of a 10-A measuring current. The series resistance of the test sample for and after each test should be recorded.

Table P.1 describes a test sequence for high current testing of rotating components.

During the test, the bearing should not be in rotation or under load conditions unless otherwise specified by the manufacturer.

In addition, a measurement of the temperature close to the injection point is advisable.

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Table P.1 – Test sequence for high current testing of rotating components

Test ID	Type of test	Parameter/value
1	Measure the series resistance of the test sample	-
2	First short stroke	I_{imp} (10/350 µs)
3	Long stroke	I_{long} (0,5 s)
4	Low impedance measurement	-
5	First short stroke	I_{imp} (10/350 µs)
6	Long stroke	I_{long} (0,5 s)
7	Measure the series resistance of the test sample	-
8	First short stroke	I_{imp} (10/350 µs)
9	Long stroke	I_{long} (0,5 s)
10	Measure the series resistance of the test sample	-

P.5 Pass/fail criteria

After impulse testing in accordance with P.3, the bearing should be examined visually and by measurement of series resistance of the test sample between inner and outer bearing ring (see Figure P.4). For the measurement, a current source with a minimum current of 10 A should be used.

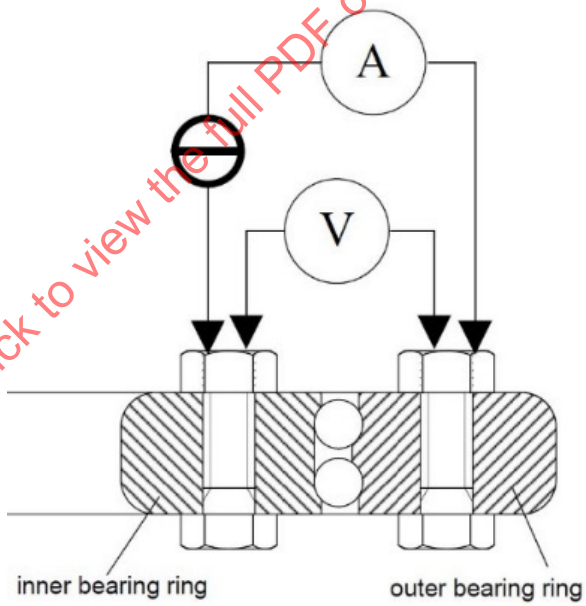

Figure P.4 – Example measurement of the series resistance of the test sample

The final evaluation of bearing testing should be done by the manufacturer of the bearing, and the evaluation should include an evaluation of the remaining operational lifetime of the bearing after testing.

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Annex Q
(informative)

Earthing systems for wind farms

A wind farm typically consists of a number of structures such as wind turbines, buildings, cables or overhead line infrastructure, high-voltage substations and signal cables.

Each wind turbine should have its own earthing 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. This is particularly beneficial if good earthing resistance is difficult to obtain at each individual wind turbine position.

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.

The earthing system of a wind farm is very important for the protection of the electrical systems, because a low-impedance earthing system reduces the potential difference between the different structures of the wind farm and so reduces the interference injected into the electrical systems.

In order to reduce the probability of direct lightning flashes to cable routes in the ground and to reduce induced lightning effects on the cables, an earthing conductor or, in the case of wider cable routes, a number of earthing conductors are recommended to be installed above the cable routes.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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WIND ENERGY GENERATION SYSTEMS –

Part 24: Lightning protection

FOREWORD

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IEC 61400-24 edition 2.1 contains the second edition (2019-07) [documents 88/709/FDIS and 88/713/RVD] and its amendment 1 (2024-11) [documents 88/1040/FDIS and 88/1054/RVD].

This Final version does not show where the technical content is modified by amendment 1. A separate Redline version with all changes highlighted is available in this publication.

International Standard IEC 61400-24 has been prepared by IEC technical committee 88: Wind energy generation systems.

This second edition cancels and replaces the first edition, published in 2010. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) it is restructured with a main normative part, while informative information is placed in annexes.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

The committee has decided that the contents of this document and its amendment will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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INTRODUCTION to Amendment 1

This amendment to IEC 61400-24:2019 addresses an update of the content in Annex L regarding monitoring systems for detecting lightning strikes on wind turbines.

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WIND ENERGY GENERATION SYSTEMS –

Part 24: Lightning protection

1 Scope

This part of IEC 61400 applies to lightning protection of wind turbine generators and wind power systems. Refer to Annex M guidelines for small wind turbines.

This document defines the lightning environment for wind turbines and risk assessment for wind turbines in that environment. It defines requirements for protection of blades, other structural components and electrical and control systems against both direct and indirect effects of lightning. Test methods to validate compliance are included.

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

Guidance regarding personal safety is provided.

Guidelines for damage statistics and reporting are provided.

Normative references are made to generic standards for lightning protection, low-voltage systems and high-voltage systems for machinery and installations and electromagnetic compatibility (EMC).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60364-4-44, *Low-voltage electrical installations – Part 4-44: Protection for safety – Protection against voltage disturbances and electromagnetic disturbances*

IEC 60364-5-53, *Electrical installations of buildings – Part 5-53: Selection and erection of electrical equipment – Isolation, switching and control*

IEC 60364-5-54, *Low-voltage electrical installations – Part 5-54: Selection and erection of electrical equipment – Earthing arrangements and protective conductors*

IEC 60364-6, *Low-voltage electrical installations – Part 6: Verification*

IEC TS 60479-1, *Effects of current on human beings and livestock – Part 1: General aspects*

IEC TR 60479-4, *Effects of current on human beings and livestock – Part 4: Effects of lightning strokes*

IEC 60664-1, *Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests*

IEC 61000 (all parts), *Electromagnetic compatibility (EMC)*

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IEC 61000-4-5, *Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test*

IEC 61000-4-9, *Electromagnetic compatibility (EMC) – Part 4-9: Testing and measurement techniques – Impulse magnetic field immunity test*

IEC 61000-4-10, *Electromagnetic compatibility (EMC) – Part 4-10: Testing and measurement techniques – Damped oscillatory magnetic field immunity test*

IEC TR 61000-5-2, *Electromagnetic compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 2: Earthing and cabling*

IEC 61400-23, *Wind turbine generator systems – Part 23: Full-scale structural testing of rotor blades*

IEC 61587-3, *Mechanical structures for electronic equipment – Tests for IEC 60917 and IEC 60297 – Part 3: Electromagnetic shielding performance tests for cabinets and subracks*

IEC 61643-11, *Low-voltage surge protective devices – Part 11: Surge protective devices connected to low-voltage power distribution systems – Requirements and test methods*

IEC 61643-12, *Low-voltage surge protective devices – Part 12: Surge protective devices connected to low-voltage power distribution systems – Selection and application principles*

IEC 61643-21, *Low voltage surge protective devices – Part 21: Surge protective devices connected to telecommunications and signalling networks – Performance requirements and testing methods*

IEC 61643-22, *Low-voltage surge protective devices – Part 22: Surge protective devices connected to telecommunications and signalling networks – Selection and application principles*

IEC 61936-1, *Power installations exceeding 1 kV a.c. – Part 1: Common rules*

IEC TS 61936-2, *Power installations exceeding 1 kV a.c. and 1,5 kV d.c. – Part 2: d.c.*

IEC 62305-1:2010, *Protection against lightning – Part 1: General principles*

IEC 62305-2:2010, *Protection against lightning – Part 2: Risk management*

IEC 62305-3:2010, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC 62305-4:2010, *Protection against lightning – Part 4: Electrical and electronic systems within structures*

IECRE OD-501, *Type and Component Certification Scheme (wind turbines)*

ITU-T K.20, *Resistibility of telecommunication equipment installed in a telecommunications centre to overvoltages and overcurrents*

ITU-T K.21, *Resistibility of telecommunications equipment installed in customer premises to overvoltages and overcurrents*

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3 Terms and definitions

For the purposes of this document, the following terms and definitions apply. However, in general the definitions given in IEC 62305-1, IEC 62305-2, IEC 62305-3 and IEC 62305-4 will take precedence.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
air-termination system
part of an external LPS using metallic elements such as rods, mesh conductors or catenary wires intended to intercept lightning flashes

3.2
average steepness
maximum current of the impulse I divided by the front time of the impulse T_1

Note 1 to entry: See Definitions 3.2 and 3.4 and Figure A.3.

3.3
bonding bar
metal bar on which metal installations, external conductive parts, electric power lines, telecommunication lines and other cables can be bonded to an LPS

3.4
collection area
A_d
area of ground surface that has the same annual frequency of direct lightning flashes as the structure

3.5
connecting leader
lightning leader developing from a structure as a response to an external electric field imposed either by a charged cloud overhead or by a downward leader approaching the structure

3.6
conventional earthing impedance
ratio of the peak values of the earth-termination voltage and the earth-termination current that, in general, do not occur simultaneously

3.7
coordinated SPD system
SPDs properly selected, coordinated and installed to form a system intended to reduce failures of electrical and electronic systems

Note 1 to entry: Coordination of SPD protection includes the connecting circuits to provide insulation coordination of complete systems.

3.8
down-conductor system
part of an external LPS intended to conduct lightning current from the air-termination system to the earth-termination system

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3.9
downward flash
lightning flash initiated by a downward leader from cloud to earth

Note 1 to entry: A downward flash consists of a first impulse, which can be followed by subsequent impulses. One or more impulses may be followed by a long stroke.

3.10
earth electrode
part or a group of parts of the earth-termination system that provides direct electrical contact with and disperses the lightning current to the earth

3.11
earth-termination system
part of an external LPS that is intended to conduct and disperse lightning current into the earth

3.12
efficiency of a LPS
observed statistical number of strikes intercepted correctly (i.e. the interception efficiency) and conducted safely towards ground divided by the total number of strikes to the turbine/blade observed (in the field)

3.13
effectiveness of a LPS
observed statistical number of successful laboratory tests divided by the total number of laborarory tests

3.14
height
H
for a wind turbine, the highest point the blades reach, i.e. hub height plus rotor radius

3.15
external lightning protection system
part of the LPS consisting of an air-termination system, a down-conductor system and an earth-termination system

Note 1 to entry: The down conductor is often placed inside wind turbine blades.

3.16
flash charge
Q_{FLASH}
value resulting from the time integral of the lightning current for the entire lightning flash duration

3.17
front time
T_1
virtual parameter defined as 1,25 times the time interval between the instants when the 10 % and 90 % of the peak value are reached

Note 1 to entry: See Figure A.3.

3.18
foundation earth electrode
conductive part buried in the soil under a building foundation or, preferably, embedded in concrete of a building foundation, generally in form of a closed loop

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3.19
ground flash density
N_G
number of lightning flashes per square kilometre per year in the region where the structure is located

3.20
high voltage
voltage higher than 1,0 kV a.c. or higher than 1,5 kV d.c.

3.21
internal lightning protection system
part of the LPS consisting of lightning equipotential bonding and/or electrical insulation of external LPS

Note 1 to entry: Compliance with the separation distance and the reduction of the electromagnetic effects of lightning current within the structure to be protected may be considered as parts of an internal lightning protection system.

3.22
interception efficiency
probability with which the air-termination system of an LPS intercepts a lightning flash

3.23
leader connection point
place in the air gap between test object and HV electrode where positive and negative leaders meet and the discharge is initiated

3.24
lightning current
i
current flowing at the point of strike

3.25
lightning electromagnetic impulse
LEMP
all electromagnetic effects of lightning current via resistive, inductive and capacitive coupling that create surges and radiated electromagnetic fields

3.26
lightning equipotential bonding
EB
bonding to LPS of separated metallic parts by direct conductive connections or via surge protective devices to reduce potential differences caused by lightning current

3.27
lightning flash to a wind turbine
lightning flash to a structure
lightning flash striking a structure (wind turbine) to be protected

3.28
lightning flash to earth
electric discharge of atmospheric origin between cloud and earth consisting of one or more strokes

Note 1 to entry: A negative flash lowers negative charge from the thundercloud to the earth. A positive flash results in positive charge being transferred from the thundercloud to the earth.

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3.29
lightning protection level
LPL
number related to a set of lightning current parameter values relevant to the probability that the associated maximum and minimum design values will not be exceeded in naturally occurring lightning

Note 1 to entry: Lightning protection level is used to design protection measures according to the relevant set of lightning current parameters.

3.30
lightning protection system
LPS
complete system used to reduce physical damage due to lightning flashes to a structure

Note 1 to entry: It consists of both external and internal lightning protection systems but not measures taken to protect internal systems against the effects of LEMP.

3.31
lightning protection zone
LPZ
zone where the lightning electromagnetic environment is defined

Note 1 to entry: The zone boundaries of an LPZ are not necessarily physical boundaries (e.g. walls, floor and ceiling).

3.32
lightning stroke
single electrical discharge in a lightning flash to earth

3.33
line
power line or telecommunication line connected to the structure to be protected

3.34
long stroke
part of the lightning flash which corresponds to a continuing current

Note 1 to entry: The duration time T_{LONG} of this continuing current is typically more than 2 ms and less than 1 s (see Figure A.4).

3.35
magnetic shield
closed, metallic, grid-like or continuous screen enveloping the structure to be protected, or part of it, used to reduce failures of electrical and electronic systems

Note 1 to entry: The protection effect of a magnetic shield is achieved through attenuation of the magnetic field.

3.36
metal installations
extended metal items in the structure, which may form a path for lightning current, such as the nacelle bed plate, elevator guide rails and wires, ladders, platforms and interconnected reinforcing steel

3.37
multiple strokes
lightning flash consisting on average of 3 to 4 strokes, with typical time interval between them of about 50 ms

Note 1 to entry: Events having up to a few dozen strokes with intervals between them ranging from 10 ms to 250 ms have been reported.

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3.38
natural component of LPS
conductive component installed not specifically for lightning protection that can be used in addition to the LPS, or in some cases could provide the function of one or more parts of the LPS

Note 1 to entry: Examples of the use of this term include:

– natural air termination;
– natural down conductor;
– natural earthing electrode.

3.39
number of dangerous events due to flashes to a structure
N_D
expected average annual number of dangerous events due to lightning flashes to a structure

3.40
peak value
I
maximum value of the lightning current

3.41
point of strike
point where a lightning flash strikes the earth or a protruding structure (e.g. structure, LPS, line, tree)

Note 1 to entry: A lightning flash may have more than one point of strike.

3.42
receptor
form of air termination on wind turbine blades, for example discrete metal studs through the blade surface connected to a down conductor system

3.43
risk
R
probable average annual loss due to lightning, in a structure or in a considered zone of the structure

3.44
separation distance
necessary distance between a conductor carrying partial lightning current and other conductive parts to avoid dangerous sparking

3.45
personal safety distance
separation distance as defined in IEC 62305-3, as a minimum, to avoid uncontrolled flashovers to persons in the turbine

3.46
short stroke
part of the lightning flash that corresponds to an impulse current

Note 1 to entry: This current has a time T_2 to the half peak value on the tail typically less than 2 ms (see Figure A.3).

Note 2 to entry: For power lines, a suitable test current I_n is defined in the Class II test procedure of IEC 61643-11.

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3.47
specific energy
W/R
value resulting from time integral of the square of the lightning current for the entire flash duration

Note 1 to entry: It represents the energy dissipated by the lightning current in a unit resistance.

3.48
surge
transient created by LEMP that appears as an overvoltage and/or an overcurrent

Note 1 to entry: Surges caused by LEMP can arise from (partial) lightning currents, from induction effects in installation loops and as residual surges downstream of SPD.

Note 2 to entry: Surges can arise from other sources such as switching operations or fuses operating.

3.49
surge protection measures
SPM
measures taken to protect internal systems against the effects of LEMP

Note 1 to entry: This is part of the overall lightning protection.

3.50
surge protective device
SPD
device intended to limit transient overvoltages and divert surge currents; contains at least one nonlinear component

Note 1 to entry: An SPD is a complete assembly, having appropriate connecting means.

3.51
tolerable risk
R_T
maximum value of the risk that can be tolerated for the structure to be protected

3.52
upward flash
lightning flash initiated by an upward leader from an earthed structure to cloud

Note 1 to entry: An upward flash consists of a first long stroke with or without multiple superimposed impulses. One or more impulses may be followed by a long stroke.

3.53
voltage protection level
U_P
maximum voltage to be expected at the SPD terminals due to an impulse stress with defined voltage steepness and an impulse stress with a discharge current with given amplitude and waveshape

Note 1 to entry: The voltage protection level is given by the manufacturer and may not be exceeded by:

– the measured limiting voltage, determined for front-of-wave sparkover (if applicable) and the measured limiting voltage, determined from the residual voltage measurements at amplitudes up to I_n and/or I_{imp} respectively for test classes II and/or I;

– the measured limiting voltage determined for the combination wave measurements up to U_{oc} for test class III.

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4 Symbols and units

A_D	Collection area of lightning flashes to an isolated structure
A_{Deff}	Effective collection area of flashes to an isolated structure using effective height
A_{DWF}	Collection area of lightning flashes to a wind farm
A_L	Collection area of lightning flashes to a service line
A_I	Collection area of lightning flashes near a service line
A_M	Area of influence for lightning flashes near a structure
C_S	Latent heat of melting
C_t	Total value of structure in currency
C_W	Thermal capacity
C	Mean value of possible loss
C_E	Environmental factor
C_D	Location factor
C_{DWL}	Location factor due to winter lightning activity
C_{DC}	Location factor due to complexity of local terrain
C_{DH}	Location factor due the height above sea level
C_T	Correction factor for an HV/LV transformer on the service line
D_{1D}	Electric shock resulting from direct strike to human beings
D_{1T}	Electric shock to human beings resulting from resistive and inductive coupling
D_2	Dangerous sparking triggering fire or explosion
D_3	Surges due to all sources of damage
H	Height of the wind turbine
H_{eff}	Height of the wind turbine including local terrain variations
h_z	Factor increasing the loss when a special hazard is present
i	Current
I	Peak current
I_n	Nominal test current; discharge current
I_t	Current in cable shield
I_{imp}	Impulse test current
IC	Intra cloud lightning
di/dt	Time derivative of current, average steepness
$di/dt_{30/90\ \%}$	Current steepness between points of 30 % and 90 % peak amplitude on front
L_{AD}	Loss related to injury to human beings by electric shock resulting from direct strike to those human beings (flashes to structure)
L_{AT}	Loss related to injury to human beings by electric shock resulting from resistive and inductive coupling (flashes to structure)
L_B	Loss related to physical damage to a structure (flashes to structure)
L_C	Loss related to failure of internal systems (flashes to structure)
L_D	Typical mean ratio of persons injured by direct lightning stroke relative to the total number of persons exposed in the zone, due to one dangerous event
L_{F1}	Typical mean ratio of persons injured by fire or explosion relative to the total number of persons in the zone, due to one dangerous event

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L_{F2}	Typical mean ratio of physical damage of social relevance by fire or explosion relative to the maximum amount of damage of social relevance in the zone, due to one dangerous event
L_M	Loss related to failure of internal systems (lightning flashes near structure)
L_O	Typical mean ratio of persons injured by failure of internal systems relative to the total number of persons in the zone, due to one dangerous event
L_T	Typical mean ratio of persons injured by touch and step voltages relative to the total number of persons in the zone, due to one dangerous event
L_{UT}	Loss related to injury to human beings by electric shock resulting from resistive and inductive coupling (flashes to line)
L_V	Loss related to physical damage to a structure (flashes to line)
L_W	Loss related to failure of internal systems (flashes to line)
L_X	Loss consequent to damages
L_Z	Loss related to failure of internal systems (flashes near a line)
L_1	Injury to living beings
L_2	Physical damage to the structure and its content
L_3	Failure of electrical and electronic systems
N_D	Number of dangerous events due to lightning flashes to a structure per annum
N_X	Number of dangerous events per annum
N_d	Number of dangerous events due to flashes to structure
N_M	Number of dangerous events due to flashes near a structure
N_L	Number of dangerous events due to flashes near a line
N_L	Number of dangerous events due to flashes to a line
$N_{d,x}$	Number of lightning flashes to a structure at the "x" end of a line per annum
N_G	Annual lightning ground flash density
$N_{G\ LLS}$	Ground flash density obtained from lightning location system
$N_{G\ corrected}$	Corrected ground flash density obtained from lightning location system
N_{SG}	Annual lightning ground strike-point density
N_t	Total (ground CG + cloud IC) density of optical flashes per annum
P_{AT}	Probability that a flash to a structure will cause dangerous touch and step voltage
P_{AD}	Probability that a flash to a structure will strike a person
P_B	Probability of physical damage to a structure (flashes to a structure)
P_C	Probability of failure of internal systems (flashes to a structure)
P_{LD}	Probability that lightning flashes to a service line will cause failure of internal systems
P_{LI}	Probability that lightning flashes near a service line will cause failure of internal systems
P_M	Probability of failure of internal systems (flashes near a structure)
P_{SPD}	Probability that an apparatus will be damaged, in spite of protection by a coordinated SPD system
P_U	Probability of injury to human beings by electric shock (flashes to a connected line)
P_V	Probability of physical damage to a structure Probability of failure of internal systems (flashes to connected line)

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P_W	Probability of failure of internal systems (flashes to connected line)
P_X	Probability of damage
P_Z	Probability of failure of internal systems (flashes near a connected line)
r_t	Reduction factor associated with the type of surface soil
r_f	Factor reducing the loss due to physical damage depending on the risk of fire
r_p	Factor reducing the loss due to physical damage depending on provisions taken
R	Risk
r	Rolling sphere radius
R_S	Cable shield resistance per unit length
R_T	Tolerable risk
R_X	Risk component for a structure
S	Spacing between earth rods
T_p	Time in hours per annum in which persons are present in a dangerous place
t or T	Time
Δt	Time interval
T_X	Time parameter
t_{long}	Time duration of long stroke
u_a, u_c	Anode or cathode voltage drop
U_C	Voltage between shield and wires of cable
U_W	Impulse withstand voltage
U_p	Voltage protection level
Q	Charge of the lightning current
Q_{flash}	Flash charge
Q_{short}	Short stroke charge
Q_{long}	Long stroke charge
W/R	Specific energy
Z_T	Transfer impedance
α	Temperature coefficient of the resistance (1/K)
γ	Material density
μ_0	Permeability of air (vacuum)
Φ	Magnetic flux
ρ	Resistivity
ρ_0	Specific ohmic resistance at ambient temperature
Θ	Temperature
Θ_0	Start temperature
Θ_s	Melting temperature
Θ_u	Ambient temperature
A	Ampere
C	Coulomb
°C	Degrees Celsius
H	Henry

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K	Kelvin
S	Siemens
g	Gram
Hz	Hertz
J	Joule
m	Metre
Ω	Ohm
s	Second
V	Volt
Wb	Weber
W	Watt

5 Abbreviated terms

AC	alternating current
CFRP	carbon fibre reinforced plastic
CG	cloud to ground lightning
DE	detection efficiency
EB	lightning equipotential bonding
EGM	electro geometrical model
EMC	electromagnetic compatibility
GFRP	glass fibre reinforced plastic
IC	intra-cloud lightning
LEMP	lightning electromagnetic impulse
LLS	lightning location system
LPE	lightning protection environment
LPL	lightning protection level
LPS	lightning protection system
LPZ	lightning protection zone
LV	low voltage
HV	high voltage
OCPD	overcurrent protection device
PE	protective earth
QA	quality assurance system
SCIG	squirrel cage induction generator
SEMP	switching electromagnetic impulse
SPD	surge protective device
SPM	surge protection measures
WRIG	wound rotor induction generator
WTG	wind turbine generator

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6 Lightning environment for wind turbine

6.1 General

The lightning environment for wind turbines in terms of lightning current parameter values to be used for dimensioning, analysis and testing of the lightning protection systems is defined in IEC 62305-1.

An informative discussion of the lightning phenomenon in relation to wind turbines is included in Annex A.

6.2 Lightning current parameters and lightning protection levels (LPL)

In IEC 62305-1, four lightning protection levels (I to IV) are introduced. For each LPL, a set of maximum and minimum lightning current parameters is fixed.

The maximum values of lightning current parameters relevant to LPL I will not be exceeded with a probability of 99 %. The maximum values of lightning current parameters relevant to LPL I are reduced to 75 % for LPL II and to 50 % for LPL III and IV (linear for I, Q and di/dt, but quadratic for W/R). The time parameters are unchanged.

Table 1 – Maximum values of lightning parameters according to LPL (adapted from IEC 62305-1)

Current parameters		Symbol	Unit	LPL			
				I	II	III	IV
First positive short stroke	Peak current	I	kA	200	150	100	
	Charge	Q_{SHORT}	C	100	75	50	
	Specific energy	W/R	MJ / Ω	10	5,6	2,5	
	Time parameters	T_1 / T_2	µs / µs	10/350			
First negative short stroke [a]	Peak current	I	kA	100	75	50	
	Average steepness	di/dt	kA / µs	100	75	50	
	Time parameters	T_1 / T_2	µs / µs	1/200			
Subsequent short stroke	Peak current	I	kA	50	37,5	25	
	Average steepness	di/dt	kA / µs	200	150	100	
	Time parameters	T_1 / T_2	µs / µs	0,25 / 100			
Long stroke	Charge	Q_{LONG}	C	200	150	100	
	Time parameter	T_{LONG}	s	0,5			
Flash	Charge	Q_{FLASH}	C	300	225	150	

[a] First negative stroke concerns only calculations and not testing.

The maximum values of lightning current parameters for the different lightning protection levels are given in Table 1 and are used to design lightning protection components (e.g. cross-section of conductors, thickness of metal sheets, current loading capability of SPDs, separation against dangerous sparking) and to define test parameters simulating the effects of lightning on such components (see Annex D and IEC 62305-1).

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For wind turbines placed in certain geographical areas where they are exposed to high numbers of upward lightning, particularly during winter, it may be relevant to increase the required durability of air termination systems (e.g. receptors) with regard to flash charge to more than lightning protection level I, Q_{flash} = 300 C, as this parameter decides the wear (melting) of materials and therefore influences the need for maintenance of air termination systems, spark gaps etc. (i.e. components subject to erosion due to arcing). In locations exposed to winter lightning, charge levels may reach Q_{flash} = 600 C due to upward winter lightning. In addition, the exposure and thereby the number of incidents between maintenance needs to be considered (see Clause 7 and Annex B for further information. Table D.2 provides test current parameters for winter lightning).

Although derived for application for lightning protection on land, the lightning parameters given in Table 1 shall also be used for offshore wind turbines, as there is no evidence of lightning parameters being significantly different offshore.

NOTE 1 Protection against lightning whose maximum and minimum exceed those relevant to LPL I needs more efficient measures, which can be selected on an individual basis but always following this document (in terms of design guidance and tests).

NOTE 2 Cigré Brochure 549, Lightning Parameters for Engineering Applications, 2013, provides information about upward lightning [1][1].

NOTE 3 The statistical basis for the 600C representing the 99 percentile of the charge in upward winter lightning is available in [2].

The minimum values of lightning current amplitude for the different LPLs are used to derive the rolling sphere radius in order to define the lightning protection zone LPZ θ_B, which is not exposed to lightning attachment. The minimum values of lightning current parameters together with the related rolling sphere radius are given in Table 2. They are used for positioning of the air termination system and to define the lightning protection zone LPZ θ_B.

Table 2 – Minimum values of lightning parameters and related rolling sphere radius corresponding to LPL (adapted from IEC 62305-1)

Interception criteria			LPL			
	Symbol	Unit	I	II	III	IV
Minimum peak current	I	kA	3	5	10	16
Rolling sphere radius	r	m	20	30	45	60

7 Lightning exposure assessment

7.1 General

Lightning exposure assessment is used to determine two things:

1) The LPL necessary for the particular exposure, defining the maximum design requirement and test levels for the verification tests in Annex D.
2) The annual occurrence of lightning events used to define the required lifetime of wearing components and subsystems. The expected impact (occurrence and severity) shall be aligned with inspection, maintenance and replacement intervals.

If LPL I is chosen for the design by default, the risk exposure assessment does not need to include this part. Only the assessment of annual exposure for the turbine and site and the risk of injury to living beings shall be conducted and documented. Refer to Annex K for guidance on classification of lightning damage based on risk management.

[1] Figures in square brackets refer to the Bibliography.

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Wind turbines are tall structures and are often placed in such a way that they are very exposed to lightning. It has long been recognised that wind turbines generally need to be protected against lightning as a precaution against economical losses due to damage and loss of revenue, as protection against hazards to living beings (primarily service personnel) and as a means to reduce the maintenance required.

The design of any lightning protection system shall take into account the risk of lightning flashes striking and/or damaging the structure in question. Lightning damage to an unprotected wind turbine can take the form of damage to the blades, to the mechanical parts and to the electrical and control systems. Furthermore, people in and around wind turbines are exposed to hazards from step/touch voltages or explosions and fires caused by a lightning flash.

The goal of any lightning protection system is to reduce the hazards to a tolerable level R_T. The tolerable level is based on an acceptable risk if human safety is involved. If the risk is below the level acceptable for humans then the need for further protection may be based on a purely economic analysis, which is done by assessing the cost of the lightning protection system against the cost of the damage it will prevent over a certain period.

It is the responsibility of the authority having jurisdiction to identify the value of tolerable risk. A representative value of tolerable risk R_T, where lightning flashes may cause risk of loss of human life or permanent injuries is 10^{-5} year^{-1}.

NOTE 1 Values for tolerable risk are given in IEC 62305-2.

The risk of lightning flashes attaching to any structure is a function of structure height, the local topography and the local level of lightning activity. Risks associated with lightning can be assessed in detail in accordance with IEC 62305-2.

Assessing the frequency of lightning, as described in 7.2 follows the principles described in IEC 62035-2.

Lightning risk predictions require the estimation of lightning flashes to or near wind turbines and their service lines. During the last years, estimation of direct lightning flashes to wind turbines has been an object of discussion. The number of lightning flashes to wind turbines in a wind farm is difficult to predict because of the high influence of local topography together with local lightning activity. Moreover, wind turbines experience both downward and upward lightning in different percentages at different locations. A methodology used to estimate the total number of lightning flashes to the turbines of a wind farm as well as the percentage of upward flashes are described in Clause B.2.

Information about local lightning conditions should be collected whenever possible (for example at locations where upward lightning may pose a special threat, such as in mountains and in areas with winter lightning).

NOTE 2 Information about the worldwide occurrence of winter lightning is included in Annex B.

As a word of caution, such a risk assessment will never be more accurate than the information entered into the calculation, and furthermore, because the assessment is probabilistic, because lightning occurrence information is statistical averages, and because the lightning event in itself is stochastic in nature, the user should not expect very accurate short-term prediction of the number of lightning events for individual wind turbines or wind farms. However, a risk assessment does make it possible to evaluate the risk reduction achieved by applying lightning protection and will allow comparison of risks for different wind turbine projects. Further details are provided in Annex B.

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7.2 Assessing the frequency of lightning affecting a single wind turbine or a group of wind turbines

7.2.1 Categorization of lightning events

The average annual number of dangerous events that may endanger a wind turbine may be separated into:

N_D due to lightning flashes to the wind turbine [year^{-1}];

N_M due to lightning flashes near the wind turbine (within 350 m) [year^{-1}];

N_L due to lightning flashes to the service lines connecting the wind turbine, i.e. the power cable and the communication cable connecting the wind turbine [year^{-1}];

N_I due to lightning flashes near the service lines connecting the wind turbine, i.e. the power cable and the communication cable connecting the wind turbine [year^{-1}];

N_{DJ} due to lightning flashes to an adjacent wind turbine or another adjacent structure at the far end of the service lines connecting the wind turbine in question [year^{-1}].

7.2.2 Estimation of average number of lightning flashes to a single or a group of wind turbines

7.2.2.1 General

The effect of flashes with multiple ground strike-points is to double the values of lightning ground flash density N_G in accordance with IEC 62858 and hence:

$$N_{SG} = 2N_G \tag{1}$$

where

N_{SG} is the lightning ground strike-point density [km^{-2}·year^{-1}];

N_G is the lightning ground flash density [km^{-2}·year^{-1}].

NOTE Some lightning location systems LLS can directly give N_{SG}.

The average annual frequency of lightning flashes attaching to a wind turbine or a group of wind turbines can be assessed as:

$$N_D = N_{SG} \cdot A_D \cdot C_D \cdot 10^{-6} \tag{2}$$

Where

N_{SG} is the lightning ground strike-point density per km^2 per year;

A_D is the equivalent collection area of the structure [m^2];

C_D is the location factor of the structure.

NOTE In areas with isolated tall structures, a more accurate evaluation of N_D may be advisable. Further information may be provided by NCs.

A detailed description of each of the parameters composing Equation (2) is found in 7.2.2.3 and 7.2.2.4.

Before describing the different parameters, it is very important to note that, for complex environmental conditions, high prediction errors can occur because of increase in collection area (by means of effective height) or location factor. Guidelines on how to estimate the average number of lightning flashes can be found in Clause B.2.

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7.2.2.2 Annual average ground flash density N_G

When assessing the frequency of lightning flashes to a structure, the collection of data detailing the local ground flash density (N_G) is necessary.

NOTE 1 Particularly high and standalone structures can alter the lightning density at ground in their vicinity. The designer can investigate further with the LLS provider.

In areas without ground-based lightning location systems or lightning flash counters, the recommended estimate of ground flash density in temperate regions with limited accuracy is

$$N_G = 0{,}25 \cdot N_t \tag{3}$$

where N_t is the total (ground CG + cloud IC) density of optical flashes per km^2 per year, obtained through NASA's website [3].

NOTE 2 In most areas of the world, an indication of lightning activity can be obtained from observations of lightning optical transients. Satellite-based sensors respond to all types of lightning with relatively uniform coverage in all areas. With sufficient averaging, optical transient density data provide better estimates of ground flash density than thunder observations, which have a wide range of relations between ground flash density and thunderstorm hours or thunderstorm days. There are also regional variations in the ratio of ground flashes (CG) to total flashes (CG + IC).

Local ground flash density (N_G) with a higher accuracy can be obtained from Lightning Location System (LLS) data suppliers. When higher precision is required, it is necessary to correct local ground flash density (N_G) as:

$$N_{Gcorrected} = \frac{N_{G_{LLS}}}{DE} \tag{4}$$

where

$N_{Gcorrected}$ is the corrected annual average ground flash density considering detection efficiency of the LLS [km^{-2}·year^{-1}];

N_{GLLS} is the annual average ground flash or density obtained from the LLS [km^{-2}·year^{-1}];

DE is the flash or stroke detection efficiency per unit of the LLS-Network in the area of interest [p.u.].

NOTE 3 In general, long duration currents in upward lightning without any superimposed impulse currents are not detected by a typical LLS; only strokes in upward lightning with impulse currents can be detected by an LLS. Hence, detection efficiency from LLS for upward lightning generated by wind turbines is much lower than for downward lightning. Therefore, the ground flash or stroke density from LLS usually does not consider all upward lightning events.

NOTE 4 The detection efficiency, DE, can be discussed with the lightning location system data provider. A detection efficiency of one can be considered for a simple and low-precision estimation of this parameter.

NOTE 5 Further guidance on how to use lightning location systems for estimating lightning densities can be found in IEC 62858.

7.2.2.3 Collection area of a single wind turbine and a group of wind turbines A_D

The collection area of a structure is defined as an area of ground surface which has the same annual frequency of lightning ground flashes as the structure. For isolated structures, the equivalent collection area is the area enclosed with a borderline obtained from the intersection between the ground surface and a straight line with a 1:3 slope which passes from the upper parts of the structure (touching it there) and rotating around it.

It is recommended that all wind turbines are modelled as a tall mast with a height equal to the hub height plus one rotor radius. This is recommended for wind turbines with any type of blades including blades made solely from non-conductive material such as glass-fibre reinforced plastic.

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Figure 1 shows the collection area produced by a wind turbine placed on flat ground. Clearly this is a circle with a radius of three times the turbine height.

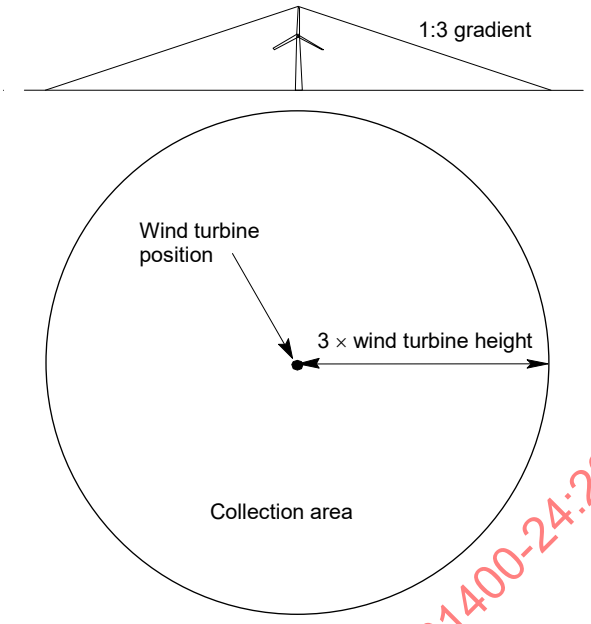

Figure 1 – Collection area of the wind turbine

The following Equation (5) can therefore be used when estimating the annual number of lightning flashes to a single wind turbine placed on flat ground (i.e. C_D = 1).

$$N_D = N_{SG} \cdot A_D \cdot C_D \cdot 10^{-6} = N_{SG} \cdot 9\pi \cdot H^2 \cdot 10^{-6} \quad (5)$$

where

H is the height of the wind turbine [m].

The collection area of a complete wind farm (A_{DWF}) should consider the overlap with neighbouring wind turbines. In such cases, the collection areas should simply be divided between the turbines where the 1:3 gradient lines from the top of the wind turbines intersect without taking into account height differences of the surrounding terrain. Figure 2 shows a general example of collection area for a wind farm composed of 10 wind turbines represented as points:

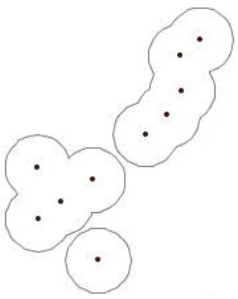

Figure 2 – Example of collection area for a complete wind farm (A_{DWF}) with 10 wind turbines (black points) considering overlapping

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7.2.2.4 Location factor C_D

Wind farms are located in different weather conditions and in different topographical regions. Wind farm location may have a high impact on the number of average annual lightning flashes to the wind turbines. Certain conditions lead to an increase of upward lightning being triggered from wind turbines or an increase of the number of downward lightning. The local topography of a mountain (mountain shape) and the height above sea level can have a high influence on the total number of lightning events during both warm and cold seasons. Moreover, winter lightning occurring during the cold season promotes the inception of upward lightning from tall structures. To estimate with higher accuracy the average annual frequency of lightning flashes attaching to a wind turbine or a group of wind turbines (N_D), it is recommended to increase the location factor to take into account the influence of local weather and topographical effects.

The three parameters mentioned previously (winter lightning activity, terrain complexity and effective height above sea level) are difficult to quantify and can vary significantly from site to site (see Annex B for further information). This is because winter thunderstorms have different features at different locations, and mountainous or hilly terrains can present multiple shapes and heights. Height above sea level where a wind farm is placed and cloud charge centre height can also have an influence during winter thunderstorms.

Wind farms placed offshore can also increase the average annual frequency of lightning flashes attaching to a wind turbine or a group of wind turbines (N_D), and it may be necessary to assign a higher location factor.

7.2.3 Estimation of average annual number of lightning flashes near the wind turbine (N_M)

Wind turbines may be endangered by lightning flashes near the wind turbine:

$$N_M = 0{,}5 \cdot N_{SG} \cdot A_M \cdot 10^{-6} \quad (6)$$

where

N_{SG} is the lightning ground strike-point density per km^2 per year;

A_M is the equivalent collection area of flashes striking near the structure (m^2).

The equivalent collection area A_M extends to a line located at a conventional distance of 350 m from the perimeter of the structure:

$$A_M = 350 \cdot 2 \cdot (L + W) + \pi \cdot 350^2 \quad (6.1)$$

When proper lightning protection is applied to a wind turbine and the service lines connecting it, it may be assumed that the protection also includes protection against damage to the wind turbine due to lightning flashes near the wind turbine and due to lightning flashes near service lines connecting the wind turbine.

NOTE N_M can be neglected for wind turbines with a total height of more than 100 metres. In this case, the conventional distance of 350 m is usually covered by direct strikes.

7.2.4 Estimation of average annual number of lightning flashes to the service lines connecting the wind turbines (N_L)

Large wind turbines are usually connected to a high-voltage power cable collection system and also usually connected to an external control centre via a communication line, both these service lines may be affected by lightning flashes to the service line or near to it (see Figure 3). In case the communication line is an optical fibre connection (which is recommended), the risk of lightning damaging the communication line may be neglected.

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The number of lightning flashes to a service line connecting a wind turbine can be assessed in accordance with IEC 62305-2, Annex A as:

$$N_L = N_{SG} \cdot A_L \cdot C_I \cdot C_E \cdot C_T \cdot 10^{-6} \quad (7)$$

where

N_L is the number of overvoltages of amplitude not lower than 1 kV (1/year) on the line section;

N_{SG} is the lightning ground strike-point density per km^2 per year;

A_L is the collection area of lightning flashes to the service line [m^2] – see Table 3;

C_I is the installation factor of the line: 1 for aerial, and 0,3 for buried (see IEC 62305-2 for more differentiated values of C_I);

C_E is the environmental factor: which is 1 for rural areas;

C_T is the line type factor.

The line type factor C_T = 1 if there is no transformer between the point of lightning attachment and the wind turbine, and C_T = 0,2 if there is. As there is usually a high-voltage transformer in large wind turbines, C_T = 0,2 can be assumed for the medium-voltage cables connecting the wind turbine to the grid (see IEC 62305-2).

NOTE N_L = 0 for submarine service lines (submarine high-voltage cables and communication cables).

7.2.5 Estimation of average annual number of lightning flashes near the service lines connecting the wind turbine (N_I)

The number of lightning flashes near a service line (i.e. close enough to affect the line) can be assessed as:

$$N_I = 0{,}5 \cdot N_{SG} \cdot A_I \cdot C_I \cdot C_E \cdot C_T \cdot 10^{-6} \quad (8)$$

where

N_I is the number of overvoltages of amplitude not lower than 1 kV (1/year) on the line section;

N_{SG} is the lightning ground strike-point density per km^2 per year

C_I is the installation factor of the line: 1 for aerial, and 0,3 for buried; see IEC 62305-2 for more differentiated values of C_I);

C_E is the environmental factor, which is 1 for rural areas;

C_T is the line type factor;

A_I is the collection area of lightning flashes near the service line [m^2] – see Table 3.

The line type factor C_T = 1 if there is no transformer between the point of lightning attachment and the wind turbine, and C_T = 0,2 if there is. As there is usually a high-voltage transformer in large wind turbines, C_T = 0,2 can be assumed for the medium-voltage cables connecting the wind turbine to the grid (see IEC 62305-2).

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Table 3 – Collection areas A_L and A_I of service line depending on whether aerial or buried

	Aerial	Buried
A_L	$(L_c - 3(H_a + H_b))\ 6\ H_c$	$L_c - 3(H_a + H_b)\sqrt{\rho}$
A_I	$1\ 000\ L_c$	$25\ L_c\sqrt{\rho}$
L_c	is the length of the service line from the wind turbine to the next structure on the line. A maximum value L_c = 1 000 m should be assumed [m].	
H_a	is the height of the wind turbine connected at the "a" end of the service line [m].	
H_b	is the height of the wind turbine (or other structure) connected at the "b" end of the service line [m].	
H_c	is the height of the service line conductors above ground [m].	
ρ	is the resistivity of the soil where the service line is buried [Ωm]. A maximum value ρ = 500 Ωm should be assumed.	

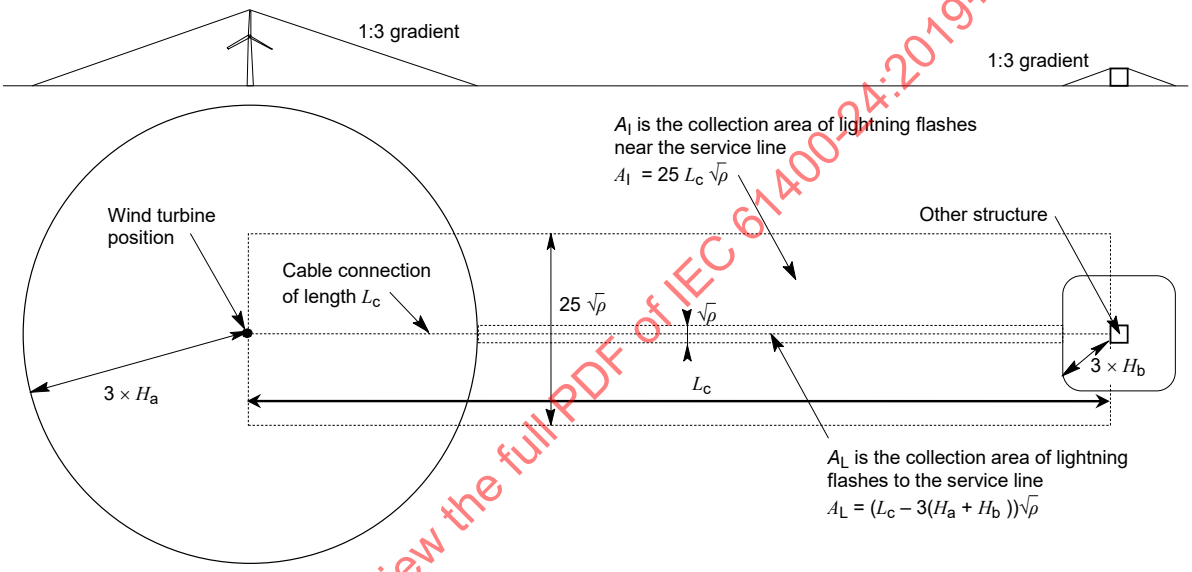

Figure 3 – Collection area of wind turbine of height H_a and another structure of height H_b connected by underground cable of length L_c

NOTE In wind farms, the collection areas of neighbouring wind turbines often overlap. In such cases, the collection areas can simply be divided between the turbines where the 1:3 gradient lines from the top of the wind turbines intersect.

7.3 Assessing the risk of damage

7.3.1 Basic equation

The risk of lightning causing damage to a wind turbine installation and thereby financial losses can be considered as the sum of many risk components. Each risk component may be expressed by the following general equation

$$R_X = N_X \cdot P_X \cdot L_X \tag{9}$$

where

R_x is the risk component for a structure (e.g. for the wind turbine);

N_x is the number of dangerous events per annum [year^{-1}];

P_x is the probability of damage;

L_x is the amount of consequent loss.

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This basic equation is to be used for assessing the risk of damage based on the probability of damage of various types and the consequent loss (see Annex B).

Protection against lightning is needed if the risk R is higher than the tolerable level R_T.

$$R > R_T \tag{10}$$

In this case, protection measures shall be adopted in order reduce the risk R to no more than the tolerable level R_T (i.e. $R \leq R_T$).

NOTE 1 The tolerable risk R_T can be stipulated by authorities or the manufacturer or be agreed between the manufacturer and the costumer.

NOTE 2 The risk components S1 to S4 can be evaluated for the specific project, either by the manufacturer, by the customer or by the two in cooperation.

7.3.2 Assessment of risk components due to flashes to the wind turbine (S1)

For evaluation of risk components related to lightning flashes to the wind turbine, the following relationships apply:

– component related to injury to human beings (D_{1D} and D_{1T})

$$R_{AT} = N_D \cdot P_{AT} \cdot P_P \cdot L_{AT} \tag{11}$$

$$R_{AD} = N_D \cdot P_{AD} \cdot P_P \cdot L_{AD} \tag{12}$$

– component related to physical damage to the structure

$$R_B = N_D \cdot P_B \cdot P_P \cdot L_B \tag{13}$$

– component related to failure of internal systems

$$R_C = N_D \cdot P_C \cdot P_P \cdot P_e \cdot L_C \tag{14}$$

Parameters to assess these risk components are given in Table 4.

NOTE In wind turbines t_z the time in hours per year that persons are present in a dangerous place is usually very low. Therefore, for personal safety refer to Clause 10, where it is mandatory that the wind turbine documentation shall define safe locations.

7.3.3 Assessment of the risk component due to flashes near the wind turbine (S2)

For evaluation of the risk component related to lightning flashes near the wind turbine, the following relationship applies:

– component related to failure of internal systems

$$R_M = N_M \cdot P_M \cdot P_P \cdot P_e \cdot L_M \tag{15}$$

Parameters to assess these risk components are given in Table 4.

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7.3.4 Assessment of risk components due to flashes to a service line connected to the wind turbine (S3)

For evaluation of risk components related to lightning flashes to an incoming service line connected to the wind turbine, the following relationships apply:

– component related to injury to human beings

$$R_U = (N_L + N_{DJ}) \cdot P_U \cdot P_P \cdot L_{UT} \quad (16)$$

– component related to physical damage

$$R_V = (N_L + N_{DJ}) \cdot P_V \cdot P_P \cdot L_V \quad (17)$$

– component related to failure of internal systems

$$R_{W1} = (N_L + N_{DJ}) \cdot P_W \cdot P_P \cdot P_e \cdot L_{W1} \quad (18)$$

Parameters to assess these risk components are given in Table 4.

7.3.5 Assessment of risk component due to flashes near a service line connected to the wind turbine (S4)

For evaluation of the risk component related to lightning flashes near a service line connected to the wind turbine, the following relationship applies:

– component related to failure of internal systems)

$$R_Z = N_I \cdot P_Z \cdot P_P \cdot P_e \cdot L_Z \quad (19)$$

For the purpose of this assessment, if $(N_I - N_L) < 0$, then assume $(N_I - N_L) = 0$.

Parameters to assess these risk components are given in Table 4.

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Table 4 – Parameters relevant to the assessment of risk components for wind turbine (corresponds to IEC 62305-2)

	Average annual number of dangerous events due to flashes
N_D [year^{-1}]	to the wind turbine
N_M [year^{-1}]	near the wind turbine
N_L [year^{-1}]	to a service line entering the wind turbine
N_I [year^{-1}]	near a service line entering the wind turbine
$N_{D,b}$ [year^{-1}]	to a structure at the "b" end of a service line (see Figure 3)
N_{SG} [year^{-1} km^{-2}]	lightning ground strike-point density
	Probability that a flash to the wind turbine will
P_{AT}	cause dangerous touch and step voltage
P_{AD}	strike a person
P_B	cause physical damage
P_C	cause failure of internal systems
	Probability that a flash near the wind turbine will
P_M	cause failure of internal systems
	Probability that a flash to a service line will
P_U	cause injury to human beings by electric shock
P_V	cause physical damage
P_W	cause failure of internal systems
	Probability that a flash near a service line will
P_Z	cause failure of internal systems
	Loss due to
L_{AT}	injury to human beings by electric shock resulting from direct strike to human beings (flashes to structure). See Clause B.5 for information on loss assessment.
L_{AD}	injury to human beings by electric shock resulting from resistive and inductive coupling (flashes to structure). See Annex B.
L_B	physical damage to a structure (flashes to structure). See Annex B.
L_C	failure of internal systems (flashes to structure). See Annex B.
NOTE Values of loss L_t; L_f; L_o; and the factors r_p, r_t, r_f reducing the loss are given in Annex B.	

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8 Lightning protection of subcomponents

8.1 General

8.1.1 Lightning protection level (LPL)

All subcomponents shall be protected in accordance with LPL I unless a detailed and documented risk assessment (according to Clause 7) demonstrates that a protection level less than LPL I is economically optimal for specific wind turbines and locations. It may be lower overall risk to differentiate, for example, that wind turbine blades are protected to a higher LPL while other parts – repairable or replaceable at less costs – may be protected to a lower LPL.

Lifetime compliance with a certain LPL may require maintenance and inspections, which may be site specific. Maintenance and inspection requirements for the lightning protection system including the earthing system should be described in the service and maintenance manuals. Maintenance and inspection procedures are outlined in Clause 12.

8.1.2 Lightning protection zones (LPZ)

A wind turbine shall be divided into physical areas which roughly define the level of the influence of a lightning flash on components in that zone. Defining the lightning exposure by division of the wind turbine into lightning protection zones is a tool to ensure systematic and sufficient protection of all components of the wind turbine. These lightning protection zones (LPZ) are defined depending on whether or not direct lightning attachment is possible and on the magnitude of the lightning current and associated magnetic and electrical fields expected in that zone (see Annex E). Lightning protection methods are then applied to ensure that components, for example blade parts, machinery, electrical systems or control systems, can withstand the effects of the magnetic and electrical fields, as well as the full or partial lightning current that may enter the zone in which the components are placed. See Annex E for further guidance on the use of LPZ.

8.2 Blades

8.2.1 General

Wind turbine blades are the most exposed parts of the turbine, and experience the full impact from the electric fields as associated with the lightning attachment process, the lightning currents, and the magnetic field associated with lightning currents. The formal explanation of the attachment process and the following current/charge conduction is included in Annex A.

Wind turbine blades are exposed to a lightning environment with distributed severity and occurrence along the blade length where the occurrence of the direct attachments are highest at the tip and decrease towards the blade root end. Field experience documenting the attachment point distribution (occurrence) is provided in Clause C.8. The manufacturer shall, in the documentation, define the lightning exposure (areas of likely attachment and corresponding lightning parameter levels) relevant for the blade in question. Guidance for defining the lightning environment is provided in the informative Annex E.

A general description of the different issues concerning lightning protection of blades is included in Annex C.

8.2.2 Requirements

The lightning protection shall be sufficient to enable the blade to intercept lightning flashes and conduct the lightning current identified by the lightning exposure assessment in Clause 7, without structural damage that would impair the functioning of the blade.

The manufacturer shall identify and implement the lightning attachment point distribution in the specific blade design, preferably based on well validated field data for similar blade designs. If field data is not available for similar blade designs, experience has shown that the outer part of the blade (typically comprising the outer 5 metres to 10 metres) is more exposed to lightning strike attachment than the remaining section of the blades. Examples are seen in Clause C.8.

The manufacturer shall document how the attachment point distribution is used in the lightning exposure assessment for the blade, by assessing risk of impact in the different span-wise areas, and ensuring that the blade can withstand the likely impact of the stroke currents for the selected LPL. The exposure shall be documented, for instance by defining the lightning environment along the blade, examples of which are given in Annex E.

The minimum topics involved to ensure proper performance are:

– definition of the lightning exposure of the actual blade, the severity and occurrence for the different strikes attaching to the blade verified as described in 8.2.3;
– correct strike interception at air termination points, discrete or distributed depending on the blade exposure;

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– a down conductor path for the lightning current; and

– insulation coordination by insulation, separation or bonding between the LPS and additional conductive paths if present, to minimise the risk of side flashes and overloading of bonding interfaces.

Damages to the blade's structural parts, the blade skin or the blade LPS due to lightning shall be limited to that which can be tolerated until the next scheduled maintenance.

8.2.3 Verification

The ability of the air-termination system and down-conductor system to intercept lightning flashes and conduct lightning currents shall be defined in accordance with the exposure considered for the specific blade, and verified by one or more of the following methods:

a) high-voltage and high-current tests in accordance with 8.2.5;

b) demonstration of similarity of the blade type (design) with a blade type previously verified by testing according to a). Two blades are defined as 'similar' if the differences do not affect the interception effectiveness, the current-carrying capability and the lightning protection insulation coordination as identified by testing or analysis. An informative checklist to validate similarity is provided in Annex N;

c) using analysis or simulations previously verified by comparison with test results according to a). In the documentation of the analysis or simulations, evidence of the applicability and validity of the analysis/methods applied shall be provided. Guidance on how to validate typical simulation methods is provided in Annex O.

The manufacturer shall clearly explain in the documentation how the verification plan is compiled based on the three methods above.

Testing according to point a) is mandatory for new blade protection designs unless similarity to previous designs is demonstrated. Annex N provides guidance on how to demonstrate similarity.

All conductive parts of the blade shall be considered in the verification process, to ensure that their interaction with the LPS during lightning interception and current conduction happens without structural damage that would impair the functioning of the blade.

The blade manufacturer shall produce documentation that describes which of the above methods are used and the results of the verification.

The high-voltage strike attachment tests used to determine the performance of the air termination system – position, integration and insulation coordination – cannot be used to determine the interception efficiency of the blade as identified for the specific LPL. The high-voltage tests are a means of verification of the performance, giving the processes and requirements in Annex D. The performance of the blade LPS concerning a specific LPL is established by the high-current verification tests, where compliance can be determined by the described test procedures and test levels.

8.2.4 Protection design considerations

8.2.4.1 General

The following subclauses describe the issues that are important for design and incorporation of the lightning protection systems associated with the blade.

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8.2.4.2 Air-termination system

The lightning air-termination systems are placed in the surface areas on the blade where connecting leaders might originate and cause lightning flash attachments or punctures if no air terminations are present. The air-termination systems may be part of the blade structure itself, components added to the blade, or combinations thereof.

Field experience has shown that the majority of lightning attachment occurs at the outer parts of the blade (see Clause C.8 for further information), hence the lightning exposure analysis identified for the blade shall reflect this fact. The air-termination system positioning tools (rolling sphere, protective angle, etc.) described in IEC 62305-3 do not consider probabilities of strike locations along the blade. Hence these tools shall not be used for blades.

The air-termination system shall therefore be designed according to the identified exposure in Clause 7, and shall be verified in accordance with 8.2.3.

The air termination system design shall ensure proper fixation in the mountings, and shall be made of materials able to withstand the expected wear due to the environment such as wind, moisture and pollution with salt and dirt particles, etc. Special attention should be paid to materials chosen for offshore and nearshore wind turbines owing to the harsh environment.

All internal parts of the air-termination system, the mounting of the air terminations and the connections to the down conductor shall be designed to minimise the risk of getting internal discharges (i.e. streamers and leaders) forming from these parts.

The air-termination system shall be designed so that parts of it that may be damaged or degraded by lightning or other environmental effects can be inspected, repaired or replaced according to procedures that shall be described in the service and maintenance manuals (instructions). The air terminations will wear over time owing to erosion at lightning arc roots. The erosion is related to the charge entering at the lightning arc root(s) and the surface material and geometry of the air termination system. Blades that receive large numbers of lightning flashes may eventually require replacement of the air terminations. The lifetime of the air termination system should be optimised through suitable selection of material and design and coordination with the maintenance and service cycles. The manufacturer shall define a procedure for correlating the design lifetime with the test performance to ensure that the suggested service/replacement intervals are adequate.

8.2.4.3 The lightning protection system and its connection components

The lightning protection system and its connection components is defined as all conductive parts of the blade which take part in conducting the lightning current from the air-termination system to the termination in the root end of the blade.

Interfaces to the LPS shall be firm and permanent and ensure that the entire system can withstand the combined impact of the electrical, thermal, and electrodynamic forces of the lightning current. Electrical connectivity across LPS connection components shall be verified with a suitable instrument such as a four-wire micro ohm meter. The ability of the lightning protection systems to withstand the mechanical stresses in the blades shall be verified by installing the system in a blade that is subjected to the tests in IEC 61400-23, while the ability of the system to sustain the electrodynamic forces shall be verified in accordance with 8.2.3. Limits and maximum deviation of measured resistance shall be specified beforehand by the manufacturer.

The cross-section of the down conductor and natural conductive parts of the blade used as down conductors (intended and unintended) shall be able to conduct their share of the lightning current corresponding to the chosen LPL. The design and installation shall be verified in accordance with 8.2.3.

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The lightning test current may be scaled based on the blade lightning exposure defined for the particular blade (see Annex E for guidance).

Testing of connection components shall be done in accordance with Annex D. The current test levels should be selected according to the first short stroke of the selected LPL. If non-rigid connections are used, such as rotating links, bearings or spark gaps, then testing should be done with the long stroke current as well. If several paths for the lightning current exist, the test current magnitude and waveforms for each path may be scaled according to the distribution of the current between the paths.

All internal parts of the down conductor system and connection components shall be designed to minimise the risk of internal discharges forming from these parts. The intention with this is to impede the development of electrical discharges from structures elsewhere than the external air termination system; whereby the risk of such internal discharges puncturing the blade skin is limited.

Down conductor and connection components subject to electrodynamic forces such as connections between blade down conductor and hub shall be tested according to Annex D in a test setup realistically representing the physical configuration in the wind turbine.

Externally mounted down conductors exposed to direct lightning attachment are defined as air-termination systems, hence the requirements in 8.2.4.2 apply.

The manufacturer shall define a procedure for regular inspection of any parts of the down conductor system and its connection components that may be degraded by service environments so that the lifetime and service intervals of these parts can be correlated.

Tests for verifying the capability of down conductors and connection components are described in Annex D.

Verification of the down conductor system and its connection components shall be done as described in 8.2.3.

8.2.4.4 Additional conductive components

If additional conductive components (conductive structural components, carbon fibre reinforced plastic, weights, tip brake cables, electrical cables for sensors, heating, warning lights, etc.) are present in the blade, the installation of these components shall be coordinated with the lightning protection system. Coordination can be achieved either by insulation or separation distance. If coordination cannot be ensured by insulation or separation, then suitable equipotential bonding shall be applied (see IEC 62305-3 for information about separation distance).

Insulation coordination and assessment of the current distribution dictated by the design shall be achieved by engineering analysis, numerical modelling, or testing. Possible verification methods are described in the IEC 60243 series, IEC TS 62561-8 or similar. Verification of engineering analysis and numerical modelling shall be provided by comparative testing. Examples of such validation is provided in Annex O.

Conductive components shall then be designed to conduct their share(s) of lightning current, and the required current-carrying capability of the different current paths shall be verified by high-current testing as described in 8.2.5.3.

Electrical and electronic equipment shall be protected with appropriate shielding, surge protection and equipotential bonding (see 8.5).

Attention shall be paid to the effects of electrodynamic forces.

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NOTE 1 The highest voltages appearing between conductive components typically occur during conduction of the subsequent stroke, whereas the highest specific energy and charge content flow in the different current paths during the first return stroke.

NOTE 2 The calculation of the separation distance in accordance with IEC 62305-3 and the testing methods provided in IEC 62561-8 consider the high voltages during conduction of negative subsequent negative short stroke.

8.2.4.5 Electrical field stress impact on composite material design

Owing to the elevation and exposure of wind turbine blades, the entire structure of the blade will be exposed to high electric fields many times during its service life. High static and transient electric fields are produced by thunder clouds and electrically applied to the blade structure. Approaching lightning leaders expose the blade structure to higher electric fields. In both cases, the electric fields may over time degrade the insulating properties of non-conducting composite materials. Therefore, the lightning protection systems should be designed considering high-voltage insulation design principles.

8.2.5 Test methods

8.2.5.1 General

The following test methods apply to entire blade designs or sub-sections such as blade tips or laminate coupons. The tests can be used as engineering tests supporting the design process and iterations, and are mandatory for the final verification of the blade designs.

8.2.5.2 High-voltage tests

Interception effectiveness of the air termination systems on the blade shall be evaluated using the initial leader attachment test described in Annex D, Subclause D.2.2.

Improvement of the ability of the blade laminate to impede internal discharges and prevent them from puncturing the blade skin can be achieved by increasing the electrical breakdown field strength of the materials, and designing internal parts to minimise field enhancements. The breakdown field strength of insulating composites and coating layers can be evaluated according to IEC 60060-1, IEC 60243-1 (AC), IEC 60243-3 (impulse voltage) and IEC 60464-2 (coating).

When electrical activity occurs on insulating surfaces (streamers, surface flashovers, etc.), the surface can deteriorate through tracking and electrical erosion. The impact, in connection with moisture, can change the properties of the insulating surface to be more conductive, and thereby increase the risk of direct lightning attachment. The resistance to tracking of various blade and coating materials can be evaluated and compared using IEC 60587.

8.2.5.3 High-current tests

The air termination systems will mainly be affected by the impact of the charge in the lightning flash (i.e. the time integral of the lightning current), which shall be evaluated by the high-current physical damage test in Annex D, Clause D.3.

Connection components and all parts of the down conductor system shall be tested by the high-current physical damage test in Annex D, Clause D.3.

The current test waveforms and levels should include the first short stroke and if relevant also the long stroke (continuing current) defined for the selected LPL. Based on the specific lightning environment defined for the blade in question, the lightning current magnitude and waveforms can be scaled to fit the actual exposure. Detailed test specifications are provided in Annex D.

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8.3 Nacelle and other structural components

8.3.1 General

Lightning protection of the nacelle and other structural components of the wind turbine should be made using the large metal structures as much as possible for lightning air termination, electrical bonding, shielding and conduction of lightning current to the earthing system. Additional lightning protection components such as air termination systems for protection of meteorological instruments and aircraft warning lights on the nacelle, down conductors and bonding connections shall be made and dimensioned in accordance with IEC 62305-3.

Insulation coordination and assessment of the current distribution (lightning current sharing) dictated by the design shall be achieved by engineering analysis, numerical modelling, or testing. All parts and connections exposed to lightning current shall be able to withstand the thermal and electromechanical effects associated with conducting the relevant levels of lightning current. Possible verification methods are described in the IEC 60243 series, IEC 62561-8 or similar. Verification of such engineering analysis and numerical modelling shall be provided by comparative testing. Examples of such validation are provided in Annex O.

Parts of the nacelle and other structural components used as natural down-conductors shall fulfil the requirements of natural down-conductors in accordance with IEC 62305-3. Verification by testing is not required for structural components with dimensions clearly fulfilling the requirements in IEC 62305-3.

Documentation of the LPS for all subsystems shall be provided as described in Clause 11.

8.3.2 Hub

The hub for large wind turbines is typically a hollow cast iron sphere of several metres in diameter. Hence the material thickness alone ensures that the hub structure itself is immune to lightning. In most cases, electrical and mechanical control systems and actuators are placed in the hub with circuits going to the outside of the hub, to the blades and to the nacelle. The hub should be made into a Faraday cage by providing magnetic shields in the openings in the hub towards the blades, the front and the nacelle (i.e. the hub could be defined as a LPZ). In many cases, these openings are closed by blade flange plates and the main shaft flange, which can be considered very effective magnetic shields. When the openings are closed with effective magnetic shields as described above, the contents of the hub require no particular lightning protection. Lightning protection of the hub is then limited to equipotential bonding and transient protection of systems placed outside the hub, such as blade actuator systems, and of electrical and control systems in the hub connected to circuits extending to the outside of the hub.

8.3.3 Spinner

Typically the hub has a glass fibre cover, called the spinner, which is mounted on the hub and rotates with it. As the rolling sphere model would always indicate that there is a possibility of lightning attaching to the front end of the spinner, lightning protection shall be considered. In some wind turbine designs there are also electrical and mechanical control systems and actuators placed outside the hub and covered by the spinner. Such systems shall be shielded from lightning attachment with air termination systems. In case no such systems are placed under the spinner, it may be reasonable to accept the risk of lightning puncturing through the spinner and not have any lightning protection of the spinner. However, in most cases, simple and practical lightning protection of the spinner can probably be made using the metal support structure for the spinner as air termination system and connection to the hub.

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8.3.4 Nacelle

The nacelle structure should be part of the lightning protection so that it is ensured that lightning attaching to the nacelle will either attach to natural metal parts able to withstand the stress or attach to a lightning air-termination system designed for the purpose. Nacelles with GFRP cover or similar should be provided with a lightning air-termination system and down conductors forming a cage around the nacelle. The lightning air-termination system including exposed conductors in this cage should be able to withstand lightning flashes corresponding to the chosen lightning protection level. Other conductors in the Faraday cage should be dimensioned to withstand the share of lightning currents that they may be exposed to. Lightning air-termination systems for protection of instruments, etc. on the outside of the nacelle should be designed according to the general rules in IEC 62305-3, and down conductors should be connected to the above-mentioned cage.

A metal mesh could be applied to nacelles with GFRP cover to provide shielding against external electric and magnetic fields, and magnetic fields from currents flowing in the mesh. Alternatively, all circuits inside the nacelle could be placed in closed metal conduits or cable trays, etc. An equipotential bonding system shall be established in which the major metal structures in and on the nacelle are included, as it is required in the electrical codes, and as it will provide an efficient equipotential plane to which all earthing and equipotential bonding connections should be made.

Lightning current from lightning attaching to the blades should preferably be conducted directly to the above-mentioned cage thereby completely avoiding lightning current passing through the blade pitch bearings and drive train bearings (see 8.2 and 8.4 for discussion of protection of blades and bearings). Different kinds of brush systems are commonly used for diverting lightning currents away from bearings. However, it may be difficult to construct brush and earth lead systems with impedance low enough to significantly reduce the current going through the low impedance of the main shaft and bearing systems to the nacelle bed plate. See 8.4.4 for further information.

NOTE A nacelle cover with such a magnetic shield will not be able to protect against effects of magnetic fields from lightning currents flowing inside the nacelle, such as in the main shaft.

8.3.5 Tower

A tubular steel tower, as predominantly used for large wind turbines, usually fulfils the dimensions required for down conductors stated in IEC 62305-3 and can be considered an almost perfect electromagnetic shield Faraday cage, as it is electromagnetically almost closed both at the interface to the nacelle and at ground level. It would therefore in most cases be reasonable to define the inside of the tower as lightning protection zone LPZ1 or LPZ2. In order to keep the tower as electromagnetically closed as possible, there should be direct electrical contact all the way along the flanges between tower sections. The tower and all major metal parts in it should be integrated into the protection earth conductor (PE) and equipotential bonding systems to make the best of the protection offered by the Faraday cage. With regards to bonding of metal structures and systems inside the tower such as ladders, wires and rails, see 9.3.5.

The interface towards the nacelle is usually closed with metal platforms and hatches, which can also serve as an electromagnetic shield closing the tower (see 8.4.2 for discussion of lightning protection of the yaw bearing).

The tower interface to the earthing system is discussed in Clause 9. If the tower is constructed as a Faraday cage as described above, then the contents of the tower require no particular lightning protection. The task of ensuring lightning protection of the tower is thereby limited to equipotential bonding and transient protection of electrical and control circuits extending to other lightning protection zones such as into the nacelle and to the outside of the tower.

Lattice towers naturally cannot be considered a very effective Faraday cage, although there will be some magnetic field attenuation and lightning current reduction inside the lattice tower.

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It is reasonable to define the inside of a lattice tower as $LPZ0_B$. Lightning down conduction should be via the lattice tower structural elements, which therefore have to fulfil the dimensions required for down conductors stated in IEC 62305-3 taking current sharing between parallel paths into account. Shields of cables in lattice towers may need to be bonded to the tower at certain interspacing in order to avoid puncture of cable insulation; this is to be assessed by calculation (see IEC 62305-2, Annex D).

In steel reinforced concrete towers, the reinforcement can be used for lightning down conduction by ensuring 2 to 4 parallel vertical connections with sufficient cross section which connect horizontally at top, bottom and for every 20 m in between. The steel reinforcement will provide quite effective magnetic field attenuation and lightning current reduction inside the tower if bonded in this way. IEC 62305-3 gives guidance on integrating steel reinforcement with lightning protection systems.

Documentation of the LPS shall be provided as described in Clause 11.

8.3.6 Verification methods

Testing methods are included in Annex D.

Suitable analysis and methods shall be used. Verification reports of analysis/methods used are required.

8.4 Mechanical drive train and yaw system

8.4.1 General

The wind turbine will in general have a number of bearings for blade pitching, main shaft rotation, gearbox, generator, and yawing systems.

Hydraulic or electrical actuator systems are used for control and operation of main components.

Bearings and actuator systems have moving parts that directly or indirectly bridge different parts of the wind turbine where lightning current may flow.

All bearings and actuator systems that may be in a lightning current path shall be protected as necessary to reduce the level of current passing through the component to a tolerable level.

8.4.2 Bearings

Bearings are difficult to monitor, and it is not acceptable that bearings have to be inspected after lightning attachment to a wind turbine. Systems for protecting bearings therefore shall be well proven and documented.

Protection can be a part of the bearing structure itself or it can be an external system installed across the bearing to bypass the current.

If the design exposes bearings to lightning current, it shall be demonstrated by analysis, documented experience relevant for the design in question, or by testing that the bearing can operate for the whole design lifetime, after being exposed to the relevant lightning current levels, and the number of lightning occurrences. If the bearing is not able to operate for the whole design life time, protection shall be applied (see 8.4.4).

The ability of the bearing to sustain lightning current to which it is exposed shall be verified by one or more of the following methods:

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a) high-current tests in accordance with 8.2.5;

b) demonstration of similarity of the bearing type (design) with a bearing type previously verified by testing according to a);

c) using analysis or simulations previously verified by comparison with test results according to a). In the documentation of the analysis or simulations, evidence of the applicability and validity of the analysis/methods applied shall be provided.

The manufacturer shall clearly explain in the documentation how the verification plan is compiled based on the three methods above.

If documentation is based on testing, then bearings with or without protection, and bypass systems for bearings shall be tested in a test setup realistically representing the operational conditions for the bearing and the protection/bypass system with regards to load, lubrication, rotation as relevant subject to design and application influencing the response to the lightning currents. Guidance for verification methods of different solutions are provided in Table 5. Whenever spark gaps are used, insulation coordination shall be determined by high-voltage testing or analysis to guarantee lightning current flow along spark gaps. Where insulation coordination relies on separation distance, this shall be based on separation distance as defined in IEC 62305-3.

Table 5 – 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
No protection	100 % in bearing	High-current testing of bearing
Bearing protection	Current sharing between bearing and its protection. Current sharing shall be determined	High-current testing of bearing and protection system
Bypass system	Negligible	High-current test of bypass system

The generic test setup for conducted current tests in D.3.3 applies. Guidance with regards to test of rotating and stationary bearings, including example test setup descriptions, is included in Annex P.

8.4.3 Hydraulic systems

If hydraulic systems are in the lightning current path, it shall be ensured that lightning current penetration will not affect the system. With hydraulic systems, it is necessary to consider the risk of fluid leaks due to damage at fittings and ignition of the hydraulic oil.

Protection measures such as sliding contacts or bonding straps can be used to make the current bypass actuator cylinders.

Hydraulic tubes exposed to lightning current shall be protected to avoid current penetration of the tubes. If hydraulic tubes have mechanical armour, it shall be bonded to the steel structure of the machinery at both ends of the tube. It shall also be ensured that the armour has sufficient cross section to conduct the parts of the lightning current, which it may be exposed to.

Similar considerations may apply to water cooling systems.

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8.4.4 Spark gaps and sliding contacts

For bypassing bearings and actuator systems, it shall be considered to use spark gaps or sliding contacts. Such bypassing systems including their connecting leads should have considerably lower impedance than the direct natural current path through the component in order to be effective.

Spark gaps and sliding contacts shall be able to conduct the level of lightning current that it may be exposed to at the place of use in the wind turbine. Test corresponding to the chosen LPL shall be done according to D.3.3.

Both spark gaps and sliding contacts shall be designed to maintain the required performance regardless of environmental effects such as rain, ice, pollution with salt, dust, etc.

If spark gaps or sliding contacts are used, these shall be considered to be wear parts and the service lifetime of these devices shall be calculated and documented. Adverse effects of pollution by wear dust on other components shall be considered in the design. Spark gaps and sliding contacts shall be inspected regularly in accordance with the service and maintenance manuals.

8.4.5 Verification

All systems for protection of bearings and actuator systems shall have a documented functionality. The documentation of this functionality is provided by performing impulse current tests with waveforms and amplitudes representing the expected lightning environment at the installation point of the protection system for the LPL selected.

Suitable engineering analysis, numerical modelling or testing shall be used. Verification reports of analysis/methods used are required.

It is recommended to perform impulse current tests on full-scale test objects where the important parts of the system are represented in a test mock-up.

It shall be demonstrated by testing (see IEC 62305-1 and Annex D for normative definition of test impulses) that the protection system can withstand the damaging effect of both the first short stroke as well as the long stroke current (continuing current) for the LPL chosen. The two tests shall be applied to the same test sample, but not necessarily in the same discharge. The test documentation shall describe the exact test sequence applied.

If sliding contacts are used as part of the system, mechanical tests shall be performed in order to document the stability of the system with special focus on wear of the contact with and without the erosion effects of lightning current. The wear has to be low enough to allow unaffected operation between the planned service intervals.

Tests can be done on subsets of the entire protection systems, but calculations shall be provided to demonstrate the scaling factors and effects.

Testing methods are included in D.3.3.

NOTE If evident by design or shown by analysis that the lightning current completely bypasses a component (i.e. negligible lightning current transfer through the component), then the high-current test is not required.

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8.5 Electrical low-voltage systems and electronic systems and installations

8.5.1 General

This subclause deals with the protection of the electrical and control systems of a wind turbine against the effects of current surges and voltage transients caused by

- lightning flashes attaching to the wind turbine;
- leader currents developing from the wind turbine;
- indirect lightning flashes (i.e. effect through LEMP of lightning flashes not affecting the wind turbine directly).

All types of lightning flashes generate lightning electromagnetic impulses (LEMP).

NOTE 1 For general requirements for electrical equipment on machines, see IEC 60204-1.

Electrical and control systems are subject to damage from LEMP. Therefore, surge protective measures (SPM) shall be provided to avoid failure of these systems. Effective protection of the electrical and control system of a wind turbine against LEMP requires the systematic approach of the lightning protection zone (LPZ) concept in accordance with IEC 62305-4. SPM is part of the lightning protection zone (LPZ) concept for the complete wind turbine, described in Annex E.

The wind turbine manufacturer shall provide a surge protection measures (SPM) system following the basic principles given in IEC 62305-4 for the complete electrical system. Given the space constraints in even large turbines, where the lightning current propagates only a few metres from sensitive equipment, special precautions shall be taken to ensure compliance with the lightning environment.

Examples of the application of the lightning protection zones (LPZ) concept in a wind turbine are given in Annex E. Protection against LEMP is based on the lightning protection zone (LPZ) concept: The wind turbine is divided into zones (i.e. volumes of space), which may correspond to parts of the wind turbine such as the inside of the large structural components: hub, the nacelle, the tower, and smaller components, such as cabinets and components. The subdivision of the structure in zones may be adapted to facilitate a convenient systematic definition of LEMP severity for each zone. Within these zones, it shall be documented that the LEMP severity is compatible with the withstand level of the internal systems enclosed.

Permanent failure of electrical and electronic systems due to LEMP can be caused by

- conducted and induced surges transmitted to equipment via connecting wiring,
- effects of radiated electromagnetic fields impinging directly onto equipment itself.

In order to characterize the LEMP severity (both conducted and radiated effects) of the individual LPZs of a wind turbine, the LEMP environment shall be assessed by verified analysis methods or in accordance with IEC 62305-3 and IEC 62305-4.

NOTE 2 It can be assumed that effective LEMP protection measures also provide effective protection against the effects of indirect lightning flashes.

Basic protection measures in a surge protection measures (SPM) system in accordance with IEC 62305-4 include:

- bonding – see 8.5.2;
- magnetic and electrical shielding of cables and line routing (system installation) – see 8.5.4;
- SPD protection – see 8.5.5;
- earthing – see Clause 9.

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Figures 4a) to 4d) give examples of possible SPM (surge protection measures) – derived from IEC 62305-4.

Additional methods include:

- insulation, circuit design, balanced circuits, series impedances, etc.

For the SPM, the following basic information shall be documented (see also Clause 11):

- definition of lightning protection level (LPL) according to IEC 62305-1;
- drawings of the wind turbine defining LPZ and their boundaries, circuit diagrams showing SPDs, cable shields and cable shield bonding points.

Figures E.6 and E.7 in Annex E provide basic examples of such documentation.

In the case of no partial lightning currents inside the LPZ, protection against over voltages is only necessary for cables passing from one zone into a zone with more sensitive components (i.e. from a lower LPZ number to a higher LPZ number), whereas internal connections within the zone may be unprotected. This approach is detailed further in IEC 62305-4, and it is discussed in Annex E. In the case of partial lightning currents flowing inside the LPZ, see Annex E.

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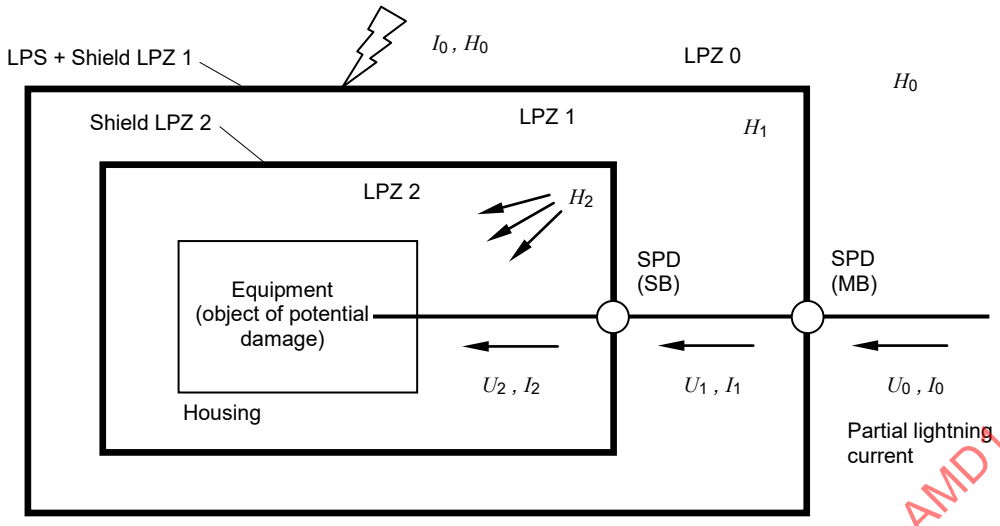
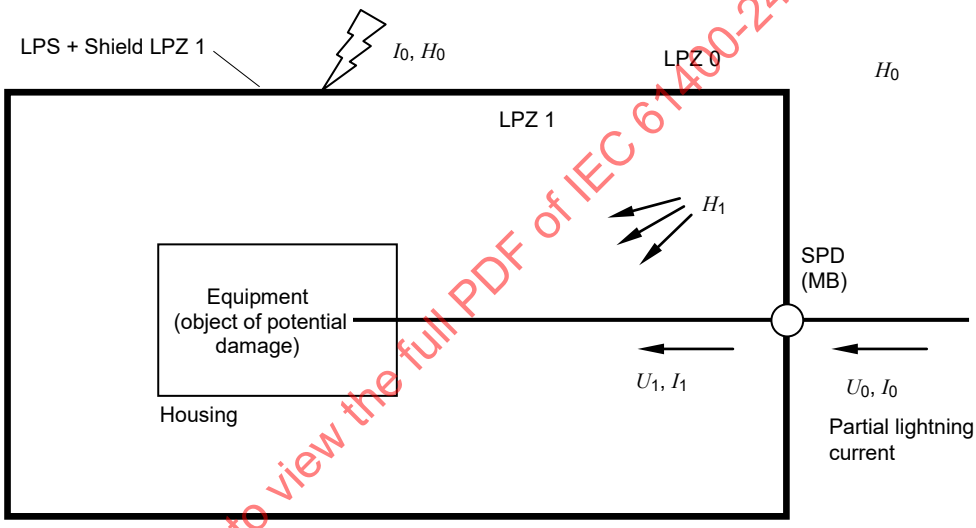


a) SPM using spatial shields and a coordinated SPD system – Equipment well protected against conducted surges (U_2<<U_0 and I_2<<I_0) and against radiated magnetic fields (H_2<<H_0)



b) SPM using spatial shield of LPZ 1 and SPD protection at entry of LPZ 1 – Equipment protected against conducted surges (U_1<U_0 and I_1<I_0) and against radiated magnetic fields (H_1<H_0)

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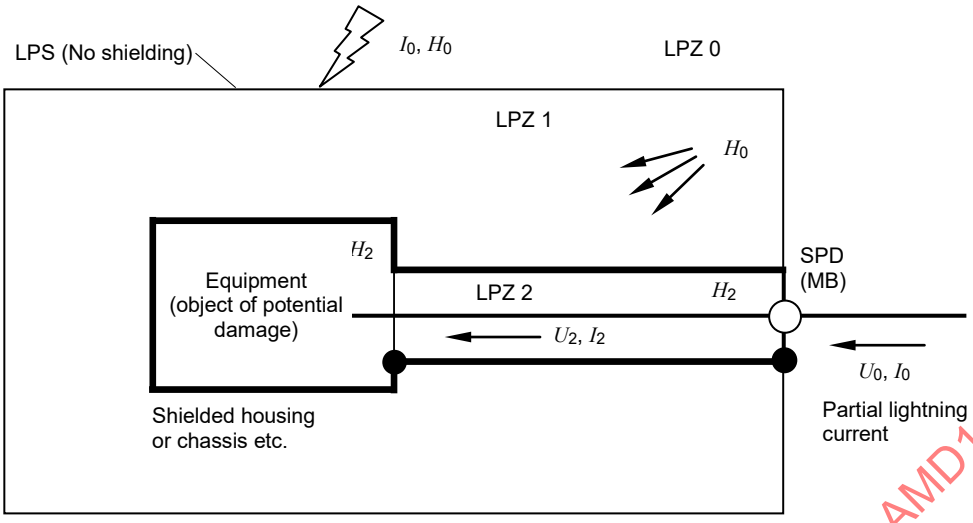
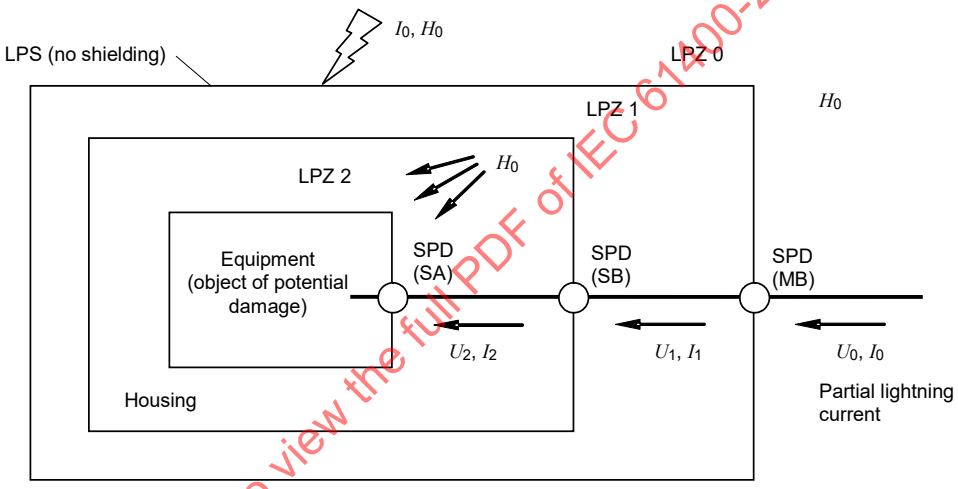


c) SPM using internal line shielding and SPD protection at entry of LPZ 1 – Equipment protected against conducted surges (U_2<U_0 and I_2<I_0) and against radiated magnetic fields (H_2<H_0)



d) SPM using a coordinated SPD system only –Equipment protected against conducted surges (U_2<<U_0 and I_2<<I_0), but not against radiated magnetic field (H_0)

Key

shielded boundary

non-shielded boundary

NOTE 1 SPDs can be located at the following points:

– at the boundary of LPZ 1 (e.g. at main distribution board MB);

– at the boundary of LPZ 2 (e.g. at secondary distribution board SB);

– at or close to equipment (e.g. at socket outlet SA).

NOTE 2 For detailed installation rules, see also IEC 60364-5-53.

NOTE 3 This figure is derived from IEC 62305-4.

Figure 4 – Examples of possible SPM (surge protection measures)

Figure 5 shows two LPZ 1 connected by electrical or signal lines. Special care should be taken if both LPZ 1 represent separate structures with separate earthing systems, spaced tens or hundreds of metres from each other. In this case, a large part of the lightning current can flow along the connecting lines, which are not protected.

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Figure 6 shows that this problem can be solved using shielded cables or shielded cable ducts to interconnect both LPZ 1, provided that the shields are able to carry the partial lightning current. The SPD can be omitted if the voltage drop along the shield is not too high.

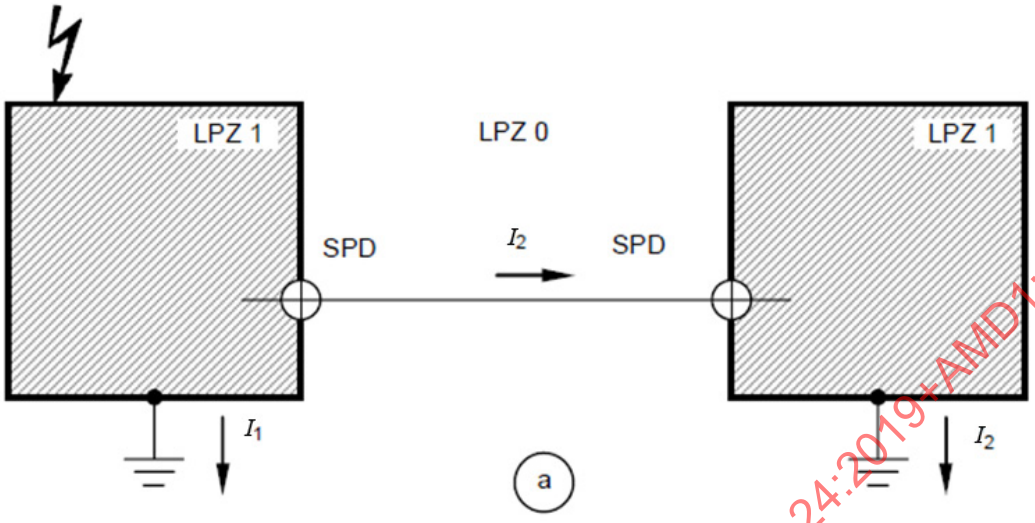

Figure 5 – Interconnecting two LPZ 1 using SPDs

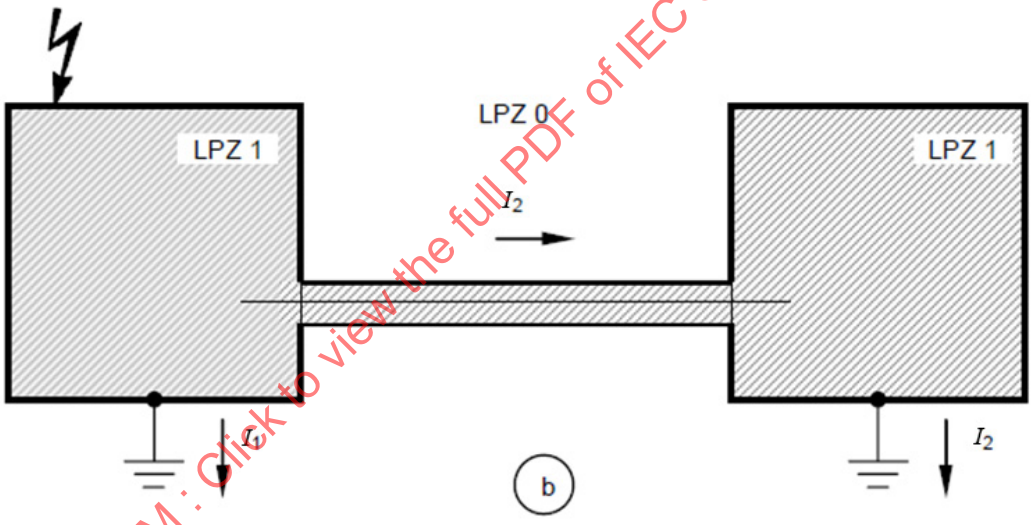

Figure 6 – Interconnecting two LPZ 1 using shielded cables or shielded cable ducts

8.5.2 Equipotential bonding within the wind turbine

Equipotential bonding in accordance with IEC 62305-4 and IEC TR 61000-5-2 shall be used within a wind turbine to ensure that potentially dangerous sparking and arcing caused by electrical discharges cannot take place between conducting parts of the wind turbine. These equipotential bonds provide protection against touch and step voltages during lightning attachment. Equipotential bonds play an important role in reducing the probability of damage to electrical and control systems. Low-impedance bonding connections prevent dangerous potential differences between equipment inside the wind turbines.

In order to be most effective, the bonding connections shall make maximum use of the large metal structures of the wind turbine (i.e. mainly tower, nacelle bed plate, nacelle frame and hub). Such bonding conductors may additionally reduce the magnetic field levels caused by lightning. Metal connections, such as those depicted in Figure E.3 and Figure E.4, facilitate uniform current distribution in the outer metal structures of the wind turbine and thus reduce the influence of the electromagnetic field inside the structure (e.g. inside nacelle or tower).

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The large metal structures provide maximum electromagnetic shielding when electrically interconnected. High electromagnetic shielding efficiency of a structure is obtained when permanent bonding of metal constructive elements are carried out at sufficiently small intervals.

For example, if bonding connections are placed between metal platforms and the tower wall at several positions distributed around the platform-tower interface, it will effectively provide electromagnetic shielding of the inside of the tower.

Much of the damage experienced in wind turbine control systems can be prevented by means of effective bonding and shielding. Some further considerations about the bonding needed in a wind turbine are discussed in Annex G.

8.5.3 LEMP protection and immunity levels

8.5.3.1 General

The transient voltage and current withstand levels (immunity) of the equipment shall be documented by testing in accordance with EMC test standards IEC 61000-4-X, and the immunity levels identified thereby shall be used for evaluating the necessity of additional protection for the equipment in the environments in the individual LPZs.

Notwithstanding the minimum withstand requirements stated herein, equipment shall always have an immunity level corresponding to the threat level of the environment wherein it is placed.

If a test fails, an individual analysis of the withstand level shall be performed. If manufacturer's specification requires external protection or measures that are clearly specified in the user's manual, the test requirements shall be applied with the external protection device or measures in place.

8.5.3.2 Withstand of equipment power ports

The equipment impulse withstand (or resistibility) levels for power ports are defined in IEC 61000-6-2 and tested in accordance with IEC 61000-4-5. A summary of the minimum impulse withstand requirements:

AC ports (230V / 400V):

- ± 2 kV line to ground;
- ± 1 kV line to line;
- further insulation/withstand level requirement in accordance with IEC 60664-1 shall be fulfilled as well.

DC ports (50V):

- ± 1,0 kV Line to ground
- ± 0,5 kV Line to line
- Further insulation/withstand level requirement in accordance with IEC 60664-1 shall be fulfilled as well.

8.5.3.3 Withstand of equipment signal ports

The equipment impulse withstand (or resistibility) levels for signal ports are defined by ITU-T Recommendations K.21 and K.20 for telecommunication and IEC 61000-6-2/ IEC 61000-4-5 for signal ports in general for equipment installed at customer's premises and exchange building respectively. A summary of the minimum impulse withstand requirements for equipment at customer's premises is:

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Telecommunication ports:

- Port connected to external line, i.e. a line that goes outside the building:
  - 1,5 kV common mode test (port to earth);
  - 1,5 kV differential mode test (between signal conductors).
- Port connected to unshielded internal line, i.e. line that remains wholly within the building (no direct connection to an external line):
  - 1 kV common mode test.

For signal ports in general:

- Signal port shall be tested regardless of their unshielded or shielded cable length:
  - 0,5 kV common mode test, tested as unshielded (port to earth).

8.5.3.4 Electromagnetic immunity of electronics

The equipment magnetic immunity (or resistibility) levels are defined in IEC 61000-4-9 and IEC 61000-4-10. A summary of the minimum impulse withstand requirements:

IEC 61000-4-9:

- ± 1 kA/m 8/20 [µs].

IEC 61000-4-10:

- ± 100 A/m (damped oscillatory).

The immunity shall be selected according to the application.

8.5.4 Shielding and line routing

Shielding is the means by which electromagnetic field levels are attenuated. The reduction of electromagnetic fields can substantially reduce levels of voltages induced into circuits.

The magnetic field caused inside an LPZ by lightning flashes to the structure or the nearby ground may be reduced by spatial shielding of the LPZ only. Surges induced into the control system via the connecting cabling can be minimised either by spatial shielding, or by line routing and shielding (e.g. shielded cables bonded at both ends), or by a combination of both methods.

Magnetic shielding and line routing in accordance with IEC 62305-4 should be used, and the general guidelines on EMC-correct installation practices described in IEC TR 61000-5-2 should be followed.

The requirements on material and dimensions of magnetic shields shall comply with IEC 62305-4:2010, Clause 6.

The use of shielding and line routing should be documented by analysis and/or testing.

The assessment of the magnetic field strength inside LPZ shall be based on magnetic field calculations according Annex A of IEC 62305-4:2010. Computer modelling can be used, provided that these models have been verified according Annex O.

The assessment for the shielding effect of enclosures shall be done in accordance with the methods described in IEC 61000-5-7 and IEC 61587-3.

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8.5.5 SPD protection

8.5.5.1 General

Coordinated SPD protection consists of a set of SPDs properly selected, coordinated and installed to reduce failures of electrical and electronic systems.

NOTE Coordination of SPD protection includes the connecting circuits to provide insulation coordination of complete systems.

Coordinated SPD protection limits the effects of lightning surges and internally generated switching surges. The protection of the electrical and control systems requires a systematic approach of coordinated SPDs for both electrical low-voltage power systems and control systems. Recommendations for coordinated SPD protection within wind turbines are given in Annex F.

8.5.5.2 Location of SPDs

According to IEC 62305-4, in a surge protection measures (SPM) system, SPDs shall be located at the line entrance into each LPZ:

- as close as possible to the boundary of LPZ 1, SPDs tested with I_{imp} (Class I test), as classified in IEC 61643-11, shall be installed;
- as close as possible to the boundary of LPZ 2 and higher, and if necessary as close as possible to the equipment to be protected, SPDs tested with I_n (Class II test), as classified in IEC 61643-11, shall be installed.

If not located at the LPZ entrance, it shall be documented that the equipment connected at both sides of the entrance can cope with the expected surge voltage. It shall as well be ensured that the conducted surge current does not compromise the magnetic environment in the entered LPZ, see Figure 7.

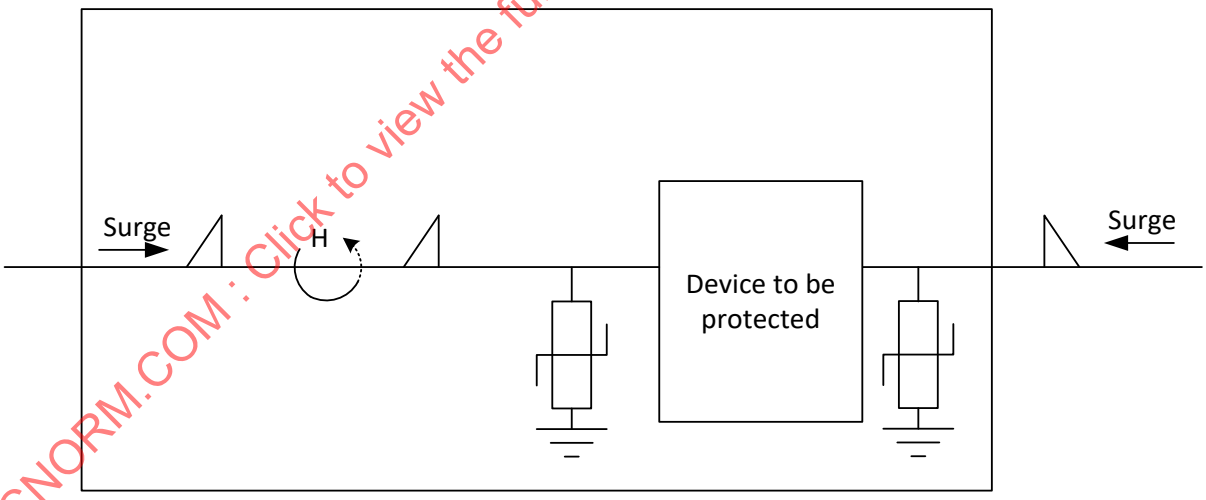

Figure 7 – Magnetic field inside an enclosure due to a long connection cable from enclosure entrance to the SPD

Where the distance between the SPD and the equipment to be protected is greater than 10 m (cable length), additional protective measures should be provided such as:

– Figure 8a: an additional SPD installed as close as possible to the equipment to be protected; its voltage protection level U_P shall in no case exceed the required rated impulse withstand voltage U_W of the equipment; or

– Figure 8b: the use of one-port SPDs at or near the origin of the electrical circuit; their voltage protection level U_P shall in no case exceed 50 % of the required rated impulse

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withstand voltage U_W of the equipment to be protected. This measure should be implemented together with other measures such as the use of shielded wiring in the whole protected circuit(s); or

– Figure 8c: the use of two-port SPDs (IEC 61643-11) at or near the origin of the electrical circuit; their voltage protection level U_P shall in no case exceed the required rated impulse withstand voltage U_W of the equipment to be protected. This measure should be implemented together with other measures such as the use of shielded wiring in the whole protected circuit(s).

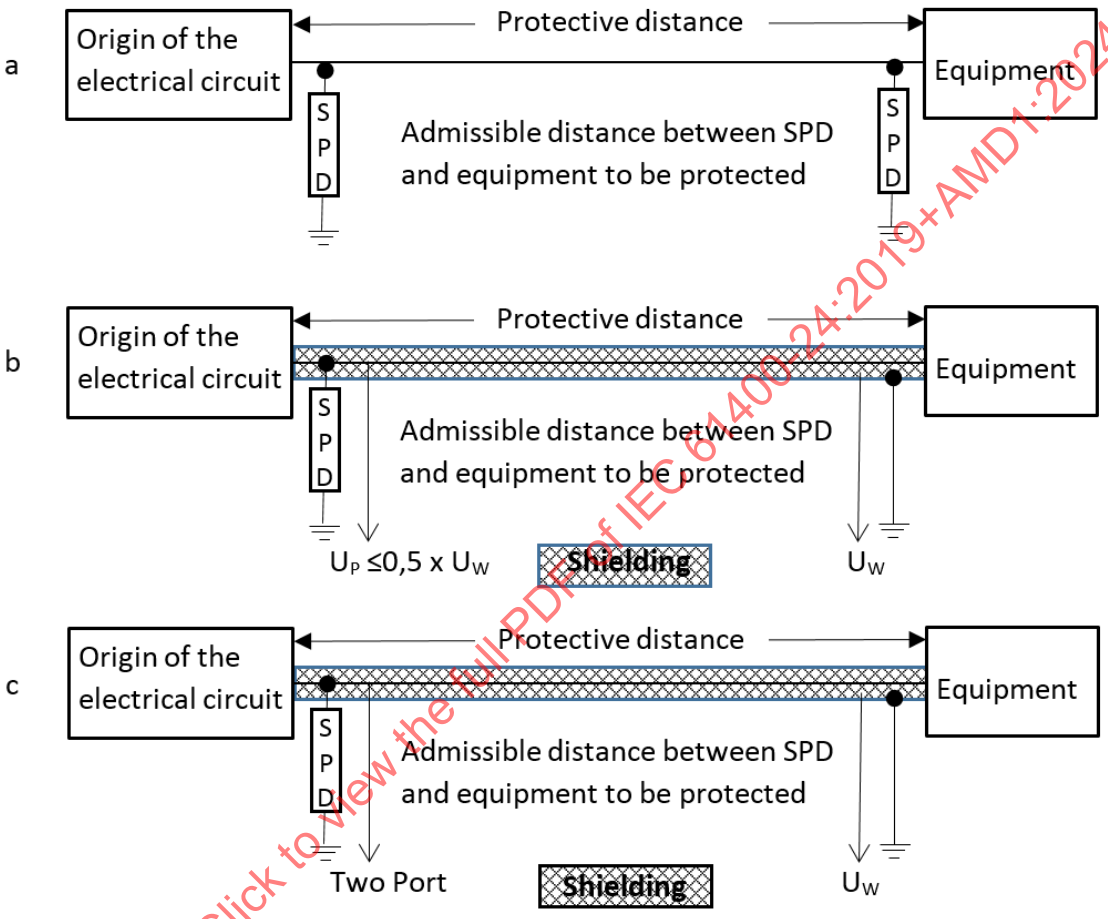

Figure 8 – Additional protective measures

8.5.5.3 Selection of SPDs

SPDs that shall withstand a partial lightning current with the typical waveform 10/350 µs require a corresponding impulse test current I_{imp}. For power lines, a suitable test current I_{imp} is defined in the Class I test procedure of IEC 61643-11.

SPDs which shall withstand induced surge currents with the typical waveform 8/20 µs require a corresponding impulse test current I_n. For power lines, a suitable test current I_n is defined in the Class II test procedure of IEC 61643-11.

SPDs shall comply with:

- IEC 61643-11 for power systems;
- IEC 61643-21 for telecommunication and signalling systems.

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8.5.5.4 Installation of SPDs

SPDs shall comply with the installation rules given in

- IEC 60364-4-44, IEC 60364-5-53 and IEC 61643-12 for the protection of power systems;
- IEC 61643-22 for the protection of the control and communication systems.

The installation locations of the SPDs shall be documented, e.g. by means of drawings and wiring diagrams according to the surge protection measures (SPM) system. For the SPDs installed at the different LPZ boundaries and possible surge protection components installed inside equipment, the requirements for energy coordination in accordance with IEC 62305-4 and IEC 61643-12 shall be fulfilled.

According to IEC 62305-4, considerations shall be made regarding the coordination of SPDs in the electrical and control systems. Sufficient information shall be provided in the documentation on how coordination between SPDs is achieved.

Further guidelines for the bonding (earthing) and cabling of electrical and control systems and installations are given in 8.5.1 to 8.5.4 and exemplified in Annex G.

8.5.5.5 Environmental stresses

SPDs shall withstand the environmental stresses characterising the installation place such as:

- ambient temperature;
- humidity;
- corrosive atmosphere;
- vibration and mechanical shock.

If no specific values are specified by the wind turbine manufacturer, SPDs installed in the nacelle or in the turbine tower could be stressed by vibrations with the following parameters:

– frequency: 0,1 Hz to 10 Hz;
– acceleration: 0,5 m/s^2.

These typical values of vibration withstand of SPDs used in wind turbine systems are based on EN 50539-22 and can be applied if no other information is available.

Depending on conditions at the point of installation within the wind-turbine, additional and specific requirements on the performance and installation of SPDs might arise. If necessary, the manufacturer of the wind turbine should take into account the environmental conditions for specific points of installation, e.g. nacelle and hub.

8.5.5.6 Maintenance

Maintenance and replacement of SPDs shall be done according to a maintenance plan provided in the wind turbine service and maintenance manuals.

SPDs shall be installed in such a way that they can be inspected and exchanged.

8.5.5.7 SPD monitoring

SPD protection of critical parts of the electrical and control systems of wind turbines may require monitoring.

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8.5.5.8 Selection of SPDs with regard to protection level (U_p) and system immunity

The required protection level U_p in an LPZ shall be defined in accordance with the established immunity levels of the equipment in the LPZ as described in 8.5.3.

8.5.5.9 Selection of SPDs with regard to continuous operating voltage (U_c)

Specific requirements with regard to continuous operating voltage (U_c) of the SPD might apply to SPDs owing to large voltage variations and temporary overvoltages within the electrical system of a wind turbine. In such cases, the relevant parts of the electrical systems and voltage levels, current levels and duration shall be identified by analysis and/or testing and SPDs selected accordingly.

For the selection of SPD protection, the source alternator excitation circuit and the line side circuit of the source, the following parameters need to be considered in addition:

- the maximum voltages (L-L and L-Earth) including regulation tolerances,
- U_c should be selected so as to sustain the stress of repetitive transients superimposed on the operating voltages,
- the maximum frequency,
- operating frequency should be selected taking into account the switching frequency of the source.

Further examples hereof are given in Annex F.

Evidence shall be provided that the selected SPDs can withstand these specific stress levels.

8.5.5.10 Selection of SPDs with regard to discharge current I_n and impulse current I_{imp}

An analysis of the lightning current distribution within the wind turbine in accordance with IEC 62305-1 and IEC 62305-4 is recommended. Based on these calculations, SPDs can be selected with regard to discharge current I_n and impulse current I_{imp}.

SPDs for particularly exposed circuits may require higher ratings than those given in IEC 60364-5-53 or such circuits could be shielded. Such circuits particularly exposed to either high stresses or repeated stresses should be identified by analysis. If applicable, such exposed circuits within the electrical and control systems of a wind turbine shall be documented in the wiring diagrams by the wind turbine manufacturer. Further information hereof is given in Annex F.

8.5.5.11 Selection of SPDs with regard to short-circuit current and the follow current interrupt rating

The short-circuit withstand current rating of the combination of the SPD and the overcurrent protective device (OCPD – e.g. a fuse) and the follow current interrupt rating of the SPD as declared by the SPD manufacturer shall be equal to or higher than the maximum short-circuit current expected at the point of installation. In addition, when a follow current interrupt rating is declared for the SPD, it shall be confirmed by either calculation or testing that the actual OCPD installed in the specific power circuit does not operate.

8.5.5.12 Behaviour of SPDs in case of multiple lightning flashes

Owing to the relatively high frequency of lightning flashes to wind turbines and the critical nature of the installation of SPDs within wind turbines, SPDs shall be able to withstand multiple lightning flashes.

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8.5.5.13 Protection against transient switching overvoltages created within wind turbines

Transient overvoltages and surges caused by switching operations in electrical systems (switching electromagnetic impulse, SEMP) needs to be considered as well. However, it is outside the scope of this document. For general information, the reader is referred to IEC TR 62066 for discussion of switching overvoltages.

Protection against transient switching overvoltages can be provided by installing SPDs located as close as possible to the origin of such threats. Overvoltages due to switching can be longer in duration and can contain more energy than the transient overvoltages of atmospheric origin. This has to be considered for the selection of SPDs with regard to nominal discharge current and impulse discharge current.

Clause F.7 gives some information on the selection of SPDs with regard to overvoltages created within wind turbines.

8.5.6 Testing methods for system immunity tests

System immunity tests in accordance with Annex H shall be performed for systems with power ports or signal ports connected to incoming lines coming from LPZ 0_A or 0_B (with partial lightning currents flowing on these lines). Typical examples are warning and control systems mounted on the top of the nacelle, e.g. aviation light, electronics inside blades.

For all other electrical systems, the tests in Annex H give additional information about the system level immunity – see also 8.5.5.8.

8.6 Electrical high-voltage (HV) power systems

Large wind turbines are usually connected via a high-voltage (HV) transformer to an underground HV cable system, which may connect an array of wind turbines either directly to the grid or to a transformer station stepping up the voltage to that of the sub-transmission system at for example 132 kV.

The wind turbine HV transformer is usually placed in the nacelle, in the bottom of the tower or next to the wind turbine tower.

HV surge protection devices are usually referred to as surge arresters. In a wind turbine application, surge arresters serve to protect the transformer and the high-voltage system in general against earth potential rise due to lightning currents passing through the wind turbine earthing system, and to protect against transients entering the wind turbines from the HV cable system outside the wind turbine. The need for surge arresters on the HV side of the transformer should be evaluated based on the principles in IEC 62305-2 and IEC 60071 (see Clause 7 and Annex B).

Assessment of the levels of transients coming from the HV cable system outside the wind turbine requires special transient electrical network simulations. The studies should be made in accordance with the IEC 60071 series. In case such studies are not performed, HV surge arresters are advisable as a general precaution. See also IEC 62305-4 for guidance on how to use transient network simulations.

HV surge arresters should be metal-oxide surge arresters without gaps in accordance with IEC 60099-4 and should be selected and applied in accordance with IEC 60099-5.

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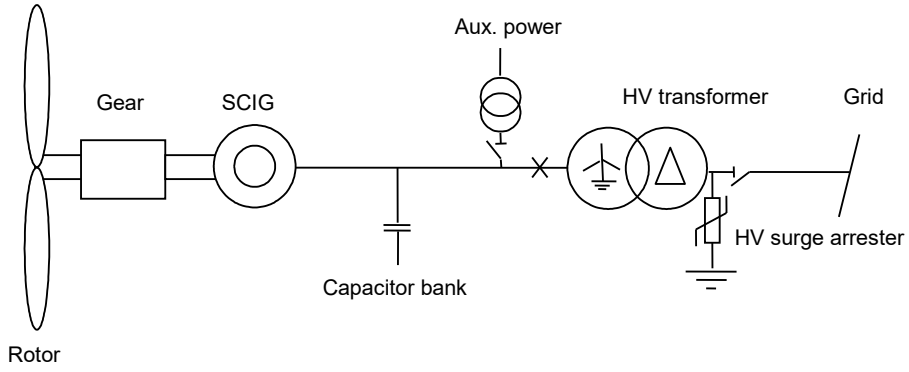
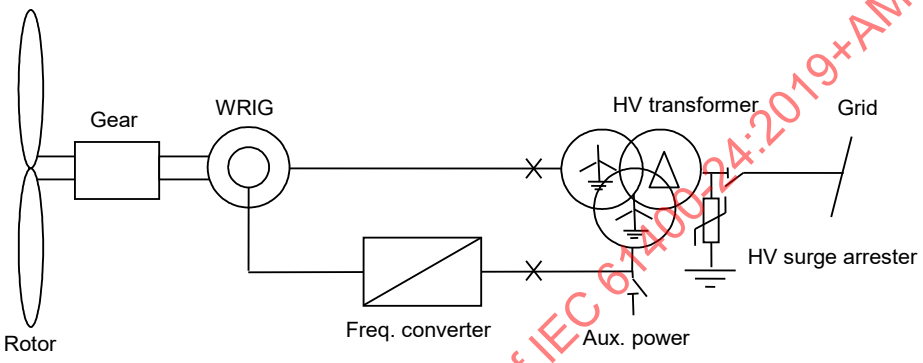


a) Squirrel cage induction generator (SCIG)



b) Doubly fed induction generator (DFIG)

Figure 9 – Examples of placement of HV arresters in two typical main electrical circuits of wind turbines

High-voltage surge arresters should preferably be placed at the HV transformer terminals as shown in Figure 9, thereby providing maximum protection for the transformer. However, as it may be convenient to place surge arresters at a distance from the object to be protected, the allowed distance shall be decided by calculation. A distance of up to 10 m between the arrester and the object to be protected can usually be allowed. If the distance is larger or circumstances require a closer study, it is necessary to decide if for instance arresters at the bottom of the tower can provide the needed protection for a transformer placed in the nacelle. If the transformer is placed outside the tower, it is important that the transformer earthing system is connected to the wind turbine earthing system, and preferably it should be one earthing system.

SPDs on the low-voltage (LV) side of the HV transformer are probably an appropriate general precaution, particularly if significant transients may pass through the transformer from the high-voltage side, in which case a type of SPD for transformer application should be chosen (i.e. SPDs with high energy absorption capability). The transient capacitive and inductive coupling between the HV and LV sides of a transformer, and therefore also the transient levels transferred to the LV side, depend very much on the design of the transformer and particularly on the earthing connection of the LV winding (refer to IEC 60071-2:2018, Annex E for further information). It is therefore advisable as a general precaution to install SPDs on the LV side of the transformer, or alternatively to obtain a sufficiently detailed transformer model from the manufacturer for transient studies in order to decide if SPDs are required on the LV side of the transformer.

NOTE IEC 60204-11 states general requirements for high-voltage systems on machinery.

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9 Earthing of wind turbines

9.1 General

9.1.1 Purpose and scope

To disperse lightning currents and prevent damage to a wind turbine, an efficient earthing system is essential. The earthing system shall furthermore protect people and livestock against electric shock. When faults occur in the electrical grid, it is necessary to keep the touch and step voltages and the overall earth potential rise to a safe level until protection devices have tripped and safely interrupted the flow of fault current. For lightning flashes, the earthing system shall be designed to disperse and conduct high-frequency and high-energy lightning current into the earth without any dangerous thermal and/or electrodynamic effects.

It is generally recommended that one earthing system is established for a wind turbine to be used for lightning protection as well as for power system earthing purposes. Furthermore, it is recommended to include metal parts in the foundation structures in the earthing system, because using the metal parts of the large foundation structures will result in the lowest possible earthing resistance, and because attempting to separate an earthing system from the metal parts of the foundation would represent a structural hazard, particularly for concrete foundations.

Concerning the design of the earthing system to prevent high-step and touch voltages due to failures in high-voltage components, please refer to high-voltage electrical codes such as IEC 61936-1 and IEC TS 61936-2, IEC 60364-5-54, IEC 60364-6 and relevant national standards. In relation to human safety, refer to IEC TS 60479-1 and IEC TR 60479-4.

It is outside the scope of this document to specify lightning protection systems and earthing systems for wind farms as a specific design study needs to be done for each wind farm considering the site-specific conditions and the power and communication interconnections between wind turbines and to the outside systems. Guidance with regards to earthing systems for wind farms is included in informative Annex Q.

9.1.2 Basic requirements

The earthing system of the wind turbine shall be designed to provide sufficient protection against damage due to fault currents and lightning strikes intercepted by the turbine. The design of the earthing system shall correspond to the LPL for which the wind turbine protection system is designed.

The earthing system shall be designed to meet four basic design requirements:

a) ensure personal safety with regard to the step and touch voltages which appear during earth faults and lightning current exposure;

b) prevent damage to equipment;

c) withstand the thermal and electrodynamic forces it will be subjected to during a fault current and lightning exposure;

d) have sufficient long-term mechanical strength and corrosion resistance.

9.1.3 Earth electrode arrangements

Two basic types of earth electrode arrangements that are described in IEC 62305-3 apply to wind turbines:

- type A arrangement: This arrangement is not recommended for wind turbines, but can be used for minor buildings (for example buildings containing measurement equipment or office sheds that are connected to a wind turbine farm). Type A earthing arrangements are made with horizontal or vertical electrodes connected to not less than two down conductors on the structures;

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NOTE For further information on type A arrangements, see IEC 62305-3:2010, 5.4.2.1.

- type B arrangement: The type B arrangement is recommended for use with wind turbines. This type of arrangement comprises either an external ring earth electrode in contact with the soil for at least 80 % of its total length or a foundation earth electrode. The ring electrodes and metal parts in the foundation shall be connected to the tower structure.

9.1.4 Earthing system impedance

The conventional earthing impedance of the earthing system does not affect the efficiency of the air termination system and down conducting system. The earthing system shall be designed to have as low an impedance as possible to reduce the total voltage drop when conducting transient lightning currents (i.e. minimise the earth potential rise), to reduce the partial lightning current flowing into the service lines connecting the wind turbine and to reduce the risk of sparks to other service lines close to the earthing system.

The party responsible for designing the foundation shall document the remedies implemented to reduce the earth potential rise when exposed to direct lightning attachment with stroke current of I rise time corresponding to LPL I. The documentation shall show how compliance with IEC 62305-3 is achieved, and how surge frequency impedances of the earthing system are considered with regard to touch and step voltage, DC and transient earthing system voltage rise.

Additional information is included in I.2.2.

9.2 Equipotential bonding

9.2.1 General

Equipotentialisation is achieved by interconnecting the LPS with

- structural metal parts;
- metal installations;
- internal systems;
- external conductive parts and service lines connected to the structure.

When lightning equipotential bonding is established to internal systems, part of the lightning current may flow into such systems and this effect shall be taken into account.

The manner in which lightning equipotential bonding of service lines such as telecommunication and power lines is achieved is important and shall be discussed with the operator of the telecommunication network, the electric power system operator and other operators or authorities concerned, as there may be conflicting requirements.

9.2.2 Lightning equipotential bonding for metal installations

Lightning equipotential bonding connections shall be made as direct and as straight as possible.

The minimum values of the cross section of the bonding conductors connecting different bonding bars/points and of the conductors connecting the bars/points to the earth termination system are listed in IEC 62305-3.

The minimum values of the cross section of the bonding conductors connecting internal metal installations to the bonding bars/points are listed in IEC 62305-3.

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9.3 Structural components

9.3.1 General

In general, all structural conducting components of the wind turbines will be able to conduct a part of a lightning current and thus equipotential bonding of structural conducting components shall be made.

9.3.2 Metal tubular type tower

The tower shall be considered as the primary protection earth conductor (PE) and equipotential bonding connection.

Due to the height of the towers, direct lightning attachment to the tower structure shall be expected and thus considered in the design of the tower. All electrical conducting components and all major metal parts that may conduct lightning current shall be bonded to the tower. The tower shall be used as the down conductor and constructed in such a way that lightning current can flow unobstructed.

9.3.3 Metal reinforced concrete towers

The tower shall be considered as the primary protection earth conductor (PE) and equipotential bonding connection. Due to the height of the tower, direct lightning attachment to the tower structure shall be expected and thus considered in the design of the tower (see IEC 62305-3).

External lightning protection systems can be considered for use with concrete towers, but should always be bonded to the steel reinforcement of the tower.

Equipotential bonding outlets connected to the steel reinforcement shall be placed at strategic termination points for bonding of equipment inside the tower. The reinforced concrete tower shall be designed in accordance with 9.3.6.

Due to the increasing height, towers are also designed as "hybrid towers" where the upper part is designed as a metal tubular tower (see 9.3.2). The lower part is designed as a metal reinforced concrete tower. Special attention shall be paid to the equipotential bonding connections placed between the upper and lower part of the tower. These connections need to be distributed around the platform-tower interface wall at several positions at equal spacing around the perimeter in order to effectively provide electromagnetic shielding of the inside of the tower and facilitate the protection of internal installations. These connections shall withstand the electromechanical and thermal effects of lightning current (see IEC 62305-3). This can be achieved by choosing components that have successfully been tested in accordance with IEC 62561-1.

For concrete towers wholly or partly constructed of elements and anchoring steel wires, tendons, flanges and similar designs (e.g. modular pre-cast towers), all parts and connections of such systems shall be able to sustain the effects of conducting the relevant level of lightning current and the corresponding electrodynamic forces (see IEC 62305-3) without compromising the mechanical design requirements.

9.3.4 Lattice tower

A lattice tower protects the inside of the tower against direct lightning attachment and provides some reduction of the lightning electromagnetic field, hence the space inside the tower is defined as LPZ 0_B. The lightning down conduction should be done via the lattice tower structural elements, which therefore have to fulfil the dimensions required for down conductors stated in IEC 62305-3 taking current sharing between the parallel paths into account.

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Some protection for cables can be achieved by placing them in the inside corners of the tower leg metal profiles. Shielding cable conduits or trays placed inside the lattice tower will also provide protection.

9.3.5 Systems inside the tower

The inside of the tower shall have its LPZ defined for which the protection level required for internal equipment shall be evaluated as discussed in 8.5.

Ladder systems shall be bonded to the tower at each end and at every platform. It shall be ensured by bonding that touch and step voltages never exceed values listed in IEC 62305-3.

Rails, guides for hoists, hydraulic piping, tendons, wires for personal protection and other components passing through a tower shall be bonded at each end.

If relying on separation distance in the design, this shall be specifically addressed and documented.

The HV transformer earthing system should be connected to the wind turbine earthing system. It is not recommended to use separate earthing systems for power systems and lightning protection.

9.3.6 Concrete foundation

Since the metal reinforcement of the wind turbine foundation will always be part of the lightning or fault current path to remote earth due to the mechanical and electrical connections to the tower, the metal reinforcement in a foundation shall always be considered a part of the LPS.

Electrical continuity of steelwork in reinforced concrete structures shall be ensured. Steelwork within reinforced concrete structures is considered to be electrically continuous if the major parts of vertical and horizontal bars are connected. Connections between metal reinforcement parts shall be either welded, clamped or overlapped by a minimum of 20 times their diameters and bound by conductive thread or otherwise securely connected. Special care should be exercised at the interconnections to prevent damage to the concrete due to localised arcing across poor contacts.

The connections between reinforcement elements shall be specified by the designer, and the installer shall carry out QA control of connections. The requirement for short and straight connections for the lightning protection earthing shall be recognised at all times.

If the metal reinforcement is used for the power system protective earth, the thickness of the metal reinforcement rods and the connections shall comply with the requirements for power system earthing systems which are usually stipulated in the electrical code.

Outlets for additional bonding, measurement or expansion of the earthing system shall be made at appropriate locations on the foundation.

9.3.7 Rocky area foundation

In rocky areas, the lowest resistivity is normally in the surface of the rock. ITU-R P.832-3 provides maps showing regions where high resistivity rock with conductivity of 1 mS/m or less (resistivity of 1 000 Ωm or more) is expected

The B type earth termination system shall be used. See I.1.1 for further information on design details.

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A low-frequency ground potential rise study needs to be done to analyse the conditions of the individual site, and the earthing system shall be designed based on this and fulfilling the requirements to allowed touch and step voltages.

Rock anchor bolts shall be interconnected to each other and to the ring earthing system. If metal reinforced concrete is used, please refer to 9.3.6.

In rocky areas, it may not be possible to reach a low earthing resistance without establishing very extensive earthing systems. In such areas, emphasis should therefore be on providing surface potential difference control to limit touch and step voltages at the surface where people and livestock are likely to be standing, such as by placing one or more ring electrodes around the wind turbines and other installations, while providing surge protection for all service lines connecting the wind turbines to the power collection system and communication systems (see 8.5).

9.3.8 Metal mono-pile foundation

A metal mono-pile foundation is by nature a large earth electrode. It shall be used as the primary earth electrode.

A ring electrode system for controlling the surface potential gradients close to the foundation may be necessary depending on soil resistivity.

9.3.9 Offshore foundation

The resistivity of seawater is considerably lower than most soils (See ITU-R P.832-3 for information on seawater resistivity). Therefore, for an offshore foundation, such as a mono-pile or metal reinforced concrete foundation, the earthing system requirements are considered fulfilled and no additional measures such as ring electrode, etc. are required. Interconnection of offshore foundations other than by the connection of power collection system cable shields to local earth at both ends is generally not required.

External earthing systems of copper cannot be used off shore due to corrosion issues.

9.4 Electrode shape dimensions

The minimum length, l_1, of earth electrodes depends on the lightning protection level (I-IV) and on the soil resistivity.

For soil resistivities higher than 500 Ωm, the minimum length, l_1, increases linearly up to 80 m at a soil resistivity of 3 000 Ωm.

A type B arrangement comprises either a ring conductor external to the structure to be protected, in contact with the soil for at least 80 % of its total length, or a foundation earth electrode. Such earth electrodes may also be meshed.

For the ring earth electrode (or foundation earth electrode), the mean radius, r_e, of the area enclosed by the ring earth electrode (or foundation earth electrode) shall not be less than the value l_1:

$$r_e \geq l_1 \tag{20}$$

Where l_1 is represented in Annex I, Figure I.1 according to LPS levels I, II, III and IV.

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When the required value of l_1 is larger than the convenient value of r_e, additional horizontal or vertical (or inclined) electrodes shall be added with individual lengths l_r (horizontal) and l_v (vertical) given by the following equations:

$$l_r = l_1 - r_e \quad (21)$$

$$l_v = (l_1 - r_e)/2 \quad (22)$$

The number of electrodes shall be not less than two.

The additional electrodes should be connected as equidistantly as possible.

The stated minimum length, l_1, can be disregarded if the earthing resistance of the earthing system is less than 10 Ω measured at a frequency different from power frequency (50 Hz to 60 Hz) and low order harmonics hereof.

Information about the soil resistivity, prospective earth fault current and clearance time is of utmost importance in the planning of the correct design and installation of the earthing system.

The soil resistivity will differ very much depending on the character of the soil. Methods for calculating the necessary earth electrode according to geometrical and physical shapes are given in Annex I.

9.5 Execution and maintenance of the earthing system

The earthing system designer shall prepare an installation plan, which describes the layout of the earthing system with details of connection points, the use of connectors, clamps and welds, the position and amount of outlets and their type and quality.

Inspection shall be carried out during construction work, particularly before casting of concrete.

NOTE Electrical codes can require measurement of the earthing resistance.

A service and maintenance manual shall describe how often and how to inspect and maintain the earthing system. The inspection intervals should be agreed between the designer and the operator of the wind turbines. It should take into account aggressive environments where more regular inspection might be necessary. If components in the earthing system are expected to have a certain service life time, the inspection interval cannot be longer than the shortest expected service life time of the components.

10 Personal safety

Erection of large wind turbines on land takes several days when including the time it takes to assemble and disassemble the very large cranes that are used. Offshore wind turbines on the other hand may be erected within less than a day by the use of special vessels or jack-ups. In any case, there is usually up to a few weeks of post erection completion work before the wind turbine is commissioned. During this time, many people work in, on and around the wind turbine, and they are at considerable risk of being affected if lightning strikes the wind turbine.

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Therefore safety procedures with regard to lightning should be established. Such procedures should include:

- regular checking of local weather forecasts (e.g. every morning);
- first aid training for personnel in relation to lightning injuries and injuries due to electrical accidents;
- application of intermediate earthing system connections as soon as possible;
- identification of safe locations;
- information about signal for lightning warning to everybody on the site;
- personnel instructions to
  - keep lookout for developing thunderclouds, audible thunder and visible lightning;
  - be aware of signs of high electrical fields from thunder clouds, such as hair standing on end, crackling sounds or light glow from pointed extremities such as air termination systems;
  - interrupt work and go to nearest safe location when lightning threat has been realised or lightning warning signal is received.

Such safety procedures should be included in the health and safety plan of the construction site and should be included in the wind turbine erection manual as well as the service and maintenance manual provided by the wind turbine supplier.

Safe locations should be clearly identified by marking (e.g. pictograms).

Weather bureaus usually provide reasonably accurate thunderstorm forecasts and even provide warning services by telephone, text messages, or internet, which should definitely be considered. However, it should not replace instruction of people on site to keep lookout for developing thunderclouds, thunder (audible within 10 km to 15 km) and lightning (visible within ~ 30 km). Local area and even portable lightning detection and thunderstorm warning devices, which could be useful, are available from different manufacturers. Refer to Annex L for further information on lightning monitoring systems.

Some lightning warning systems may not provide warning of all lightning flashes, especially of the first lightning flash in a developing storm (see IEC 62793 for information on thunderstorm warning systems). Therefore, it is essential that all personnel are made aware of the risk of lightning to their personal safety.

During construction work, connection of cranes, generators, etc. to the earthing system should be made as soon as possible.

People working on the outside of the nacelle and on the blades are definitely not safe, just as people stepping out of the wind turbine tower, standing next to the tower, climbing ladders, touching or working on electrical circuits, hardwired communication system etc. will be at risk if lightning strikes the wind turbine. They should therefore be instructed to stop work and go to safe locations until the danger is over.

Platforms inside tubular towers are in general considered safe locations, as the tower is a near to perfect Faraday cage. People in the wind turbine should be instructed to stop work and go to the closest platform inside the tower and stay there until the thunderstorm has passed. Other safe places are inside metal roof vehicles, metal containers, etc.

As it may be difficult to communicate effectively in a construction area, some kind of acoustic warning signal, radio or equivalent effective means of wide area warning should be agreed (it could just be repeated honking of a car horn or a compressed air horn).

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The wind turbine documentation shall define safe locations in the wind turbine including necessary personal safety distances and other precautions to be taken by people while at the safe location, such as instructions to stand or sit on the platforms and avoid touching electrically conducting systems extending vertically in the tower.

The separation distance as defined in IEC 62305-3 can be used to calculate the personal safety distance to avoid uncontrolled flashovers to persons at the safe locations.

11 Documentation of lightning protection system

11.1 General

This clause summarises all documentation required in other clauses. The descriptions are shortened and grouped for improved overview.

Documentation during assessment for design evaluation is given in 11.2, and for site assessment in 11.3. Documentation needed prior to inspection of lightning protection systems is given in 11.4, and manuals are listed in 11.5.

The documentation may either be a separate lightning protection document, or references to the other documentation where the information is available.

11.2 Documentation necessary during assessment for design evaluation

11.2.1 General

General documents (11.2.2) shall have the focus on the wind turbine as a whole and showing the protection philosophy used. They shall have links to the other, more detailed documents for rotor blades, mechanical, electrical, bonding, earthing and other systems (11.2.3 through 11.2.7).

11.2.2 General documentation

a) General arrangement drawing (single-line representation) of the wind turbines lightning-protection, comprising:
   1) the separate structures and the connections;
   2) circuit diagrams showing LPZ and their boundaries, Annex E give basic examples for such a documentation;
   3) lightning air termination systems;
   4) location of lightning down conductors;
   5) earth electrodes and surface potential control;
   6) location of the bonding conductors and bonding bars;
   7) location of SPDs;
   8) cable shield bonding points.

b) Design
   1) description of how the lightning current is conducted away from the interception points and through the wind turbine to the earthing system;
   2) lightning protection level used for the design;
   3) if less than LPL I is used the risk assessment should be documented;
   4) an analysis of the lightning current distribution within the wind turbine;
   5) selection and verification of SPD's energy coordination;
   6) specification of materials used, including corrosion properties and corrosion protection;
   7) identification of wear parts and maintenance-free parts of the LPS.

c) Personnel safety procedures with regards to lightning.

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11.2.3 Documentation for rotor blades

a) Drawing of the rotor blades containing:
   1) down conductor cross-sectional areas;
   2) any additional conductive components;
   3) connection between individual down conductor segments.

b) Description containing:
   1) mounting of the air termination and down conductor systems;
   2) measures taken to avoid internal arcing in the blade;
   3) definition of the required inspection and maintenance for the air termination system, spark gaps or sliding contacts;
   4) definition of required inspection and maintenance for down conductor system and connection components;
   5) instructions for inspection and maintenance, including definition of replacement criteria for wear parts.

c) Documentation of method of verification showing the ability of the air-termination and down conductor system to sufficiently intercept lightning strikes and conduct lightning currents.

11.2.4 Documentation of mechanical systems

a) Verification of lightning-current-conducting capability.

b) Descriptions of measures taken to protect bearings and hydraulic systems from the effect of lightning current. The description shall contain documentation and evidence of its proven technology and/or test reports verifying the effectiveness of protection measures.

c) If no protection is provided, test reports are required showing that even with regular lightning impacts, the bearings are able to be operated for the design lifetime.

11.2.5 Documentation of electrical and electronic systems

a) electrical and electronic systems shielding and installation design;

b) SPD selection and coordination;

c) immunity levels of the equipment;

d) maintenance plan for SPDs;

e) analysis defining the need for high-voltage arresters.

11.2.6 Documentation of earthing and bonding systems

a) general electric equipotential plan for all bonding and earthing in the turbine, showing the general electrical equipotential bonding system;

b) descriptions and drawings containing relevant data;

c) specification of materials used, including corrosion properties and corrosion protection applied;

d) description of QA (quality assurance) control to be made to connections in the LPS.

11.2.7 Documentation of nacelle cover, hub and tower lightning protection systems

a) Drawing containing the following information:
   1) nacelle cover, spinner showing metal parts used as lightning air termination system;
   2) air termination systems;
   3) bonding points;
   4) description and marking of earth system connection points if applicable;
   5) metal nets or closed metal conduits, where applicable;
   6) the shielding measures for the hub and nacelle;
   7) marking of measurement points.

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b) Test reports or certificates of used LPS components if applicable.

c) Bonding of external lightning protection systems for concrete towers to the reinforcement metal of the tower.

d) Lattice tower structural elements dimensions.

11.3 Site-specific information

Site-specific information and documentation is not part of the design evaluation of a wind turbine.

a) Lightning occurrence in the region of the wind farm site.

b) For earthing documentation additionally:

   1) soil resistivity;

   2) earth fault current;

   3) earth fault clearance time;

c) Health and safety plan for the construction site with respect to lightning and thunderstorms.

11.4 Documentation to be provided in the manuals for LPS inspections

a) description of the LPS;

b) description of earthing system;

c) reports of previous inspections, if relevant;

d) visual LPS inspection report template;

e) complete LPS inspection report template.

11.5 Manuals

The following manuals (instructions), which can be combined, shall cover relevant issues with regards to lightning protection and earthing systems:

a) foundation installation and maintenance manuals;

b) tower installation and maintenance manuals;

c) wind turbine transport, assembly and commissioning manuals;

d) wind turbine operation, service and maintenance manuals.

12 Inspection of lightning protection system

12.1 Scope of inspection

As part of the lightning protection concept, an inspection programme shall be defined and included in the wind turbine manuals. The objective of the inspections is to ensure that:

- the LPS continues to conform to the original design based on this document;
- all components of the LPS are in good condition and capable of performing their designed functions.

The LPS shall be designed in a way that enables the operator to inspect the vital parts of the system.

The manufacturer of the wind turbine is responsible for making an inspection plan/inspection instruction and including self policing points in work instructions, wind turbine service and maintenance manuals, and foundation maintenance manual, etc.

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12.2 Order of inspections

12.2.1 General

An inspection programme shall be established. Inspections should be performed in accordance with 12.1 and shall at least be performed during the following processes:

- production of the wind turbine;
- installation of the wind turbine;
- commissioning of the wind turbine;
- at reasonable intervals with regard to the location of the wind turbine (general maximum intervals between regular inspections are given in Table 6);
- after situations where parts of the wind turbine have been dismounted or repaired (i.e. blades, main components, controls systems, etc.).

12.2.2 Inspection during production of the wind turbine

The inspection programme can be done by quality inspectors or by self policing according to statements in the inspection plan. During the production, erection and installation of the wind turbine, it shall be secured that all installations and measures related to lightning protection are done properly. All important details shall be described in work instructions, etc.

12.2.3 Inspection during installation of the wind turbine

The earthing system shall be inspected carefully during the installation, with special focus on:

- mechanical damage during excavation and back filling;
- mechanical stability during casting;
- electrical connectivity to other steel parts (e.g. stairs on the outside);
- connection to foundation earthing systems;
- connection to external earthing systems;
- galvanic corrosion.

There might be other parts of the system not visible for inspection afterwards, which will require special focus during installation.

12.2.4 Inspection during commissioning of the wind turbine and periodic inspection

As part of the commissioning of the wind turbine, the lightning protection system shall be inspected. This shall be performed at least by visual inspection – and by continuity measurement in places where the LPS cannot be inspected. Continuity measurements shall be made in accordance with IEC 62305-3 and shall be made with an appropriate instrument, such as a four-wire micro ohm meter. Refer to Annex J for an example of defined measuring points.

NOTE Connections via brushes or spark gaps or equivalent can be short circuited if necessary to make a continuity measurement of other parts of the LPS.

When the inspection plan is made, it is important to take the following points into consideration:

- erosion and corrosion of air termination elements (only periodic inspection);
- mechanical and electrical properties of conductors, connections, sliding contacts or spark gaps;
- condition of connections, equipotential bonding, fixings, etc.;
- conditions of SPDs;

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- corrosion of earth electrodes (only periodic inspection).

With certain intervals (given in Table 6), a complete inspection including measurements of continuity in vital parts of the LPS and inspection of SPDs that are not monitored shall be performed.

The blade manufacturer and the wind turbine manufacturer may in his service and maintenance manuals define specific LPS inspection intervals as a function of N_d, the number of lightning flashes to the wind turbine per annum based on the durability of the lightning protection design documented by analysis and testing. Maintenance may depend on lightning strike occurrence if lightning strikes to the wind turbine are monitored.

Continuity measurements can be made with an appropriate four-wire resistance meter, to verify the continuity. The pass criterion to be used may depend on the design and shall therefore be defined by the manufacturer. Lack of continuity is clearly a failure, but measurement of continuity itself does not validate the design.

The objective with the measurement is to demonstrate the continuity of the connection and not to get a certain value.

The specific values can be used as references between periodic measurements. Measuring points and pass criteria shall be defined in the service and maintenance manual.

Preferably, continuity of down conductors in wind turbine blades should be ensured by the construction of the system and checked during manufacturing so that continuity measurements in the field are not needed.

The manufacturer shall provide an inspection plan for the different parts of the LPS that needs to be inspected. The plan shall define how often and how the different parts shall be visually inspected and/or inspected by measurement. A general LPS inspection plan is provided in Table 6, which shall be used if an inspection plan is not provided by the manufacturer. Other inspection intervals than those stated in Table 6 may be used if the manufacturer provides documentation for the inspection intervals relevant for the specific LPS design.

Table 6 – LPS General inspection intervals

Protection level	Visual inspection (every X year)	Complete inspection including continuity measurements (every X year)
I and II	1	2
III and IV	1	4

12.2.5 Inspection after dismantling or repair of main parts

After dismantling or repair of main parts of the wind turbine, it shall be ensured that all installations related to the LPS are restored properly. If necessary, a full inspection shall be performed.

When the wind turbine is in normal operation, the inspection frequency will be determined in accordance with the local environmental conditions, but it shall be specified that the wind turbine is inspected as defined in 12.2.4.

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12.3 Maintenance

Regular inspection is a fundamental condition for a reliable maintenance of a wind turbine LPS.

If the design of the LPS comprises wear parts (air termination points, mechanical sliding contacts, spark gaps, surge protection devices, etc.), it shall be ensured that these parts are maintained regularly during the periodic inspections – and in accordance with their expected service lifetimes – or that they are monitored by an automatic monitoring system that informs the operator of the wind turbine that a component is faulty.

All worn or defective components shall be changed without delay.

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Annex A
(informative)

The lightning phenomenon in relation to wind turbines

A.1 Lightning environment for wind turbines

A.1.1 General

The objective of this Annex A is to present in short form the most necessary information relevant for understanding the lightning phenomenon and the processes involved when lightning interact with wind turbines. More comprehensive information is available in the literature [4].

A.1.2 The properties of lightning

Lightning can be regarded as a current source, and the four lightning current parameters of concern in connection with design and dimensioning of lightning protection are: the peak lightning current (I), the steepness of the lightning stroke current impulses (di/dt), the charge transferred (Q) and the specific energy (W/R).

The recorded values of peak lightning current produced by a single stroke are in the range 2 kA to 300 kA. The maximum recorded values of charge transfer and specific energy are some hundreds of Coulombs (C) and, on very rare occasions, up to 20 MJ/Ω, respectively. These lightning current parameters govern the amount of physical damage that is done to wind turbine blades and/or the lightning protection system hardware. The stroke currents produce the high pressures that sometimes rupture blade composite structures. They also influence the magnitudes of lightning-indirect effects on electrical and electronic systems. The charge transferred produce melting at places of lightning attachment, such as the receptors, and at other places where lightning currents pass across gaps in the current path. The effects of the four lightning current parameters on lightning protection systems are summarised in Table A.3.

The maximum values of these parameters occur in only a small percentage of lightning flashes. The median value of peak lightning current is approximately 30 kA with median values of charge transfer and specific energy of 5 C and 55 kJ/Ω, respectively. In addition, the electrical characteristics of a lightning current vary with the type of lightning flash, season of the year and the geographical location.

The electric fields that immediately precede lightning attachments are also part of the lightning environment. These fields determine where lightning will attach to a structure, and whether non-conducting surfaces of the structure get punctured by streamers and connection leaders induced by these fields from internal conducting elements.

A.1.3 Lightning discharge formation and electrical parameters

Lightning flashes are produced following a separation of charge in thunderstorm clouds by processes described in the scientific literature (e.g. [4]). A lightning flash is observed when this charge is discharged to the earth or to a region of opposite polarity charge within the same cloud or a neighbouring cloud. The discussion that follows is concerned only with lightning flashes striking earth, resulting in the transfer of charge between a thundercloud and the earth.

A lightning flash usually consists of several components. The whole event following the same ionised path is called a lightning flash, which lasts up to about 1 s. The individual components of a flash are called short strokes and long strokes, where the latter are more commonly known as continuing currents.

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Lightning flashes are one of two basic types, downward or upward initiated. A downward initiated flash starts at the thundercloud and heads towards the earth. In contrast, an upward initiated flash starts at an exposed location on the earth (for example a mountain top) or at the top of a tall earthed structure and heads towards a thundercloud. Commonly, these basic types are referred to as "cloud-to-ground flash" or "downward flash" and "ground-to-cloud flash" or "upward (initiated) flash", respectively.

Both types of lightning are further sub-divided according to the polarity of the charge removed from the thundercloud. A negative flash lowers negative charge from the thundercloud to the earth. A positive flash results in positive charge being transferred from the thundercloud to the earth. The majority of lightning flashes are negative, making up about 90 % of all cloud-to-ground flashes. Positive discharges make up the remaining about 10 % of all cloud-to-ground flashes. Normally, the positive flashes exhibit the most powerful current parameters (i.e. higher I, Q and W/R), while the negative flashes exhibit the steepest current impulses (i.e. highest di/dt).

Each lightning flash is different due to the natural variations in the thundercloud that produced it and the individual paths to ground. For example, it is not possible to predict that the next lightning flash to a particular structure will have a peak current of a given value. What can be said is that the structure has a given probability of being struck by a lightning flash with current parameters exceeding a certain value.

Probability distributions of the electrical parameters that are used to describe a lightning stroke have been produced using direct measurements of actual strokes to tall towers. This statistical data on lightning current parameters is used in the lightning protection standards of the IEC 62305 series (see Table A.1). Further information is now becoming available worldwide from regional and national lightning location systems. These systems can record the location of a lightning stroke and estimate the peak current.

The probability distributions that describe the current parameters of a lightning are different for each type of lightning (upward/downward and positive/negative first, subsequent and continuing current). The appropriate probability distributions are described below along with the typical wave shape of each type of discharge. The probability level given indicates the probability of the specified current parameter of a particular lightning exceeding the tabulated value.

A.1.4 Cloud-to-ground flashes

A.1.4.1 General

A cloud-to-ground flash (downward initiated discharge) is initially formed by a preliminary breakdown within the cloud. The physics of this process are not fully understood at this time. The parts of the discharge process taking place below cloud level are much better known.

A.1.4.2 Negative cloud-to-ground flashes

In the case of a negative flash, a stepped leader descends from the cloud towards the ground in steps of several tens of metres with a pause time between the individual steps of approximately 50 μs. The steps have short-duration (typical 1 μs) impulse currents of more than 1 kA. The leader channel contains, when fully developed, a total charge of about 10 C or more. The channel diameter is in the range of up to a few tens of metres. The total duration of the stepped leader process is a few tens of milliseconds. The faint leader channel is usually not visible to the naked eye.

The end of the leader, the leader tip, is at a potential in excess of 10 MV with respect to the earth. As the leader tip approaches the earth, this high potential raises the electric field strength at the surface of the earth. When the electric field at ground level exceeds the breakdown value of air, "answering" (upward moving) leaders are emitted from the earth or from structures on the ground. These upward moving leaders are commonly called connecting leaders. Connecting leaders play an important role in determining the attachment point of a lightning flash to an object.

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When the descending stepped leader meets the upward moving connecting leader, a continuous path from cloud to ground is established. The charge deposited in the leader channel is then discharged to ground by a current wave propagating up the ionised channel at about one third of the speed of light. This process is called the first return stroke. The first return stroke may have a peak value of up to a few hundred kilo amperes and duration of a few hundred microseconds. The process of downward propagating lightning attachment is illustrated in Figure A.1, where it is illustrated that, relative to reference conditions (e.g. sea level), the exposure of objects on the ground is enhanced in areas with elevated ground and on mountains.

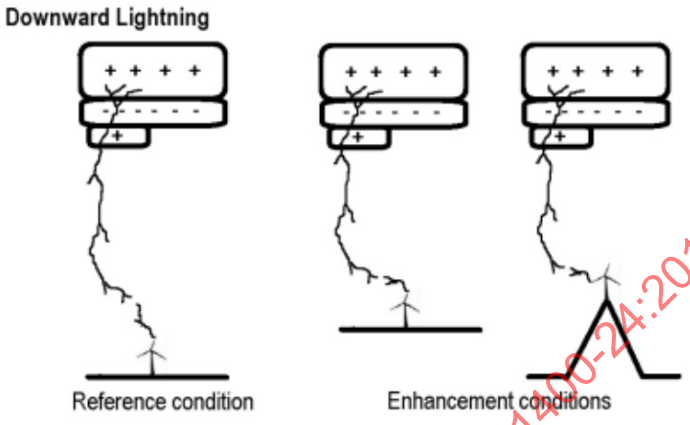

Figure A.1 – Processes involved in the formation of a downward initiated cloud-to-ground flash

After a time interval in the order of 10 ms to a few hundred ms, further leader/return stroke sequences may follow the path taken by the first return stroke. The (dart) leader preceding these subsequent return strokes is usually not stepped and much faster (duration of a few milliseconds). On average, a lightning flash contains three to four return strokes (including the first one). The return strokes constitute the visible part of the lightning flash.

Following one or more of the return strokes, a continuing current (also called a long stroke) may flow through the still-ionised channel. Continuing currents are quite different compared to the short-duration, high-amplitude currents of return strokes: the average current amplitude is in the range of a few hundred amperes, while the duration may be as long as several hundred milliseconds. Continuing currents transfer high quantities of charge directly from the cloud to ground. About one-half of all cloud-to-ground flashes contain a continuing current component.

Figure A.2 shows a typical profile of the lightning current in a negative cloud-to-ground flash. Following the contact of the stepped leader and the connecting leader, there is a first return stroke resulting (at ground) in a high-amplitude impulse current lasting for a few hundred microseconds. The current peak value is in the range of a few kA to 100 kA, the median value being about 30 kA (Table A.1). Following the first return strokes, subsequent return stroke(s) and continuing current(s) may occur. Although subsequent return strokes generally have a lower current peak value and a shorter duration than first return strokes, they generally have a higher rate of rise of current. Negative cloud-to-ground discharges may be composed of various combinations of the different current components mentioned above, as demonstrated in Figure A.5.

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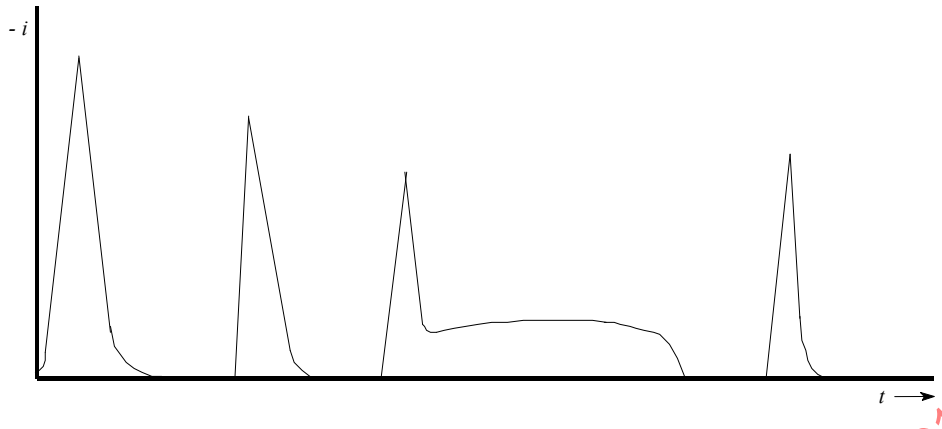
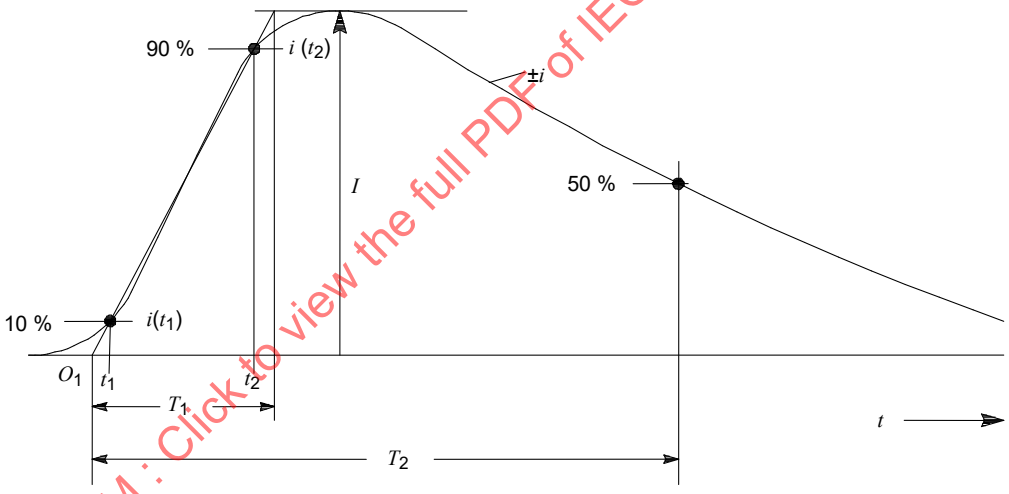


The drawing is not to scale.

Figure A.2 – Typical profile of a negative cloud-to-ground flash

A lightning current consists of one or more different strokes:

- short strokes with duration of less than 2 ms (Figure A.3);
- long strokes with duration of more than 2 ms (Figure A.4).



Key

O_1 virtual origin
I peak current
i current
t time
T_1 front time
T_2 time to half value

Figure A.3 – Definitions of short stroke parameters (typically T_2 < 2 ms)

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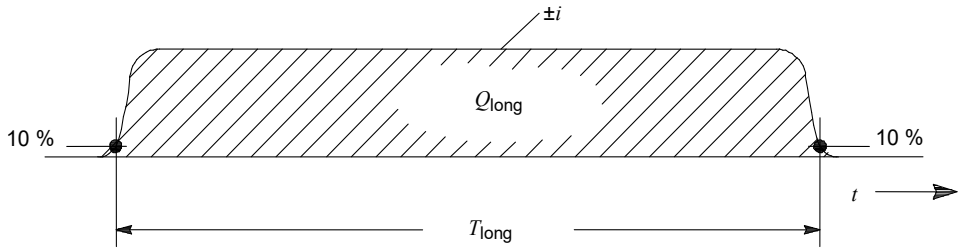

Key

T_{long} duration time

Q_{long} long stroke charge

This figure is adapted from IEC 62305-1.

Figure A.4 – Definitions of long stroke parameters (typically 2 ms < T_{long} < 1 s)

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Table A.1 – Cloud-to-ground lightning current parameters

Parameter	Fixed values for LPL I	Values			Type of stroke
		95 %	50 %	5 %	
I (kA)		4(98 %)	20(80 %)	90	First negative short stroke
	50	4,9	11,8	28,6	Subsequent negative short stroke
	200	4,6	35	250	First positive short (single) stroke
Q_{flash} (C)		1,3	7,5	40	Negative flash
	300	20	80	350	Positive flash
Q_{short} (C)		1,1	4,5	20	First negative short stroke
		0,22	0,95	4	Subsequent negative short stroke
	100	2	16	150	First positive short (single) stroke
W/R (kJ/Ω)		6	55	550	First negative short stroke
		0,55	6	52	Subsequent negative short stroke
	10 000	25	650	15 000	First positive short stroke
di/dt_{max} (kA/µs)		9,1	24,3	65	First negative short stroke
		9,9	39,9	161,5	Subsequent negative short stroke
	20	0,2	2,4	32	First positive short stroke
$di/dt_{30/90\ \%}$ (kA/µs)	200	4,1	20,1	98,5	Subsequent negative short stroke
Q_{long} (C)	200				Long stroke
t_{long} (s)	0,5				Long stroke
Front duration (µs)		1,8	5,5	18	First negative short stroke
		0,22	1,1	4,5	Subsequent negative short stroke
		3,5	22	200	First positive short (single) stroke
Stroke duration (µs)		30	75	200	First negative short stroke
		6,5	32	140	Subsequent negative short stroke
		25	230	2 000	First positive short (single) stroke
Time interval (ms)		7	33	150	Multiple negative strokes
Total flash duration (ms)		0,15	13	1 100	Negative flash (all)
		31	180	900	Negative flash (without single)
		14	85	500	Positive flash
This table is adapted from IEC 62305-1.					
NOTE The values of I = 4 kA and I = 20 kA correspond to a probability of 98 % and 80 %, respectively.					

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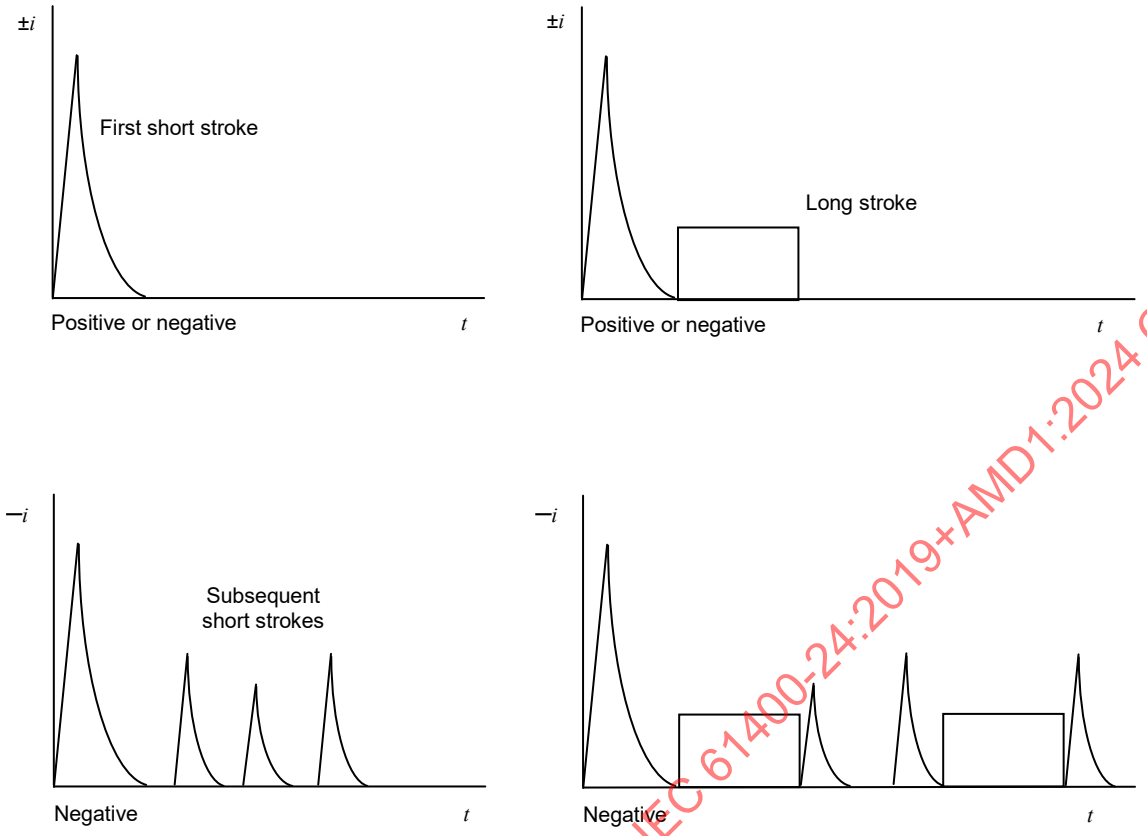

This figure is adapted from IEC 62305-1.

Figure A.5 – Possible components of downward flashes (typical in flat territory and to lower structures)

A.1.4.3 Positive cloud-to-ground flashes

In contrast to negative flashes, positive cloud-to-ground flashes are initiated by a continuously downward propagating leader which does not show distinct steps. The connecting leader and return stroke phases are similar to the processes described above for negative flashes. A positive cloud-to-ground flash usually consists of only one return stroke which may be followed by a continuing current.

Positive cloud-to-ground flashes are of great importance for practical lightning protection because the current peak value (I), total charge transfer (Q), and specific energy (W/R) can be larger compared to the negative flash. The return stroke tends to have a lower rate of current rise in comparison to a negative first return stroke. A typical current profile for a positive cloud-to-ground flash is shown in Figure A.6. Typical electrical parameters are summarised together with the parameters of negative discharges in Table A.1.

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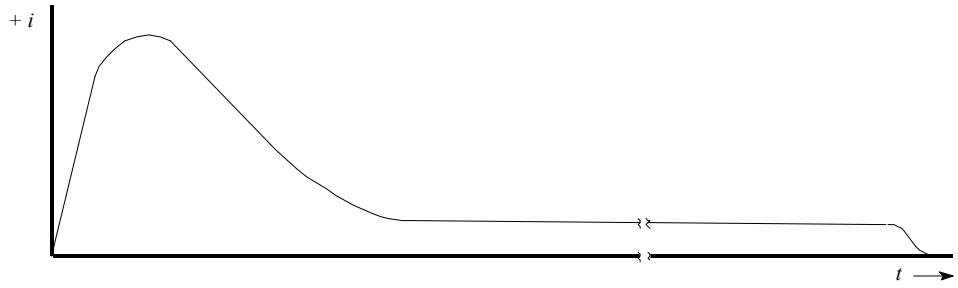

Figure A.6 – Typical profile of a positive cloud-to-ground flash

A.1.5 Upward initiated flashes

The charge in the thundercloud causes an elevation of the electric field on the surface of the earth, but usually not sufficient to launch an upward moving leader. However, the electric field may be significantly enhanced at mountains, objects placed on high ground, or at tall structures like towers or wind turbines (Figure A.7). At such locations, the electric field strength may become large enough to initiate an upward moving leader from ground towards the thundercloud. Structures with heights in excess of 100 m above the surrounding terrain (like modern wind turbines) are particularly exposed to upward initiated flashes.

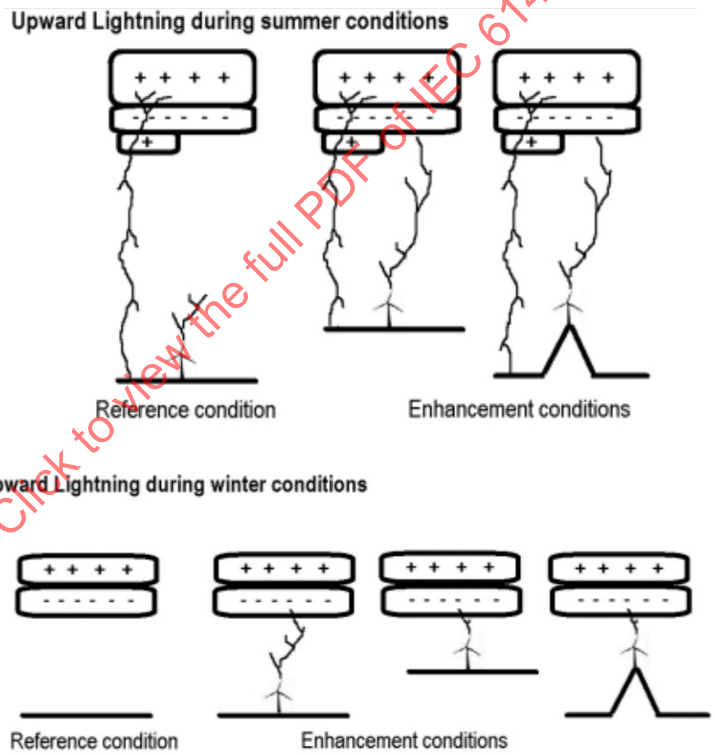

Figure A.7 – Processes involved in the formation of an upward initiated cloud-to-ground flash during summer and winter conditions

An upward initiated flash starts with a continuing current phase. Impulse currents can be superimposed on the continuing current (Figure A.8). The continuing current phase may be followed by subsequent return stroke(s) along the same channel. These return strokes are quite similar to the subsequent return strokes of cloud-to-ground flashes. Upward initiated flashes do not contain a component analogous to the first return stroke of cloud-to-ground flashes. The location where an upward lightning flash attaches to a structure is simply the same point where the upward leader is formed.

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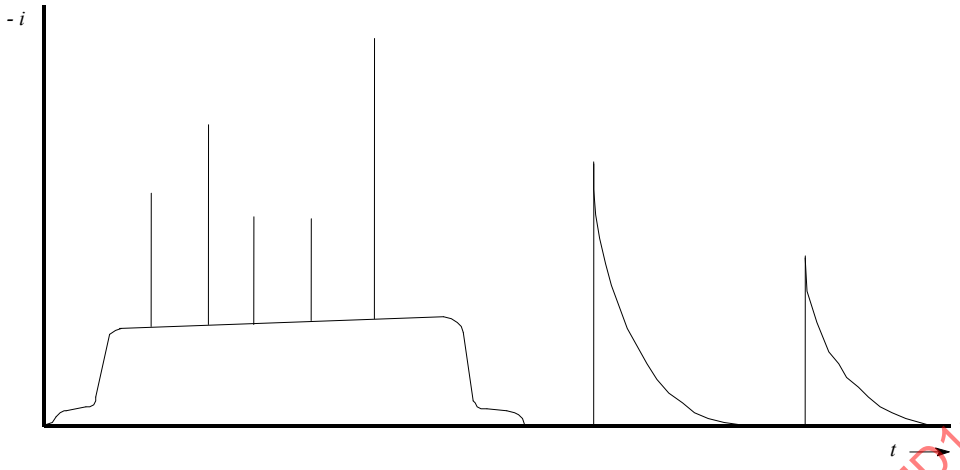

Figure A.8 – Typical profile of a negative upward initiated flash

Measurements of upward initiated flash parameters are made on tall objects that are prone to this type of flash. Detailed information from world-wide observations as well a comprehensive discussion of upward flashes by Rakov and Uman can be found in [4]. In recent years, upward flashes have also been studied by measurements on wind turbines.

The following information on current parameters relates to upward negative flashes since, although observed, upward initiated positive flashes are rare.

Although the current peak values of about 10 kA are relatively low, the charge transfer associated with the initial continuing current has in rare cases been as high as 300 C as shown in Table A.2 [4]. Upward initiated flashes, too, may be composed of various combinations of the different current components mentioned above, as illustrated in Figure A.9.

In general, upward initiated flashes have lower current parameter values when compared to downward lightning flashes, possibly with the exception of the total charge transferred. Furthermore, it is evident that tall objects placed at exposed locations may experience very frequent upward lightning flashes, particularly during winter thunderstorms where tens of upward lightning flashes have been observed on very exposed tall objects.

This is highly relevant for wind turbines because high and exposed locations are preferable for wind turbines owing to favourable wind conditions. Hence, it is necessary to consider the risk of upward lightning flashes, and developers are advised to seek information about winter lightning conditions at prospected sites. As upward lightning flashes originate from the extremities of the wind turbines (i.e. the blades and the air termination systems protecting the meteorological instrumentation on the nacelle), the point of attachment is given, and provided that the lightning protection is properly designed, it can be expected to function well also for upward lightning flashes.

However, a high frequency of winter lightning may make more durable air termination systems or periodic exchange of air termination systems necessary.

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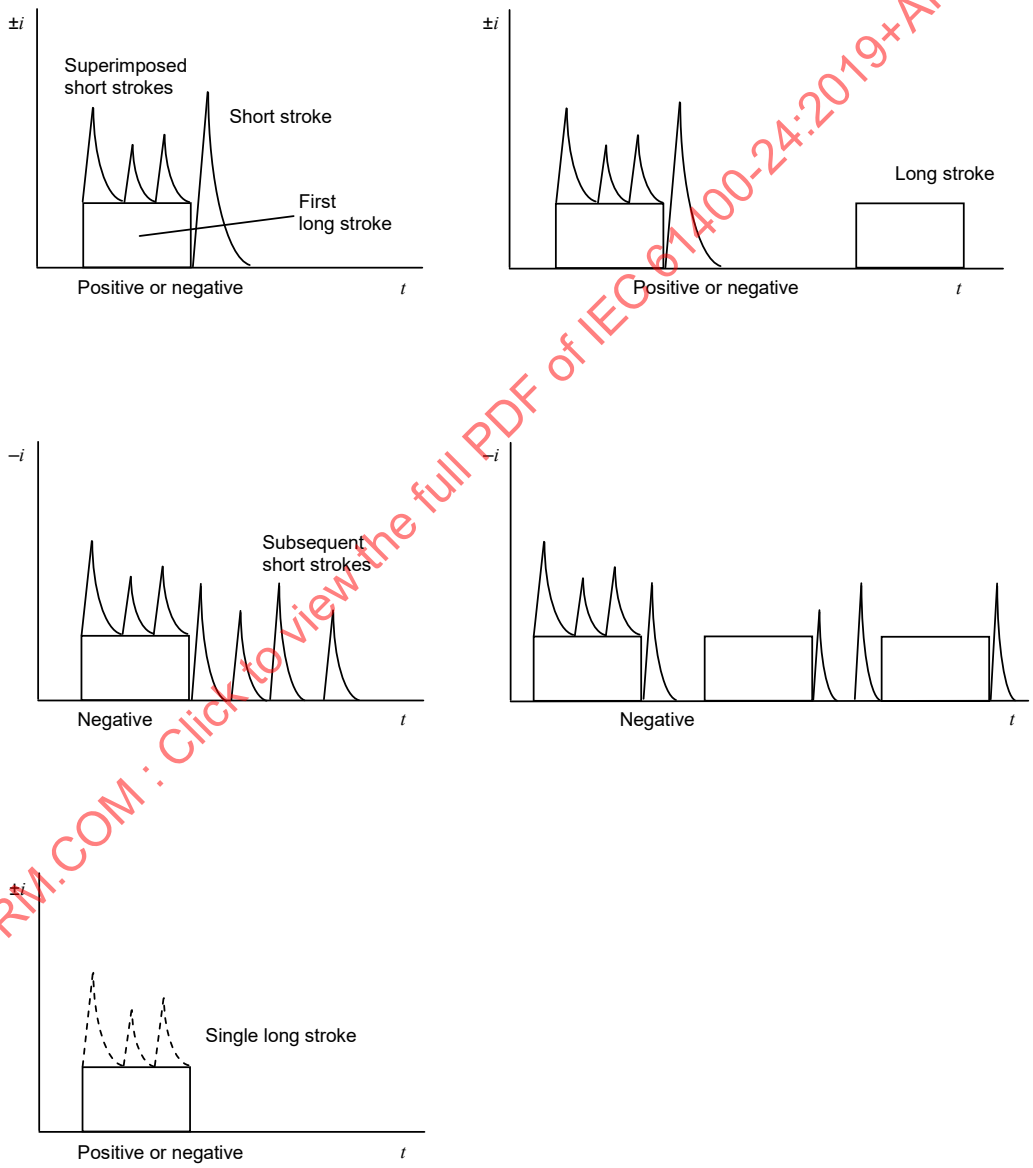
Table A.2 – Upward initiated lightning current parameters

Parameter		Maximum value
Total charge transfer	C	300[a]
Total duration	s	0,5 to 1,0
Peak current	kA	20[b]
Average rate of rise superimposed impulse currents	kA/μs	20
Number of superimposed impulse currents		50

[a] Extensive research shows that the total charge transfer in upward initiated winter lightning in Japan has a maximum value of 1 000 C.

[b] Extensive research shows that the peak current in upward initiated winter lightning in Japan has a maximum value of 100 kA.



This figure is adapted from IEC 62305-1.

Figure A.9 – Possible components of upward flashes (typical to exposed and/or higher structures)

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A.2 Lightning current parameters relevant to the point of strike

The lightning current parameters playing a role for the physical integrity of an LPS are in general the peak current I, the charge Q, the specific energy W/R, the duration T and the average steepness of the current di/dt. Each parameter tends to dominate a different failure mechanism. The current parameters to be considered for tests are combinations of these values, selected to represent in laboratory the actual failure mechanism of the part of the LPS being tested. Table A.3 records the maximum values of I, Q, W/R, T and di/dt to be considered for tests as a function of the protection level required (see IEC 62305-1, Annex D for further details).

Table A.3 – Summary of the lightning threat parameters to be considered in the calculation of the test values for the different LPS components and for the different LPL

Component	Main problem	Lightning threat parameters					Notes
Air termination	Erosion at attachment point (e.g. thin metal sheets)	LPL	Q_{long} C	T			
		I	200	< 1 s (apply Q_{long} in a single shot)			
		II	150				
		III-IV	100				
Air termination and down conductor	Ohmic heating	LPL	W/R kJ/Ω	T			Dimensioning with IEC 62305-3 renders testing superfluous
		I	10 000	Apply W/R in an adiabatic configuration			
		II	5 600				
		III-IV	2 500				
	Mechanical effects	LPL	I kA	W/R kJ/Ω			
		I	200	10 000			
		II	150	5 600			
		III-IV	100	2 500			
Connecting components	Combined effects (thermal, mechanical, and arcing)	LPL	I kA	W/R kJ/Ω	T		
		I	200	10 000	< 2 ms (apply I and W/R in a single impulse)		
		II	150	5 600			
		III-IV	100	2 500			
Earth terminations	Combined effects (thermal, mechanical, and arcing)	LPL	I kA	W/R kJ/Ω	T		Dimensioning usually determined by mechanical/ chemical aspects (corrosion, etc.)
		I	200	10 000	< 2 ms (apply I and W/R in a single impulse)		
		II	150	5 600			
		III-IV	100	2 500			
SPDs containing spark gaps	Combined effects (thermal, mechanical and arcing)	LPL	I kA	Q_{short} C	W/R kJ/Ω	di/dt kA/µs	Apply I, Q_{short}, and W/R in a single impulse (duration T < 2 ms); apply di/dt in a separate impulse
		I	200	100	10 000	200	
		II	150	75	5 600	150	
		III-IV	100	50	2 500	100	

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Component	Main problem	Lightning threat parameters					Notes
SPDs containing metal-oxide resistor blocks	Energy effects (overload)	LPL	Q_{short} C				Both aspects need to be checked
		I	100				
		II	75				
		III-IV	50				
	Dielectric effect (flashover/cracking)	LPL	I kA	T			Separate tests can be considered
		I	200	< 2 ms (apply I in a single impulse)			
		II	150				
		III-IV	100				
This table is adapted from IEC 62305-1.							

A.3 Leader current without return stroke

Upward leaders are initiated from the wind turbine itself when high electrostatic fields are present due to thunderclouds overhead or approaching leaders from thunderclouds. When such upward leaders do not connect to a leader from the cloud, there is no return stroke. The impulse currents associated with leaders are typically a few kA and can be up to 10 kA. The leaders can only start where high electrostatic fields can be generated. The magnitude as well as the current gradient implies an EM environment, which should be considered in the wind turbine EMC design.

A.4 Lightning electromagnetic impulse, LEMP, effects

LEMP effects cause overvoltages, which may include less energy than surges, caused by direct lightning strikes but which might occur more frequently. These kinds of overvoltages and surges might result from:

- conducted partial lightning currents;
- inductive/capacitive coupling;
- lightning flashes near the wind turbine;
- transmitted by line (power lines and/or communication lines due to lightning flashes to or near these lines).

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Annex B
(informative)

Lightning exposure assessment

B.1 General

In Clause B.2, a methodology to determine the average annual number of flashes to the wind turbines of a wind farm is presented and described. This methodology constitutes a guideline to estimate this parameter owing to the influence of many different conditions found throughout the world.

In Clause B.3, the terms used in this Annex B are explained.

Clause B.4 concerns the assessment of the probability of damage to the wind turbine.

In Clause B.5 concerns the assessment of the amount of loss L_X in a wind turbine.

B.2 Methodology to estimate the average annual flashes or strokes to the wind turbines of a wind farm and upward lightning activity in wind turbines

B.2.1 General

The methodology described in this clause can be used as a guideline to estimate the number of average annual flashes to the turbines in a wind farm. This methodology is not accurate in its current form and it is necessary to determine the values or range of values and the corresponding associated uncertainties of the different parameters. If a high accuracy of results is required, it is necessary to determine the values and reduce the uncertainties associated with each parameter. This can be done by means of field analysis and calibration.

B.2.2 Methodology to determine average annual flashes to turbines of a wind farm estimation by increase of the location factor to consider upward lightning from wind turbines

This methodology quantifies the increase of the average annual number of flashes by increasing the location factor, C_D. As described in Clause 7, the location factor can be used to consider local increase in lightning density (e.g. mountainous terrain) and quantify the increase of upward lightning being triggered in some conditions that favour the inception of triggered lightning from wind turbines.

N_{SG} defined in 7.2.2 is for downward lightning and has almost nothing to do with the frequency of upward lightning from tall structures; however, to estimate annual N_D it is recommended in 7.2.2.4 to use the location factor C_D for adjustment of the calculated N_D to match the actual frequency of lightning flashes attaching to a wind turbine increased by upward lightning. As a result, the location factor due to winter lightning activity C_{DWL} becomes relatively high in areas where winter lightning activity is relatively high (i.e. where winter lightning activity is high relative to the lightning activity in the summer/warm season).

The basic equation for flashes is:

$$N_D = N_{SG} \cdot A_D \cdot C_D \cdot 10^{-6} \quad \text{(B.1)}$$

Parameters in Equation (B.1), except the location factor, C_D, can be calculated as described in Clause 7. The increase of the annual average of lightning flashes per year in a wind farm is

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due to the amount of winter lightning activity, complexity of the mountain or hill and height above sea level where the wind farm is placed.

In order to quantify the different influence that location may have on wind turbines, the location factor, C_D, can be expressed as the sum of location factors:

$$C_D = C_{DWL} + C_{DC} + C_{DH} \tag{B.2}$$

where

C_{DWL} is the location factor due to winter lightning activity;

C_{DC} is the location factor due to complexity of local terrain;

C_{DH} is the location factor due to the height above sea level.

C_{DWL}, C_{DC} and C_{DH} are individual parameters that can be combined differently depending on local conditions.

In the following Table B.1, the recommended values of the specific location factors are summarized to be used in different locations.

Table B.1 – Recommended values of individual location factors

Winter lightning (C_{DWL})		Terrain complexity (C_{DC})			Height above sea level (C_{DH})	
Activity level	**C_{DWL} value[a]**	**Description**	**Complexity ratio[b]**	**C_{DC} value**	**Description**	**C_{DH} value**
No activity	0	Flat or moderate	< 0,3	1	< 800 m	0
Low activity	2	Hill	0,3 to 0,4	3	800 to 1 000 m	1
Medium activity	4	Mountain	> 0,4	4	> 1 000 m	2
High activity	6[c]					

[a] Degree of winter lightning may be found using the winter lightning world map in Figure B.1, or the detailed winter lightning maps in Figure B.2 (the Figure B.2, or by analysis of local lightning activity in the region of interest).

[b] Calculated according to Figure B.3.

[c] Could even be higher in some locations.

Terrain complexity considers the influence of the surrounding terrain on the increase of lightning activity (for both downward and upward lightning). This may be done by estimating the slope around wind turbines. Slopes may be calculated as the ratio between the height difference h and horizontal distance d from the turbine ranging from 300 m to 1 000 m. It is recommended to obtain the mountain profile and select the slope in the direction of highest value. In the range 300 m to 1 000 m, choose a distance value which leads to the highest slope. This slope method may not apply for all worldwide terrain complexities. Terrain definition given in Table B.1 can also be used to determine complexity (flat or moderate terrain, hill and mountain).

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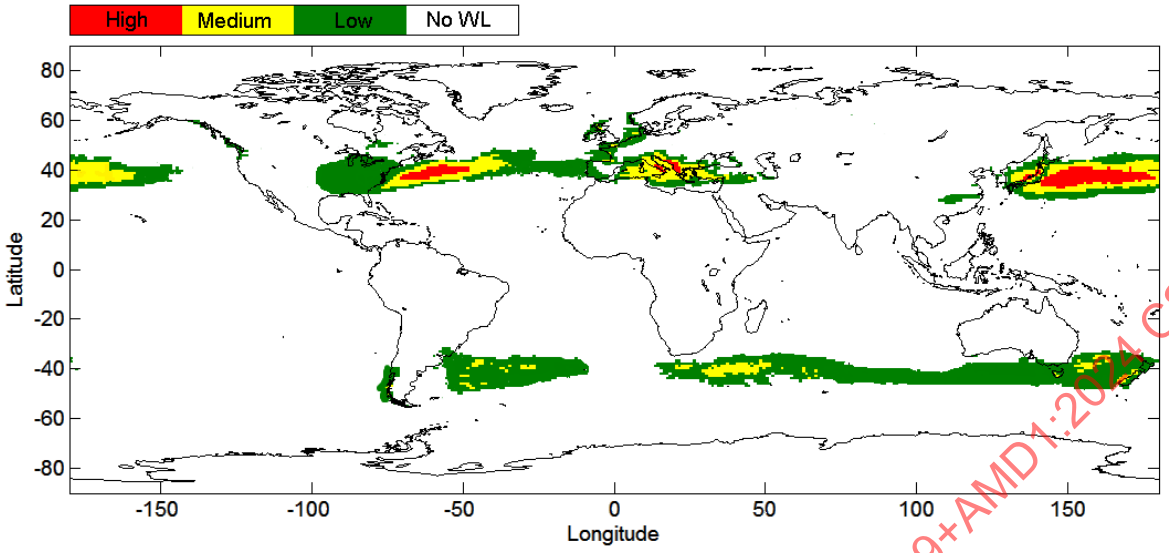

Colour scale indicates activity level high (red), medium (yellow), low (green) and no winter lightning (white).

Source: see [5]

Figure B.1 – Winter lightning world map based on LLS data and weather conditions

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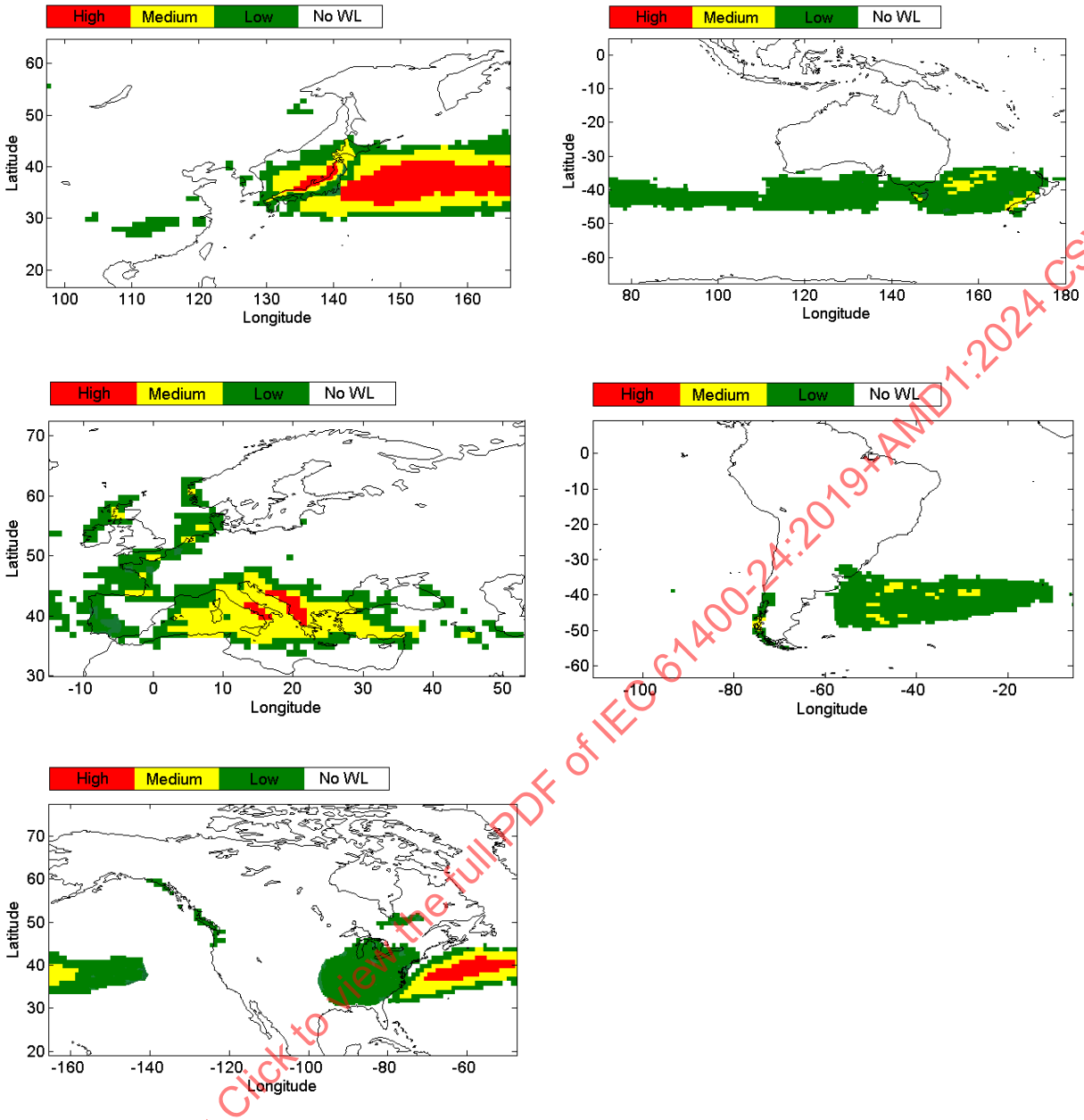
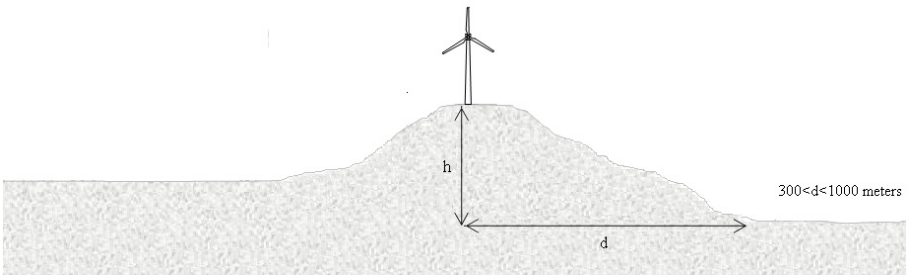


Colour scale indicates activity level high (red), medium (yellow), low (green) and no winter lightning (white).

Source: see [5]

Figure B.2 – Detailed winter lightning maps based on LLS data and weather conditions



d can take a value between 300 m and 1 000 m.

Figure B.3 – Ratio *h/d* description

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B.2.3 Upward lightning percentage in wind farms

Upward lightning activity should be expected for tall structures such as wind turbines as described in Annex A. Experience has shown that even wind turbines located in flat terrain without winter lightning activity can be affected by significant percentages of upward lightning activity. Upward lightning activity according to the mechanisms described in Annex A may be influenced by winter lightning activity as well as by local topographic conditions where the wind farm is erected. The following Table B.2 presents a percentage of upward lightning under winter lightning conditions for typical wind turbine heights in flat terrain. The percentages of upward lightning presented in Table B.2 may be higher for wind farms placed in mountainous terrain or at high elevation above sea level.

Table B.2 – Range of upward lightning activity as a function of winter lightning activity for wind farm located in flat terrain

Winter lightning activity level	Percentage of upward lightning %
High activity	80 to 99
Medium activity	40 to 90
Low activity	20 to 50
No activity	10 to 40

B.3 Explanation of terms

B.3.1 Damage and loss

Terms covering the topics damages and loss are defined in IEC 62305-2. Here are included the terms and topics considered relevant for wind turbines.

The lightning current is the primary source of damage. The following sources are defined depending on the lightning striking point:

S1: lightning flashes striking the wind turbine (flashes to the structure);

S2: lightning flashes striking near a wind turbine (flashes near a structure);

S3: lightning flashes striking a service line (incoming line e.g. power cable or telecommunication cable);

S4: lightning flashes striking near a service line (incoming line e.g. power cable or telecommunication cable);

NOTE 1 S2 lightning flashes striking near a wind turbine is not considered a threat when protection against direct lightning strikes to the wind turbine is provided.

NOTE 2 S4 lightning flashes striking near a service line is not considered a threat when protection against direct lightning strikes to the wind turbine is provided.

Four causes of damage are considered:

D_{1D}: electric shock to human beings resulting from direct lightning flashes strikes to those human beings;

D_{1T}: electric shock to human beings resulting from resistive and inductive coupling;

D_2: dangerous sparking triggering fire or explosion and/or leading to mechanical and chemical effects that may also endanger the environment;

D_3: surges due to all sources of damage.

The damage to a wind turbine due to lightning may be limited to a part of the wind turbine or may extend to the entire wind turbine.

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Lightning affecting a service line can cause damage to the service line system itself (e.g. the service line cable) or to electrical and electronic systems connected to the service line.

Each cause of damage, alone or in combination with others, may produce the following types of damages in the wind turbine. The types of damage considered relevant for wind turbines are:

L_1: injury to human beings. It is a consequence of D_{1D}, D_{1T}, D_2 and even D_3;

L_2: physical damage (thermal, mechanical, chemical or explosion etc.) of the wind turbine. It is a consequence of D_2 and even D_3 in structures with risk of explosion.

L_3: failure of electrical and electronic systems. It is a consequence of D_3.

The type of damage L_3 may unacceptably impair the availability of the internal systems of the wind turbine (e.g. the control system).

The risk R is the relative value of a probable average annual loss. For each type of damage which may appear in a wind turbine, the relevant risk should be evaluated.

To evaluate the risks, R, the relevant risk components (partial risks depending on the source and type of damage) should be defined and calculated.

Each risk, R, is the sum of its risk components. When calculating a risk, the risk components may be grouped according to the source of damage and the type of damage.

The risks to be evaluated due to lightning striking the wind turbine (source S1) are:

R_{AD}: risk component related to type of damage L_1 (injury to human beings), caused by a flash to human beings exposed on the wind turbine – owing to lightning striking wind turbine;

R_{AT}: risk component related to type of damage L_1 (injury to human beings) caused by electric shock due to touch and step voltages inside the wind turbine and outside in the zones within a distance of 3 m from the tower;

R_B: Component related to type of damage L_1 and L_2 (physical damage) caused by dangerous sparking inside the wind turbine triggering fire or explosion, which may also endanger the environment.

R_C: Component related to type of damage L_1 and L_2, caused by failure of internal systems because of LEMP.

The risks to be evaluated for a wind turbine due to lightning striking near the wind turbine (source S2) are:

R_M: Component related to type of damage L_1 and L_2, caused by failure of internal systems because of LEMP.

The risks to be evaluated for a wind turbine owing to lightning striking the service lines connected to the wind turbine (source S3) are:

R_U: Component related to type of damage L_1, caused by electric shock due to touch voltages inside the structure.

R_V: Component related to type of damage L_1 and L_2 caused by fire or explosion (triggered by dangerous sparking between external installation and metallic parts generally at the entrance point of the line into the wind turbine) due to lightning current transmitted through or along incoming lines.

R_W: Component related to type of damage L_1 and L_2, caused by failure of internal systems by overvoltages induced on incoming lines and transmitted to the wind turbine.

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The risks to be evaluated for a wind turbine due to lightning striking near the service lines connected to the wind turbine (source S4) are:

R_Z: Component related to type of damage L_1 and L_2, caused by failure of internal systems by overvoltages induced on incoming lines and transmitted to the structure.

B.3.2 Composition of risk

The risk R is the sum of the risk components according to the type of damage or the source of damage.

Composing the risk according to the type of damage:

$$R = R_{AT} + R_{AD} + R_B + R_C{}^2 + R_U + R_V + R_W{}^2 + R_Z{}^2 \quad \text{(B.3)}$$

Composing the risk according to the source of damage:

$$R = R_{S1} + R_{S2} + R_{S3} + R_{S4} \quad \text{(B.4)}$$

where:

$R_{S1} = R_{AT} + R_{AD} + R_B + R_C{}^2$

$R_{S2} = R_M{}^2$

$R_{S3} = R_U + R_V + R_W{}^2$

$R_{S4} = R_Z{}^2$

B.3.3 Assessment of risk components

Each risk component R_{AT}, R_{AD}, R_B, R_C, R_M, R_U, R_V, R_W and R_Z may be expressed by the following general equation:

$$R_X = N_X \cdot P_X \cdot L_X \quad \text{(B.5)}$$

where

R_X is the risk component for a structure (e.g. for the wind turbine)

N_X is the number of dangerous events per annum [year^{-1}];

P_X is the probability of damage to the structure (a function of various protection measures);

L_X is the amount of consequent loss.

This basic equation is to be used for assessing the risk of damage based on the probability of damage of various types and the consequent.

For evaluation of risk components owing to lightning flashes to the wind turbine (S1), the following relationships apply:

$$R_{AT} = N_D \cdot P_{AT} \cdot P_P \cdot L_{AT} \quad \text{(B.6)}$$

$$R_{AD} = N_D \cdot P_{AD} \cdot P_P \cdot L_{AD} \quad \text{(B.7)}$$

$$R_B = N_D \cdot P_B \cdot L_B \quad \text{(B.8)}$$

[2] Only in case failure of internal systems immediately endangers human life.

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$$R_C = N_D \cdot P_C \cdot P_P \cdot L_C \quad \text{(B.9)}$$

For evaluation of risk components owing to lightning flashes near the wind turbine (S2), the following relationship applies:

$$R_M = N_M \cdot P_M \cdot P_P \cdot L_M \quad \text{(B.10)}$$

For evaluation of risk components owing to lightning flashes to a line connected to the wind turbine (S3), the following relationships apply:

$$R_U = (N_L + N_{DJ}) \cdot P_U \cdot P_P \cdot L_{UT} \quad \text{(B.11)}$$

$$R_V = (N_L + N_{DJ}) \cdot P_V \cdot L_V \quad \text{(B.12)}$$

$$R_W = (N_L + N_{DJ}) \cdot P_W \cdot P_P \cdot L_W \quad \text{(B.13)}$$

For evaluation of risk components owing to lightning flashes near a line connected to the wind turbine (S4), the following relationship applies:

$$R_Z = N_I \cdot P_Z \cdot P_P \cdot L_Z \quad \text{(B.14)}$$

If the line has more than one section, the values of R_U, R_V, R_W and R_Z are the sum of the R_U, R_V, R_W and R_Z values relevant to each section of the line. The sections to be considered are those between the wind turbine and the first node. In any case, a maximum line length of 5 km for HV power lines and 1 km for LV power lines and TLC lines is to be assumed.

In the case of a wind turbine with more than one connected line with different routing feeding the same internal system, the calculations shall be performed for each line.

In the case of a structure with more than one line connected with the same routing to the same apparatus, the calculations shall be performed only for the line with the worst characteristics, i.e. the lines with the highest values of N_L and N_I , respectively (unscreened line versus screened line, LV power line versus HV power line with HV/LV transformer, etc.).

B.3.4 Frequency of damage

The frequency of damage F is the value of the number of damaging events caused by sources of damage S in the internal systems of the wind turbine to be protected. For each source of damage that may affect the wind turbine, the relevant frequency of damage may be evaluated as follows:

F_1: frequency of damage due to flashes to the structure (source S1),

F_2: frequency of damage due to flashes near the structure (source S2),

F_3: frequency of damage due to flashes to the line (source S3),

F_4: frequency of damage due to flashes near the line (source S4).

The frequency of damages F_1 and F_2 includes failure of internal systems caused by LEMP owing to flashes to the structure or to ground near the structure, respectively, whereas the frequency of damages F_3 and F_4 includes failure of internal systems caused by overvoltages transmitted from incoming lines to the structure.

The frequency of damage F is the sum of partial frequency of damage depending on the source of damage. For evaluation of the frequency of damage F, the following relationship applies:

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$$F = F_1 + F_2 + F_3 + F_4 \quad \text{(B.15)}$$

NOTE The value of frequency of damage F obtained by adding the two risk components F_2 and F_4 is overestimated. A more correct assessment of frequency could be made taking into account that a flash to ground simultaneously has influence on internal systems by direct inductive coupling and by the overvoltage induced on the connected lines, and so that their effects (component F_2 and component F_4) can be overlapped.

Each partial frequency of damage F_1, F_2, F_3, F_4, may be expressed by the following general equation:

$$F_X = N_X \cdot P_X \quad \text{(B.16)}$$

where

N_X is the number of dangerous events per annum (see also Annex A);

P_X is the probability of damage.

For evaluation of the frequency of damage related to lightning flashes to the wind turbine (S1) structure, the following relationship applies:

$$F_1 = N_D \cdot P_C \quad \text{(B.17)}$$

For evaluation of the frequency of damage related to lightning flashes near the wind turbine (S2), the following relationship applies:

$$F_2 = N_M \cdot P_M \quad \text{(B.18)}$$

For evaluation of the frequency of damage related to lightning flashes to an incoming line (S3), the following relationship applies:

$$F_3 = (N_L + N_{DJ}) \cdot P_W \quad \text{(B.19)}$$

For evaluation of the frequency of damage related to lightning flashes near a line connected to the wind turbine, the following relationship applies:

$$F_4 = N_I \cdot P_Z \quad \text{(B.20)}$$

According to IEC 62305-1 the frequency of damages F should be considered in the evaluation of the need of protection against lightning.

The following steps should be taken:

– calculation of the partial frequency of damage F_X
– calculation of the total frequency of damage F;
– identification of the tolerable frequency of damage F_T;
– comparison of the frequency of damage F with the tolerable value F_T.

B.3.5 Assessment of probability, P_X, of damage

The probabilities given in this Annex B, which is based on IEC 62305-2, are valid if protection measures conform to:

– IEC 62305-3 for protection measures to reduce injury to human beings and for protection measures to reduce physical damage;
– IEC 62305-4 for protection measures to reduce failure of internal systems.

Other values may be chosen, if justified.

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B.4 Assessing the probability of damage to the wind turbine

B.4.1 Probability, P_{AT}, that a lightning flash to a wind turbine will cause dangerous touch and step voltage

The values of probability P_{AT} that a damage due to touch and step voltage by a lightning flash to the wind turbine appear, depend on the protection measures provided:

$$P_{AT} = P_{TWS} \cdot P_{am} \cdot r_t \quad \text{(B.21)}$$

where:

P_{TWS} is the probability with which a thunderstorm warning system (TWS) does not detect a lightning related event in the target area.

P_{am} is the probability that a flash to a structure will cause damage owing to touch and step voltages according to different protection measures. Values of P_{am} are given in Table B.3.

r_t is the reduction factor as a function of the type of surface of soil or floor. Values of r_t are given in Table B.4.

NOTE P_{AT} = 0 may be assumed when the structure:

– has an extensive metal framework (see IEC 62305-3:2010, 8.1 and 8.2);

– is made of reinforced concrete cast on site, with the reinforcing rods perfectly done of building; (see IEC 62305-3:2010, E.4.3);

– is protected by an LPS complying with this document;

– is provided with a meshed earth termination system and there is no metal installation that can become a part of the path of the lightning current.

Table B.3 – Values of probability, P_A, that a lightning flash to a wind turbine will cause shock to human beings owing to dangerous touch and step voltages (corresponds to IEC 62305-2)

Protection measure	P_{am}	Comments
No protection measures	1	
Warning notices	10^{-1}	
Electrical insulation of exposed down-conductor (e.g. at least 3 mm cross-linked polyethylene)	10^{-2}	Not relevant for wind turbines using the tower structure as down conductor
Effective soil equipotentialization	10^{-2}	Mandatory for wind turbines holding HV equipment according to typical electrical codes

If more than one provision has been taken, the value of P_{am} is the product of the corresponding values.

Table B.4 – Values of reduction factor r_t as a function of the type of surface of soil or floor (corresponds to IEC 62305-2)

Type of surface	Contact resistance kΩ [a]	r_t
Agricultural, concrete	≤ 1	10^{-2}
Marble, ceramic	1 to 10	10^{-3}
Gravel	10 to 100	10^{-4}
Asphalt, wood	≥ 100	10^{-5}

[a] Values measured between a 400 cm^2 electrode compressed with force of 500 N at a point of infinity.

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B.4.2 Probability, P_{AD}, that a lightning flash to the wind turbine will cause injury to an exposed person on the structure

The values of probability, P_{AD}, that a lightning flash will strike a human being depend on the position of people in the exposed area, on the lightning protection (LPL) of adopted measures to protect the exposed areas of the wind turbine against direct lightning flash and on additional protection measures provided:

$$P_{AD} = P_{TWS} \cdot P_O \cdot P_{LPS} \quad \text{(B.22)}$$

where:

P_{TWS} is the probability with which a thunderstorm warning system (TWS) does not detect a lightning related event in the target area.

P_{LPS} is the probability depending on LPL of measures to protect the exposed areas of the structure against direct lightning flashes. Values of P_{LPS} are given in Table B.6.

If a TWS creates a warning message, immediate and complete evacuation of the exposed area shall be ensured. If this evacuation is not ensured or a TWS is not provided, P_{TWS} = 1 should be assumed. P_O is the probability factor according to the position of the person in the exposed area. Values of P_O are given in Table B.5.

Table B.5 – Values of factor P_O according to the position of a person in the exposed area (corresponds to IEC 62305-2)

Position of person	P_O
Close to the border of exposed area [a]	0,9
Far away from the border of the exposed area	0,1
[a] Within 3 m from the border of the exposed area	

Table B.6 – Values of probability, P_{LPS}, depending on the protection measures to protect the exposed areas of the wind turbine against direst lightning flash and to reduce physical damage (corresponds to IEC 62305-2)

Characteristics of wind turbine	Class of LPS	P_{LPS}
Wind turbine not protected by LPS	-	1
Wind turbine protected by LPS	IV	0,2
	III	0,1
	II	0,05
	I	0,02
Wind turbine with lightning protection of blades and nacelle conforming to LPS I with complete protection of any nacelle roof installations against direct lightning attachment and the tower acting as a continuous natural down conductor.		0,01

NOTE Values of P_{LPS} other than those in Table B.6 are possible if based on a detailed investigation – refer to IEC 62305-2:2010, Clause B.2.

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B.4.3 Probability, P_B, that a lightning flash to the wind turbine will cause physical damage

The probability P_B that a flash to a wind turbine will cause physical damage is given by:

$$P_B = P_S \cdot P_{LPS} \cdot r_f \cdot r_P \quad \text{(B.23)}$$

where:

P_S is the probability that a flash to a structure will cause dangerous sparking. Values of P_S are given in Table B.7.

P_{LPS} is the probability depending on the protection measures to reduce physical damage. Values of P_{LPS} are given in Table B.4.

r_P is the reduction factor as function of provisions taken to reduce the consequences of fire. Values of r_p are given in Table B.8.

r_f is the reduction factor as function of risk of fire or explosion of the wind turbine. Values of r_f are given in Table B.9.

Table B.7 – Values of probability P_S that a flash to a wind turbine will cause dangerous sparking (corresponds to IEC 62305-2)

Type of structure	P_S
Composite materials	1
Reinforced concrete or interconnected metalwork	0,5

Table B.8 – Values of reduction factor r_p as a function of provisions taken to reduce the consequences of fire (corresponds to IEC 62305-2)

Provisions	r_p
No provisions	1
One of the following provisions: extinguishers; fixed manually operated extinguishing installations[a]; manual alarm installations; hydrants; fire proof compartments; protected escape routes	0,5
One of the following provisions: fixed automatically operated extinguishing installations; automatic alarm installations[b].	0,2
[a] Provisons are effective only if operated by persons trained for this purpose.	
[b] Only if protected against overvoltages and other damage and if firemen can arrive within 10 min.	

If more than one provision has been taken, the value of r_p should be taken as the lowest of the relevant values.

NOTE 1 Risk of explosion is not considered relevant for wind turbines.

Table B.9 – Values of reduction factor r_f as a function of risk of fire of the wind turbine (corresponds to IEC 62305-2)

Risk of fire	r_f
High	10^{-1}
Ordinary	10^{-2}
Low	10^{-3}
None	0

NOTE 2 Structures considered as having a high risk of fire can be assumed to be structures with surface materials (blades and nacelle roofs) made of combustible materials with a specific fire load larger than 800 MJ/m^2.

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NOTE 3 Structures considered as having an ordinary risk of fire can be assumed to be structures with surface materials (blades and nacelle roofs) made of combustible materials with a specific fire load between 800 MJ/m^2 and 400 MJ/m^2.

NOTE 4 Structures considered as having a low risk of fire can be assumed to be structures with surface materials (blades and nacelle roofs) made of combustible materials with a specific fire load less than 400 MJ/m^2.

NOTE 5 Specific fire load is the ratio of the energy of the total amount of the combustible material in a structure and the overall surface of the structure.

B.4.4 Probability, P_C, that a lightning flash to the wind turbine will cause failure of internal systems

A coordinated SPD system is suitable as a protection measure to reduce P_C.

The probability, P_C, that a lightning flash to the wind turbine will cause failure of internal systems is given by:

$$P_C = P_e \cdot P_{SPD} \cdot C_{LD} \quad \text{(B.24)}$$

P_{SPD} depends on the coordinated SPD system conforming to IEC 62305-4 and on internal system characteristics. Refer to IEC 62305-2:2010, Annex B for values of P_{SPD}. For low-voltage systems and telecommunication systems.

P_e is the probability that equipment is exposed to damaging event,

C_{LD} is a factor depending on shielding, grounding and isolation conditions of the line to which the internal system is connected. Values of C_{LD} are given in IEC 62305-2 Annex B.

Values of P_{SPD} depend on the lightning protection level (LPL) for which the SPDs are designed.

NOTE 1 Only "coordinated SPD protection" is suitable as a protection measure to reduce P_C. Coordinated SPD protection is effective to reduce P_C only if the wind turbine hub, nacelle and tower are protected with an LPS, or if the structures with continuous metal or reinforced concrete framework act as a natural LPS where bonding and earthing requirements of IEC 62305-3 are satisfied.

NOTE 2 Shielding internal systems connected to external lines consisting of lightning protective cable or systems with wiring in lightning protective cable ducts, metallic conduit or metallic tubes; may not require the use of coordinated protection.

B.4.5 Probability, P_M, that a lightning flash near the wind turbine will cause failure of internal systems

Due to the height of the wind turbines, most lightning flashes will strike the turbines directly and not in the area near the wind turbine. Furthermore, the large metal structures will shield the internal systems. Hence the probability that a lightning flash near the wind turbine will cause failure of internal systems can be considered negligible when the wind turbine hub, nacelle and tower are protected with an LPS or when the structures with continuous metal or reinforced concrete framework act as a natural LPS where bonding and earthing requirements of IEC 62305-3 are satisfied.

NOTE R_M can be neglected for wind turbines with a total height of more than 100 m. In this case, the conventional distance of 350 m is usually covered by direct strikes

B.4.6 Probability, P_U, that a lightning flash to a service line will cause injury to human beings owing to touch voltage

The values of probability, P_U, of injury to human beings owing to touch voltage caused by lightning flashes to a service line (power cable or communication cable) entering the wind turbine depends on the characteristics of the service line shield, the impulse withstand voltage of internal systems connected to the service line, the typical protection measures (physical restrictions, warning notices, etc. [see Table B.8]) and the SPDs provided at the entrance of the service line in accordance with IEC 62305-3.

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NOTE A coordinated SPD protection in accordance with IEC 62305-4 is not necessary to reduce P_U in this case. SPD(s) in accordance with IEC 62305-3 are sufficient.

The value of P_U is given by:

$$P_U = P_{am} \cdot P_{EB} \cdot P_{LD} \cdot P_{TWS} \cdot C_{LD} \cdot r_t \quad \text{(B.25)}$$

where:

P_{am} depends on protection measures against touch voltages, such as physical restrictions or warning notices. Values of P_{am} are given in IEC 62305-2:2010, Annex B.

P_{TWS} is the probability with which a thunderstorm warning system (TWS) does not detect a lightning related event in the target area.

P_{LD} is the probability of failure of internal systems due to a flash to the connected line depending on the line characteristics. Values of P_{LD} are given in IEC 62305-2:2010, Annex B.

P_{EB} depends on the equipotential bonding conforming to IEC 62305-3. Values of P_{EB} are given in IEC 62305-2:2010, Annex B.

C_{LD} is a factor depending on shielding, grounding and isolation conditions of the line. Values of C_{LD} are given in IEC 62305-2:2010, Annex B.

r_t is the reduction factor as a function of the type of surface of soil or floor. Values of r_t are given in IEC 62305-2:2010, Annex B.

B.4.7 Probability, P_V, that a lightning flash to a service line will cause physical damage

The values of probability, P_V, of physical damage caused by a lightning flash to a service line entering the wind turbine depend on the characteristics of the service line shield, the impulse withstand voltage of internal systems connected to the service line and the SPDs provided for equipotential bonding at the entrance of the line in accordance with IEC 62305-3.

NOTE A coordinated SPD protection in accordance with IEC 62305-4 is not necessary to reduce P_V in this case. SPDs in accordance with IEC 62305-3 are sufficient.

The value of P_V is given by:

$$P_V = P_{EB} \cdot P_{LD} \cdot P_{TWS} \cdot C_{LD} \cdot r_f \cdot r_p \quad \text{(B.26)}$$

where:

P_{EB} depends on the equipotential bonding conforming to IEC 62305-3. Values of P_{EB} are given in IEC 62305-2:2010, Annex B;

P_{LD} is the probability of failure of internal systems due to a flash to the connected line depending on the line characteristics. Values of P_{LD} are given in IEC 62305-2:2010, Annex B;

P_{TWS} is the probability of a thunderstorm warning system (TWS) not detecting a lightning-related event in the target area;

C_{LD} is a factor depending on shielding, grounding and isolation conditions of the line. Values of C_{LD} are given in IEC 62305-2:2010, Annex B;

r_f is the reduction factor as a of provisions taken to reduce the consequences of fire. Values of r_f are given in Table B.9;

r_p is the reduction factor as a function of provisions taken to reduce the consequences of fire. Values of r_p are given in Table B.8.

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B.4.8 Probability, P_W, that a lightning flash to a service line will cause failure of internal systems

The values of probability, P_W, of failure of internal systems caused by lightning flash to a service line entering the wind turbine depend on the characteristics of the service line shielding, the impulse withstand voltage of internal systems connected to the service line and the coordinated SPD system provided.

The value of P_W is given by:

$$P_W = P_e \cdot P_{SPD} \cdot P_{TWS} \cdot P_{LD} \cdot C_{LD} \quad (B.27)$$

where:

P_e is the probability that equipment is exposed to damaging event;

P_{SPD} depends on the coordinated SPD system conforming to IEC 62305-4 and on internal system characteristics. Refer to IEC 62305-2:2010, Annex B for values of P_{SPD} for low-voltage systems and telecommunication systems;

P_{TWS} is the probability of a thunderstorm warning system (TWS) not detecting a lightning-related event in the target area;

P_{LD} is the probability of failure of internal systems due to a flash to the connected line depending on the line characteristics. Values of P_{LD} are given in IEC 62305-2:2010, Annex B.

C_{LD} is a factor depending on shielding, grounding and isolation conditions of the line to which the internal system is connected. Values of C_{LD} are given in IEC 62305-2:2010, Annex B.

B.4.9 Probability, P_Z, that a lightning flash near an incoming service line will cause failure of internal systems

The values of probability, P_Z, that a lightning flash near to a service line entering the structure will cause a failure of internal systems depend on the characteristics of the service line shield, the impulse withstand voltage of the system connected to the service line and protection measures provided.

The value of P_Z is given by:

$$P_Z = P_e \cdot P_{SPD} \cdot P_{TWS} \cdot P_{LI} \cdot C_{LI} \quad (B.28)$$

where:

P_e is the probability that equipment is exposed to damaging event;

P_{SPD} depends on the coordinated SPD system conforming to IEC 62305-4 and on internal system characteristics. Refer to IEC 62305-2, Annex B for values of P_{SPD} for low-voltage systems and telecommunication systems;

P_{TWS} is the probability of a thunderstorm warning system (TWS) not detecting a lightning-related event in the target area;

P_{LI} is the probability of failure of internal systems due to a flash near the connected line depending on the line and equipment characteristics. Values of P_{LD} are given in Table B.12 and IEC 62305-2:2010, Annex B;

C_{LI} is a factor depending on shielding, grounding and isolation conditions of the line. Values of C_{LI} are given in IEC 62305-2:2010, Annex B.

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Table B.10 – Values of probability P_{LI} depending on the line type and the impulse withstand voltage U_W of the equipment (corresponds to IEC 62305-2)

Line type	Voltage U_W in kV				
	1	1,5	2,5	4	6
	P_{LI}				
Power lines	1	0,6	0,3	0,16	0,1
TLC lines	1	0,5	0,2	0,08	0,04

B.4.10 Probability P_P that a person will be in a dangerous place

The probability P_P that a person will be in a dangerous place depends on the time t_z in hours per year for which the persons are present in the dangerous place:

$$P_P = t_z / 8\,760 \quad \text{(B.29)}$$

NOTE Where the value of t_z is not known, the ratio t_z / 8 760 should equate to the value of 1.

B.4.11 Probability P_e that equipment will be exposed to damaging event

The probability P_e that undamaged equipment is exposed to a damaging event depends on the time t_e in hours per year of exposure of equipment to the damaging event:

$$P_e = t_e / 8\,760 \quad \text{(B.30)}$$

NOTE Where the value of t_e is not known, the ratio t_e / 8 760 should equate to the value of 1.

B.5 Assessing the amount of loss L_X in a wind turbine

B.5.1 General

L_X represents the mean amount of loss consequent to a specified type of damage owing to a dangerous event, expressed in relative way related to the maximum amount of loss in the wind turbine to be protected.

The values of loss L_X should be evaluated and fixed by the lightning protection designer (or the owner of the wind turbine). The mean values of loss L_X in a wind turbine given here are considered typical values. Different values may be assigned by each national committee (or agreed between the manufacturer and the customer).

B.5.2 Mean relative loss per dangerous event

The loss L_X refers to the mean relative amount of a specified type of damage for one dangerous event caused by a lightning flash considering both its extent and effects.

The loss L_X varies with the cause of damage (D_{1D}, D_{1T}, D_2 and D_3).

The loss L_X should be determined for each zone of the wind turbine into which it is divided.

The loss L_X for each zone can be determined in accordance with Tables B.11 and B.12.

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Table B.11 – Loss values for each zone (corresponds to IEC 62305-2)

Typical loss
$L_{AT} = L_{UT} = L_T$
$L_{AD} = L_D$
$L_B = L_V = L_F = L_{F1} = L_{F2}$

where

L_T is the typical mean ratio of persons injured by touch and step voltages related to the total number of persons in the zone, owing to one dangerous event (see Table B.12);

L_D is the typical mean ratio of persons injured by direct lightning stroke related to the total number of persons exposed in the zone, owing to one dangerous event (see Table B.12);

L_{F1} is the typical mean ratio of persons injured by fire or explosion in relation to the total number of persons in the zone, owing to one dangerous event (see Table B.12);

L_{F2} is the typical mean ratio of physical damage of social relevance by fire or explosion related to the maximum amount of damage of social relevance in the zone, owing to one dangerous event (see Table C.2);

L_O is the typical mean ratio of persons injured by failure of internal systems in relation to the total number of persons in the zone, owing to one dangerous event (see Table B.12).

NOTE 1 Risk of explosion is not considered relevant for wind turbines.

NOTE 2 According to IEC 62305-2, a loss of social relevance is a loss which involves injury to human beings, unavailability of service to the public, damage of cultural heritage and in general costs that the society is forced to pay.

Table B.12 – Typical mean values of L_T, L_D, L_F and L_O (corresponds to IEC 62305-2)

Type of zones	L_T	L_D	L_{F1}	L_{F2}	L_O
Critical zones [a)]	0,01	0,1	0,01	0,1	0,0001
Normal zones [b)]	0,01	0,1	0,01	0,05	0,00001

[a)] Zones with essential equipment for carrying out processes (control, communication)

[b)] Zones open to the public

NOTE 3 Values of Table B.12 refer to continuous attendance of people in the structure.

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Annex C
(informative)

Protection methods for blades

C.1 General

C.1.1 Types of blades and types of protection methods for blades

Wind turbine blades are large hollow structures manufactured of composite materials, such as glass fibre reinforced plastic (GFRP), wood, wood laminate and carbon fibre reinforced plastic (CFRP). CFRP is typically used for reinforcement of the blade structure or for special components, such as the tip shaft for blades with tip brakes (tip-stall braking mechanism). Some parts and discrete components such as mounting flanges, balancing weights, hinges, assembly brackets for split blades, bearings, wires, electrical wiring, springs and fixtures are made of metal. Lightning strikes will attach to blades even without metallic components, and whenever a lightning arc is formed inside the blade, damage is severe.

The two sides or surface skins of a blade are normally manufactured as separate sheets of glass fibre, or other composite materials, glued together along the leading and trailing edges and to an internal load-carrying structure also made of glass fibre. Inside the blade, there are large air-filled cavities formed by the surface skin and the internal structure commonly stretching the entire length of the blade. Alternatively, the blade skins can supply the mechanical strength of the blade without a load-carrying spar. Finally, blades may be fabricated in one piece using advanced resin casting techniques without the above-mentioned glued interfaces.

There are several types of blades depending on the control and braking mechanism employed, and the use of insulating and conductive composites. Five main types are shown in Figure C.1.

Type A blades use a flap (aileron) in the outer part of the leading edge for braking. On type A blades, lightning attachment points are often found on the flap steel hinges, and severe damage is often seen since the cross-section of the steel wires used for operating the flap is usually insufficient for conducting the lightning current.

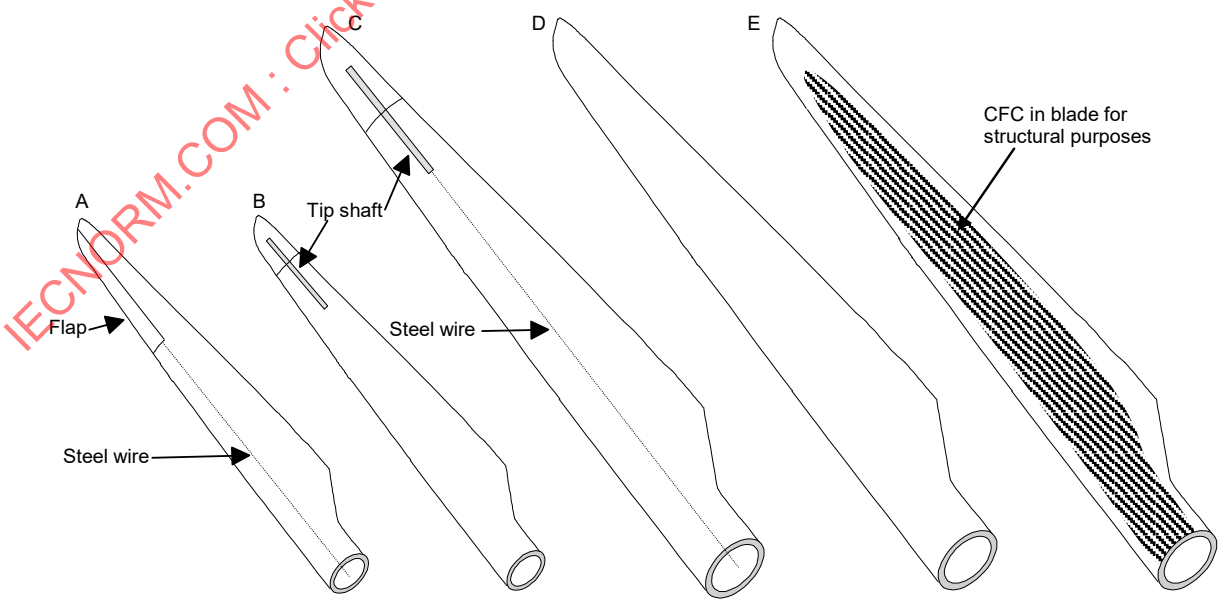

Figure C.1 – Types of wind turbine blades

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Type B blades use a tip brake which is retained by a spring and released at excessive rotational speed by centrifugal force. With type B blades, lightning attachment points are predominantly seen within a few tens of centimetres from the outermost tip, or on the sides of the tip at the position of the outermost end of the tip shaft. From the attachment point, a lightning arc is formed inside the tip section to the outermost end of the tip shaft, and from the other end of the shaft, an arc is formed inside the main blade down to the steel mounting flange at the blade root. Such internal arcs invariably cause catastrophic destruction to the blade. Blades of types A and B were commonly used with older wind turbines as large as 100 kW.

Type C is a blade with a tip brake controlled by a steel wire. With type C blades, lightning attachment points are predominantly found within a few tens of centimetres from the outermost tip of the blade, or on the sides of the tip at the position of the outermost end of the tip shaft. With type C as with type B blades, a lightning arc formed inside the tip section between the attachment point and the outermost end of the shaft causes severe damage. On type C blades, damage to the main blade is mostly seen when the steel wire has been unable to carry the lightning current. Steel wires used for this purpose are of a minimum diameter of 10 mm or 12 mm for 17-m-long blades. Such wires are capable of conducting most lightning currents, and thereby protecting the main blade from damage (see Clause C.6 for further discussion on dimensioning of protection systems).

Type D is a blade constructed entirely from non-conducting materials. Experiences with non-conducting blades are that, as with the other types of blades, lightning attachment points are mostly found close to the tip. Compared to the other types of blades, attachment points can also be found randomly distributed at other positions along the length of the blade.

Type E is a blade where some of the structural components are made with carbon fibre reinforced plastics (CFRP), since it has high stiffness for a given weight. Depending on the specific design, CFRP can be used as reinforcement of the blade skin, as well as for load carrying structural components, such as the internal spar. Owing to its electrical properties, CFRP should be coordinated carefully with the lightning protection system to ensure the necessary separation distance, electrical insulation and/or current carrying capability. The issues of lightning protection of wind turbine blades containing CFRP are treated in Clause C.3.

Lightning flashes attaching to non-conducting blades or to insulating parts of blades containing conducting parts may at least partly be explained by the fact that pollution and water make such blades more conductive over time. High-voltage laboratory experiments have shown that arc attachments occur to a non-conducting blade sprayed with saline water practically as if the blade was metallic. Another part of the explanation is that the blades are simply in the way of lightning striking the wind turbine. In addition, it is known that discharges develop along a surface more easily than through air, and especially if the surface is contaminated with saline pollution and water. In any case, practical experience shows that severe lightning damage to both non-conducting blades (type D) and blades containing CFRP (type E) is quite common and hence lightning protection is needed.

C.1.2 Blade damage mechanism

Typical types of damage at the lightning attachment points are delamination and incineration of the surface composite material, and heating or melting of metallic components serving as the attachment point.

The most severe damage to wind turbine blades occur, however, when lightning forms high energy arcs inside the blade due to attachment to an unprotected part of the blade skin. The arcs may form in the air volume inside the blade or along the internal surfaces. Another type of damage occurs when the lightning current or part of it is conducted in or between layers of composite materials or in glue cracks in connection with the down conductor system, presumably because such layers and cracks hold some moisture. The pressure shock wave caused by such internal arcs may literally explode the blade, ripping the blade surface skins apart along the edges and from the internal carrying spar. All grades of damage are seen

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ranging from surface cracking to complete disintegration of the blade. In some cases, pressure waves have propagated from the blade struck by lightning through the hub and into the other blades causing pressure damage to them.

Internal arcs often form between the lightning attachment point at the tip of the blade and some conducting component internal to the blade. With type C blades, the damage is often limited to the tip section, whereas the main blade is unharmed. Damage to type C main blades has normally been seen when an arc has formed inside the main blade. Typically, this has happened in cases where the steel wire controlling the tip brake was of insufficient cross-section to conduct the lightning current from the tip shaft to the hub. With type A blades, the main blade is destroyed.

The phenomenon responsible for the severe structural damage to wind turbine blades is therefore the formation of a pressure shock wave around an arc of lightning inside the blade. Minor damage can occur when a lightning arc is formed on the outside surface or when the lightning current is conducted by metallic components with insufficient cross-section.

The high-energy internal arcing responsible for the structural damage is not to be confused with the low-energy partial discharges mentioned in C.2.4.

C.2 Protection methods

C.2.1 General

The generic problem of lightning protection of wind turbine blades is to conduct the lightning current safely from the attachment point on the blade to the hub or nacelle in such a way that the formation of a lightning arc inside the blade is avoided. This can be achieved by diverting the lightning current from the attachment point along the surface to the blade root, using metallic conductors either fixed to the blade surface or inside the blade. Another method is to add conducting material to the blade surface material itself, thus making the blade sufficiently conductive to carry the lightning current safely to the blade root. Variations of both these methods are used on wind turbine blades (see Figure C.2).

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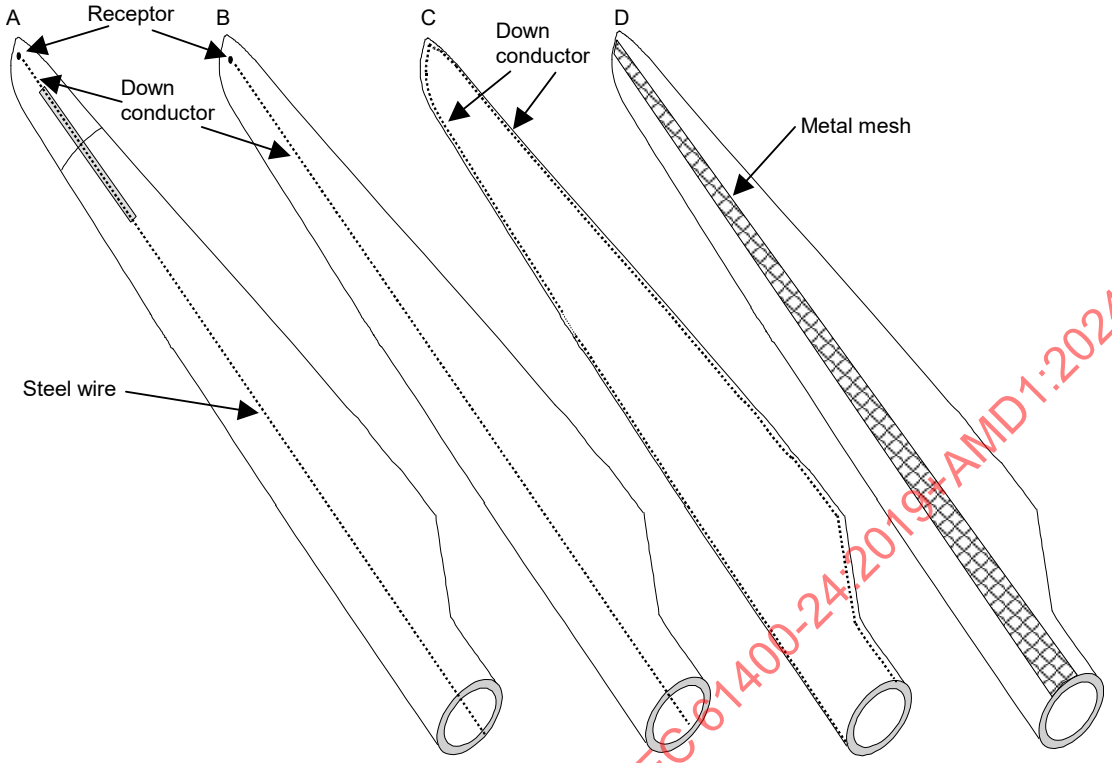

Figure C.2 – Lightning protection concepts for large modern wind turbine blades

C.2.2 Lightning air-termination systems on the blade surface or embedded in the surface

Metallic conductors on the blade surface serving as an air-termination system or a down conductor system should have sufficient cross section to be able to withstand a direct lightning attachment and conduct the full lightning current. In addition, certain dimensions are needed in order to achieve reliable fixing to the blade surface. The minimum cross section for aluminium is 50 mm^2 and achieving reliable fixing of such conductors may be problematic. Furthermore, conductors mounted on the blade surface may compromise the aerodynamics of the blade or generate undesirable noise.

For lightning conductors embedded in the blade surface, wires or braids of either aluminium or copper are used. Several protection systems exist where a metallic conductor connected to the blade root is placed either on the blade surface along the outside or embedded in the trailing edge. Some blade designs have metallic conductors placed along both the leading and the trailing edge (type C). In addition, some have metallic diverters placed on the surface around the blade at several radial locations along the blade, each of these being connected to conductors placed along the blade edges.

C.2.3 Adhesive metallic tapes and segmented diverter strips

Adhesive aluminium tape placed on the blade surface has been used in several investigations. However, such tapes tended to peel off within a few months. Provided that the problem of keeping the tape on the blade can be solved, it is possible that metallic tapes can be an interesting protection method, especially as a retrofit for existing unprotected blades. It should, however, be noted that large pressure waves are associated with guiding the flash close to the blade surface [6]. This may lead to structural damage.

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Some promising experiments with segmented diverter strips have been performed in the past. Such segmented strips are used on aircraft radomes because they do not interfere with the radar signal.

It is possible that metallic tape can be used as one-shot protection requiring replacement after a lightning stroke.

C.2.4 Internal down conductor systems

A common option is to place lightning conductors inside the blade. Metallic fixtures for the conductor penetrate the blade surface and serve as discrete lightning receptors. Such protection systems are used on aircraft [6].

The lightning protection system used on many blades currently in manufacture has discrete lightning receptors placed at the blade tip (types A and B in Figure C.2). From the receptors at the tip, an internal down conductor system leads the lightning current to the blade root. For blades with tip brakes, the steel wire controlling the tip is used as a down conductor (type A). If the blade is without tip brake, then a copper wire placed along the internal spar is used as a down conductor (type B).

Many thousands of blades with this lightning protection system (types A and B in Figure C.2) have been produced. The experiences with this lightning protection system for blades as long as 20 m are very positive. The principle with one or more external air terminations connected to an internal down conductor has up till the date of publication been used widely by many manufacturers for blades up to 60 m. For such long blades, experience has shown that there is a risk of direct lightning attachment through the laminate to the internal down conductor causing severe blade damage. These problems appear to be linked to uncontrolled partial discharges developing from the internal conductive parts (the down conductor, connection components, etc.).

When such low-energy partial discharges are allowed to be incepted from the interior metal parts of the blade, they will propagate as fast as the ones incepted from the air termination system. Once these internal discharges strike the interior surface of the blade, they will, in connection with partial discharges on the blades' exterior, intensify the electrical stress experienced by the laminate. The increased stress might not be a problem for a limited number of rapid field changes (lightning striking receptors or nearby structures), but when the blade is exposed to several impacts during its entire service lifetime, the stress might eventually develop into a complete electrical breakdown. The physical impact on the blade from such a high-voltage breakdown channel is rather limited, but the damage associated with the following lightning current may be disastrous as commented in C.1.2.

Such discharges may be impeded or delayed by encapsulating the internal down conductor and other conductive parts in the blade with electrically insulating material, thereby reducing the problem.

C.2.5 Conducting surface materials

An alternative to a lightning air-termination system placed on the blade surface is to make the surface itself conducting. In the aircraft industry, lightning protection of glass and carbon fibre composite material for wings and surfaces exposed to lightning is achieved by adding conducting material to the outer layers, thereby reducing damage to a small area at the attachment point. The conducting material can be metal sprayed onto the surface, metal-coated fibres in the outer layers of the composite material, metal wire woven into the outer layers of the composite material, or expanded metal foil mesh placed just beneath the outer surface of the composite. Lightning protection of wind turbine blades has been made with metal mesh placed along the sides of the blades just under the gel coat (D on Figure C.2). Sometimes, the extreme tip of the blade is made of metal or covered with a metal sheath.

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The advantage of using metal mesh or other thin conducting surfaces for lightning down conductors is that possible interior conductive elements (e.g. CFRP) are shielded from the electric field, and hence direct lightning attachments. The inductive voltage drop along the length of the conductor associated with the high current gradient will be slightly reduced, an important effect considering the risk of side flashes. However, the risk of getting direct lightning attachment to the edge of such thin geometries, and the possibility of uneven current distribution owing to skin effects should also be considered.

C.3 CFRP structural components

Carbon fibre reinforced plastics (CFRP) have been used for tip shafts for small blades and are now commonly used for reinforcement of large blades. The material is used either for the load-carrying centre spar or directly in the blade skins owing to a high strength-to-weight ratio. The use of CFRP for structural components is expected to increase even further as the size of blades increases owing to its weight decrease advantage.

The main issue with CFRP is how it reacts to the lightning current possibly entering and flowing within the material. Two electrical properties of CFRP make it remarkably different than isotropic conductor materials like metals – the conductivity and the degree of anisotropy.

The conductivity of CFRP is in the order of 1 000 times lower than that of aluminium. Depending on the actual construction and weaving technique, the conductivity of CFRP exhibits a very high degree of anisotropy, with higher resistance of the material in directions perpendicular to the fibre orientation. For CFRP coupons used for lightning tests in the aircraft industry, the conductivity has been measured and varies within four orders of magnitude for different current directions.

Therefore, the resistive heating of CFRP when exposed to high current densities might be critical. Especially at the lightning attachment points where high currents enter a rather confined area, the temperature due to joule losses might exceed the evaporation temperature of the resin. When the resin matrix evaporates, the pressure from evolving gases can cause rupture and delamination of the CFRP layers. The CFRP may even incinerate, in particular at the lightning attachment point.

Where CFRP is used in aircrafts, it is considered mandatory that lightning protection is provided for CFRP components that can be struck by lightning or can conduct lightning current.

There are examples of CFRP tip shafts for wind turbine blades having been damaged by lightning. Some laboratory experiments have also demonstrated problems with CFRP shafts conducting lightning current. Laboratory tests of blades with CFRP skin have shown surface delamination and incineration at the lightning attachment point. The protection concept for the blade should consider the exposure of direct strikes along the entire length of the blade, and document by testing and analysis that direct strikes to likely attachment points do not cause any damages compromising the performance requirement in 8.2.2.

Dependent on the specific blade design and LPS protection strategy, the CFRP structural components will either be considered as an integral part of the lightning current path or electrically isolated from the LPS.

It is critical that proper coordination between CFRP structural components, other conductive components and the LPS be made. Coordination should consider:

- electrical bonding and/or,
- electrical insulation and/or,
- physical separation.

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For each specific blade and LPS design, either all, or a subset of the above should be applicable.

If electrical bonding is implemented, then it should be determined whether the spacing between equipotential bonding points is adequate to avoid the development of critical voltages that could cause an uncontrolled flashover.

C.4 Particular concerns with conducting components

Conductive components in this clause cover all other conductive parts in the blade besides the receptors and down conductor system described in Clause C.2, and CFRP described in Clause C.3.

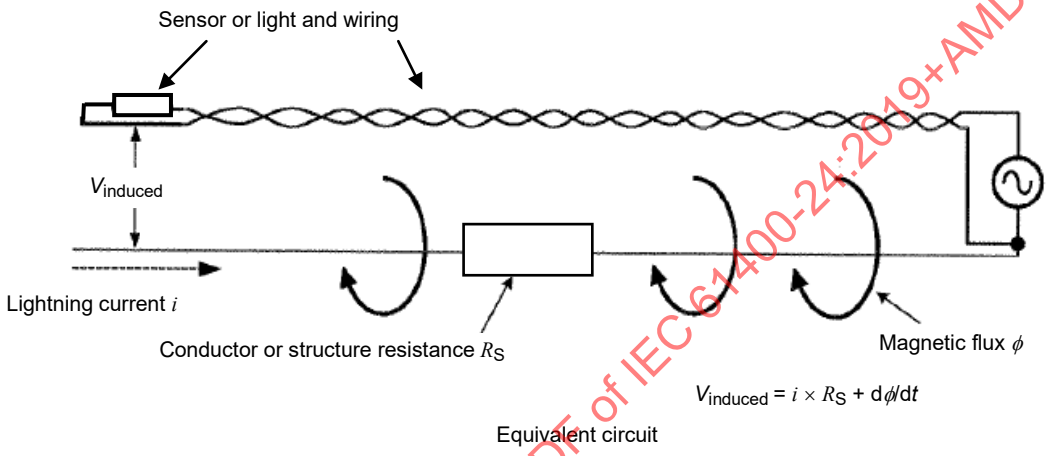

Figure C.3 – Voltages between lightning current path and sensor wiring due to the mutual coupling and the impedance of the current path

Wiring for sensors placed on or inside blades may be exposed to strong magnetic fields that can produce damaging voltages between the lightning conductor and other wiring in the blade, as illustrated in Figure C.3. Such wiring should be avoided if possible. The induced voltage is typically dominant compared to the resistive part, therefore great care needs to be taken when estimating induced voltages. The designer is advised to consult specialised literature on this issue.

If such installations are present, the protection should rely on careful coordination with the LPS. Coordination should consider:

- electrical bonding and/or,
- electrical insulation and/or,
- physical separation.

Having well exposed external lightning air termination systems directly outside of internal conducting components should protect the internal structures from direct lightning attachment. Furthermore, the risk of getting partial discharges from internal wiring is minimised by covering the conductive wiring carefully with electrically insulating materials. Note that high currents and voltages can be induced in isolated conductor loops in the vicinity of the down conductor system. Such surges can possibly result in internal sparking. It is possible that designs that integrate electrical wiring associated with sensors, lights and other systems with the lightning protection system, including the lightning down conductor, may be the most successful in avoiding damage to these systems. Careful coordination of designs of all

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systems contained within a blade is essential for successful lightning protection of the blade and functioning of the systems contained within the blade.

Metallic structural components within the blade, i.e. weights, dampers, platforms, etc. should be treated similarly. All conductive parts in the blade should be designed to minimise electric field enhancement and be coordinated carefully with the blade LPS to ensure the necessary separation distance, electrical insulation and/or current carrying to reduce the risk of internal discharges. As with the wiring, it is important that the external air terminations shield off the internal conductive components from the electric field, hence protecting these areas from direct lightning attachment.

If other conductive components are located within the blade, (e.g. blade tip navigation light, lightning sensors, condition monitoring equipment), it should always be shielded by external lightning receptors, thereby minimising the risk of direct lightning attachment to the structures. As described previously, the risk of internal discharges possibly leading to puncture of the blade skin can be minimised by encapsulating all internal conductive parts carefully in electrical insulation material.

C.5 Interception efficiency

The interception efficiency is defined as the number of strikes to the blades intercepted correctly by the air terminations relative to the total number strikes to the blade. In this sense, the interception efficiency is a parameter describing the ability of the blade LPS to intercept the strikes safely. The interception efficiency is affected by the following factors:

- the design and exposure of the air termination system (position and geometry);
- insulation level of internal conductive parts;
- the result of the HV initial leader attachment test in Annex D (interception effectiveness).

Any air terminations and extensions of air terminations (solid conductors and segmented diverters on the surface) should be placed in such a way that the likelihood of lightning puncturing insulating surfaces is reduced to an acceptable level.

The placement of air terminations would be such that the flashover voltage along the blade non-conducting surface is smaller than the breakdown voltage of the blade skin. In practice, both the breakdown voltage of the blade skin and the surface flashover voltage will be difficult to establish, as variations due to different composite materials as well as influence of ageing, cracks, humidity and pollution should be expected. Furthermore, the interception efficiency of segmented diverters and discrete air terminations will be influenced by the presence of conducting materials inside the blade [6].

Recent publication of lightning attachment distribution for wind turbine blades shows that the majority of lightning flashes attaches to the tip region of the blade, and that the likelihood of attachment decrease rapidly towards the blade root. More details are provided in Clause C.8.

High-voltage strike attachment tests on test specimens representing the design are useful for revealing interception effectiveness, and thereby identify and resolve design issues before implementing in final production.

Numerical methods used to determine likely attachment areas on blades and nacelles and estimates of the annual number of direct lightning flash attachments to certain structures are currently being developed. It is not likely, however, that numerical simulation methods can predict with certainty whether a non-conductive blade structure would be punctured, or establish the number and location(s) of receptors necessary to prevent punctures. This is owing to the complexity of most blade structures, and the dynamics of multiple streamer origination and growth. Thus, the numerical methods are useful in the design phase. Whether numerical methods or empirical evidence is used, high-voltage attachment tests, as described in Clause D.2, of candidate designs, should be used to provide additional assurance of protection effectiveness.

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C.6 Dimensioning of lightning protection systems

The materials used for lightning protection of wind turbine blades should be able to withstand the combined effects of the electric, thermal and electrodynamic stresses imposed by the lightning current. Nominal dimensions for materials used for air termination and down conductors are listed in Table C.1 (see also IEC 62305-3).

Table C.1 – Material, configuration and minimum nominal cross-sectional area of air-termination conductors, air-termination rods, earth lead-in rods and down conductors[a] (corresponds to IEC 62305-3)

Material	Configuration	Nominal cross-sectional area mm^2
Copper,	Solid tape	50
Tin plated copper	Solid round[b]	50
	Stranded[b]	50
	Solid round[c]	176
Aluminium	Solid tape	70
	Solid round	50
	Stranded	50
Aluminium alloy	Solid tape	50
	Solid round	50
	Stranded	50
	Solid round[c]	176
Copper coated aluminium alloy	Solid round	50
Hot-dip galvanised steel[b]	Solid tape	50
	Solid round	50
	Stranded	50
	Solid round[c]	176
Copper coated steel	Solid round	50
	Solid tape	50
Stainless steel[e]	Solid tape[d]	50
	Solid round[d]	50
	Stranded	70
	Solid round[c]	176

[a] Mechanical and electrical characteristics as well as corrosion resistance properties should meet the requirements of the IEC 62561 series.

[b] 50 mm^2 (8 mm diameter) may be reduced to 25 mm^2 in certain applications where mechanical strength is not an essential requirement. Consideration should, in this case, be given to reducing the spacing between the fasteners.

[c] Applicable for air-termination rods and earth lead-in rods. For air-termination rods where mechanical stress such as wind loading is not critical, a 9,5-mm diameter, 1-m long rod may be used.

[d] If thermal and mechanical considerations are important, then these values should be increased to 75 mm^2.

The cross-sectional areas given above are provided as a guideline derived for simple conductors. For such geometries, the temperature rise associated with the lightning current might be evaluated analytically or numerically. Considering components for special applications, such as flexible down conductors, and more complex geometries such as air terminations, connection components, expanded foil, etc., different dimensions can be considered. For such components, design verification should be based on laboratory tests.

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When the individual lightning protection components are put together forming the entire blade installation, testing of the final solution is recommended.

Components under load such as the steel wires for tip brakes may have to be even more solid as the mechanical strength is reduced if heated to high temperatures. There are a few experiences with steel wires for tip brake control that have broken or melted due to lightning currents even for wires of up to 10 mm diameter (cross-sectional area 78 mm^2).

The temperature rise of conductors carrying lightning current can be evaluated as shown in Equation (C.1) (see also IEC 62305-1). The designer should consider the temperature rise of all components subjected to all, or parts of, the lightning current and ensure that such components have sufficient strength to fulfil their function immediately after a lightning stroke.

$$\theta - \theta_0 = \frac{1}{\alpha} \cdot \left\{ \exp\left[\frac{(W/R \cdot \alpha \cdot \rho_0}{q^2 \cdot \gamma \cdot c_W} \right] - 1 \right\} \quad \text{(C.1)}$$

where

$\theta - \theta_0$ is the temperature rise of the conductors [K];

α is the temperature coefficient of the resistance [1/K];

W/R is the specific energy of the current impulse [J/Ω];

ρ_0 is the specific ohmic resistance of the conductor at ambient temperature [Ωm];

q is the cross-sectional area of the conductor [m^2];

γ is the material density [kg/m^3];

c_w is the thermal capacity [J/kgK].

Table C.2 shows the inputs to this equation for common materials, and Table C.3 shows temperature rises for different conductors. It should be noted that in the case of pre-loaded wires, the temperature rise does not have to reach the melting point to cause failure.

Table C.2 – Physical characteristics of typical materials used in lightning protection systems (corresponds to IEC 62305-1)

Quantity	Material			
	Aluminium	Mild steel	Copper	Stainless steel[a]
ρ_0 [Ωm]	29×10^{-9}	120×10^{-9}	$17{,}8 \times 10^{-9}$	$0{,}7 \times 10^{-6}$
α [1/K]	$4{,}0 \times 10^{-3}$	$6{,}5 \times 10^{-3}$	$3{,}92 \times 10^{-3}$	$0{,}8 \times 10^{-3}$
γ [kg/m^3]	2 700	7 700	8 920	$8{,}0 \times 10^3$
θ_s [°C]	658	1 530	1 080	1 500
c_s [J/kg]	397×10^3	272×10^3	209×10^3	–
c_w [J/kgK]	908	469	385	500
θ_s [°C] is the melting temperature; c_s [J/kg] is the latent heat of melting.				
[a] Austenitic non-magnetic.				

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Table C.3 – Temperature rise [K] for different conductors as a function of W/R (corresponds to IEC 62305-1)

Cross-section mm^2	Material											
	Aluminium			Mild steel			Copper			Stainless steel[a]		
	W/R MJ/Ω			W/R MJ/Ω			W/R MJ/Ω			W/R MJ/Ω		
	2,5	5,6	10	2,5	5,6	10	2,5	5,6	10	2,5	5,6	10
4	–	–	–	–	–	–	–	–	–	–	–	–
10	566	–	–	–	–	–	169	541	–	–	–	–
16	147	454	–	1 114	–	–	56	143	309	–	–	–
25	52	132	283	211	912	–	22	51	98	938	–	–
50	12	28	52	37	96	211	5	12	22	188	460	938
100	3	7	12	9	20	37	1	3	5	45	102	188

[a] Austenitic non-magnetic.

Considering the impact on the air termination, IEC 62305-1 suggests the use of the anode or cathode voltage-drop model to calculate the volume subject to erosion. Several attempts have been made to correlate this model with test and field experience, without any success. Further research is required to achieve a fully verified model.

C.7 Blade-to-hub connection

At the root of the blade, the down conduction system is usually either terminated via the blade mounting flange, to the hub, or directly to the nacelle (bypassing pitch bearings and main rotor bearings) using a special connection system.

If the blade is pitch regulated (type D), the lightning current is either allowed to pass through the pitch bearing or around the bearing using a sliding contact, an air gap or a flexible bonding cable with enough slack to allow for the pitch motion. The flexible bonding across the bearing can be integrated with the innermost part of the down conductor from the blade.

In blades with tip brake (type C), the hydraulic system, which actuates the control wire, should be protected. Standard hydraulic cylinders that are normally used can be damaged by flashovers from the rod to the cylinder housing. Usually, the hydraulic cylinder is protected by diverting the lightning via a flexible bonding strap with sufficient slack to allow for the motion, or alternatively a sliding air gap or brush is used to divert lightning current away from the hydraulic cylinder. Care should be taken to reduce the slack in such bonding straps, since the inductive voltage drop across the slack may become very high, thus resulting in ineffective protection of the cylinder.

No matter what type of blade to hub interface is used, the component/design should be verified using the high current physical damage test in D.3.3.

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C.8 WTG blade field exposure

C.8.1 General

WTG blades are the components most exposed to direct lightning strikes in the field. As described in C.8.2, lightning strike attachment probability cannot be determined by means of the high-voltage test described in Annex D, therefore, the best way to determine this probability is by analysis of field data for similar blades. Experience with different blades from different manufacturers have shown that the outer part of the blade receives the majority of the direct strikes. These studies indicate that the probability of direct lightning strikes increases closer to the blade tip.

C.8.2 Application

The objective of presenting field data concerning the attachment point distribution on WTGs is to ensure that manufacturers target the design and placement of the lightning protection system in an efficient manner, i.e. placing the protection emphasis at the tip region of the blade. The presented field data is based on several blade designs investigated over the past decade, revealing a clear distribution of lightning attachments and damages at different span-wise locations. The data is publicly available and show unambiguously the trend of higher strike probability towards the tip region of the blade.

The attachment point distribution presented here may differ from the findings for specific blades at specific sites, and provided manufacturers have collected such information on their own blade designs at relevant sites, such data should be used for the design inputs.

C.8.3 Field exposure

Several field campaigns are reported in literature where attachment points are identified by inspecting blades and evaluating successful lightning strike protection as well as strikes causing blade damage. The blade inspections cover blades on onshore and offshore turbines, blades made of CFRP and GFRP main laminates, and blades with different air termination and down conductor layout. The considered blade lengths range from 39 m to 45 m, with the following distribution of strikes to WTG blades vs. the distance from the blade tip. The results of these investigations are summarised in Table C.4, which can be used for reference if no specific information is available.

Table C.4 – 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
4 to 6	0 to 10
6 to 8	0 to 4
8 to 10	0 to 4
Rest	0 to 4

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Annex D
(normative)

Test specifications

D.1 General

This annex describes test methods for verifying blade designs with respect to their capability of handling the impact of a lightning discharge. The tests are described for blades herein, but may also be applied to other objects such as the spinner, hub, nacelle or parts thereof.

The manufacturer shall define the number of samples of the items to be tested. The items to be tested would be specimens of the blade, including the tip and sufficient portions of the blade inboard of the tip to represent the complete lightning protection design and the blade specimen structure, as well as the interaction of the air termination system, lightning down conductors, down conductor connection components, other components of the lightning protection system, and the blade specimen structure. The test specification is divided into two sub-sections.

The high-voltage strike attachment tests are applied to determine specific lightning attachment points and breakdown paths across or through non-conducting materials, such as wind turbine blades and nacelle covers. Since the currents that flow during these tests are representative only of lightning leader currents, and not the much more intense stroke currents, the attachment tests are intended only to show the path(s) that may be taken by lightning discharges. The damage caused by these tests is not comparable to possible damage from the lightning currents.

The high-current physical damage tests are used to assess actual damage from lightning currents. The test methods presented are applicable to both complete tip designs, and to smaller sections of the down conductor, such as connection components. These tests do not give any information about the most likely attachment points.

Pass/fail criteria for each test are described in the following subsections.

D.2 High-voltage strike attachment tests

D.2.1 Verification of air termination system effectiveness

These verification tests are used to verify the effectiveness of the air termination system on wind turbine blades. For development and design purposes, different test setups and considerations than required by the normative tests may be used.

The evaluation based on the strike attachment tests cannot be correlated with interception efficiency as stipulated by the selected LPL. The actual interception efficiency can only be verified by field observations.

NOTE For two-bladed rotors, the attachment distribution along the blades will differ from three-bladed rotors. Hence, the high-voltage initial leader attachment test required in D.2.2 can to be done with even lower angles (i.e. closer to horizontal / zero degrees) to demonstrate adequate interception efficiency for the tip as well as for inboard sections of the blade.

D.2.2 Initial leader attachment test

D.2.2.1 Test purpose

This test is intended for wind turbine blades. This test shall be used to verify the following:

- effectiveness of the air termination system for the blade in question;

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- location of possible leader attachment points and flashover or puncture paths on blades and other non-conducting structures;
- flashover or puncture paths along or through dielectric surfaces;
- performance of protection designs and/or devices.

D.2.2.2 Test specimen

The test specimen is a full-scale blade or blade tip section including all relevant design details as being present in series production. In selecting the appropriate blade length, the blade design details and the likelihood of test strike attachment to the crane slings, to other details being part of the test setup and to the root end of the blade sample shall be considered. Experience has shown that a blade length of approximately 15 % of the total blade is applicable for 10° or lower test angles.

The blade section shall be long enough to include samples of all applicable elements of the lightning protection system installed in a production representative condition. The test report shall detail the applicability rationale of the test section with respect to the full blade design.

Electrically conducting components, such as lights and sensors and the lightning conductor(s), normally installed on or within the test specimen (a single blade, a blade tip or a mid-section of a blade), shall be represented within the test specimen.

These items shall be positioned at the same locations within the test specimen as they would be in the blade. If the conducting specimens may be oriented in several positions, those that represent worst cases should be represented in the tests. Normally these are the positions that result in the smallest distances to the non-conducting skins, or the strongest electric field intensities in directions normal to the exterior surface. Either new blade samples or samples that have previously been aged mechanically could be used as long as they are undamaged by the mechanical aging process.

NOTE 1 The test description in this annex is mandatory for blade tips. The same test principles can be applied for inboard blade sections to verify performance of air termination systems in these regions, or determine likely attachment points along the blade.

NOTE 2 Experience has shown that testing blades in angles of 10° to the horizontal plane requires test samples of minimum length 10 m to avoid flashovers from the end of the blade sample.

D.2.2.3 Test setups

D.2.2.3.1 General

The initial leader attachment test is used for design and verification purposes. The verification test for blades is described in the present subclause, and the test used are test setup A or B, whereas development tests may benefit from different test setups and test configurations.

Each test arrangement is intended to result in initiation of electrical activity, such as corona, streamers and leaders, at the test specimen (and not at the external electrode) as occurs at a wind turbine blade just before a lightning attachment. Once ionisation of the air at the test specimen is initiated, the streamer will progress toward the opposite electrode which is to be a large geometric shape intended to represent an electric field equipotential surface some distance from a blade extremity. In this way, the influence of the external test electrode on test results is minimised. Overviews of the test arrangements showing the high-voltage generator, test specimen and external electrode in test setups A and B are illustrated in Figure D.1, Figure D.4 and Figure D.5.

Test setup A is the most desirable arrangement, since it usually allows a larger dimension external electrode (i.e. a conductive surface on the laboratory floor) and a more realistic electric field environment around the blade specimen to be provided.

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Test setup B is intended to create a similar electric field arrangement about the test specimen as in test setup A while allowing larger or heavier test specimens and support structures to be placed on the laboratory floor. In this arrangement, a large diameter electrode shall be suspended above the test specimen. A large diameter is essential to avoid non-realistic field intensifications owing to the edges of the suspended electrode, potentially causing flashovers between the edges of the electrode and the test sample, or between the edges of the suspended electrode and a ground plane on the laboratory floor, bypassing the blade test specimen altogether.

NOTE For very flexible blade samples, it might be considered to pitch the blade in an angle such that the force of gravity bends the blade into a geometry closer to operational conditions. This principle of a fixed blade setup applies to both setups A and B.

D.2.2.3.2 Test setup A

Test setup A is applicable for tests of large portions of a blade that includes representative portions of the lightning protection system. The general test arrangement for test setup A is illustrated in Figure D.1.

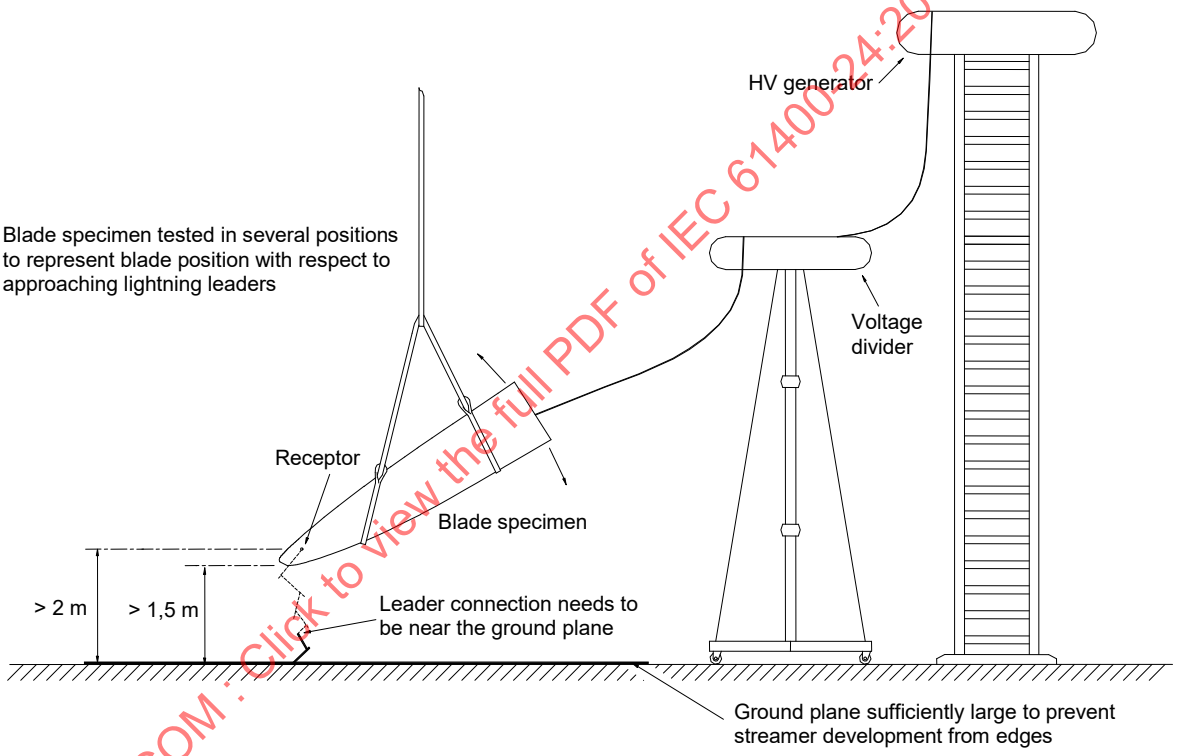

Figure D.1 – Example of initial leader attachment test setup A

The distances shown in Figure D.1 are indicative only. The minimum air-gap distance to conductive parts shall be 1,5 m.

The test specimen, having its lightning protection system connected to the output of a Marx generator, is elevated above the external electrode, a large area ground plane. The ground plane shall be of sufficient size to avoid edge effects, i.e. to avoid having flashovers terminating on the edge of the ground plane and to be regular and uniform enough to ensure that the connection point of the flashover is in the lower part of the gap. The test specimen shall be tested in the 90°, 30° and 10° orientation at all 4 blade pitch angles as defined in Figure D.2, to represent electric field directions that this part of the test specimen may experience on the turbine. The specific angles defined for the mandatory test sequence identifies likely attachment points at the most predominant blade angle relative to the field

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(90°) and also stresses inboard sections of the tip region where likely attachment points are also observed in field (30° and 10°). Additional angles may be used to investigate the blade performance during the design process.

In Figure D.2, three different angles of the blade relative to the ground plane are used (90°, 30° and 10° with horizontal, all with tolerances ±3°), and four different pitch positions. By applying three discharges of each polarity and at each orientation, the blade will experience 54 impacts.

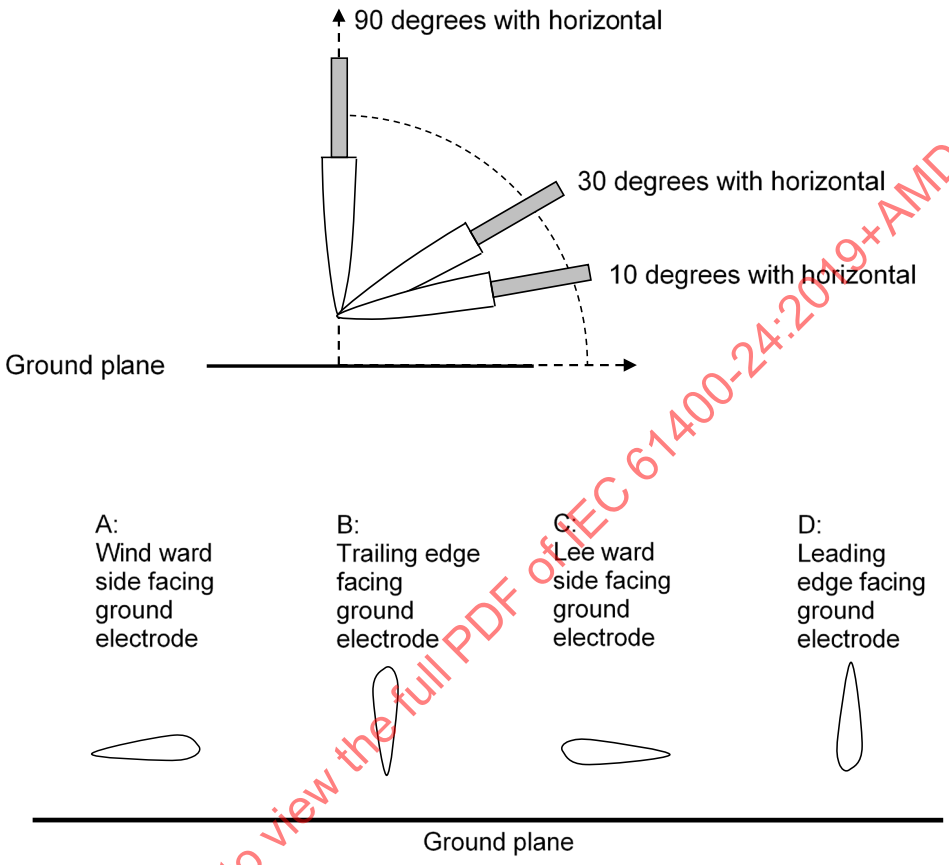

Figure D.2 – Possible orientations for the initial leader attachment test setup A

For two-bladed rotors, the attachment distribution along the blades will be different than for three-bladed rotors. Hence, the high-voltage initial leader attachment test should be conducted with even lower angles (preferably as close to 0° as possible) to demonstrate adequate interception effectiveness for the tip as well as for inboard sections of the blade. Currently, the mandatory test sequence for three-bladed rotors apply for two-bladed rotors as well, until further field experience with two-bladed rotors is published.

NOTE Tests of wet and polluted blade samples can be used to stress particular design features and emulate a naturally aged blade, but such tests are not mandatory.

The angle between the blade length axis and the external ground electrode is defined in accordance with Figure D.3. For each test configuration in Figure D.2, the blade length axis is defined as a line intersecting the closest surface (windward side (A), trailing edge (B), leeward side (C) or leading edge (D) at distances of 1 m and 5 m from the tip.

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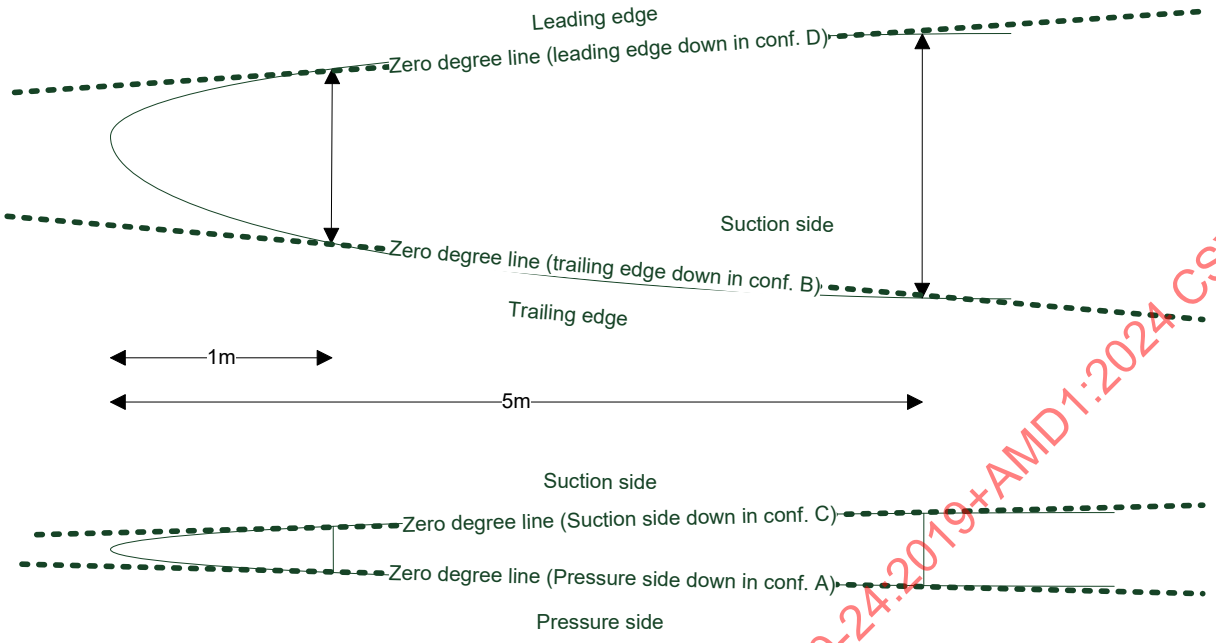

Figure D.3 – Definition of the blade length axis during strike attachment tests

For blade designs equipped with serrations, winglets, vortex generators or other aerodynamic features, the same criterion as shown in Figure D.3 applies. Sketches of the application on a blade with a winglet are shown in Figure D.4.

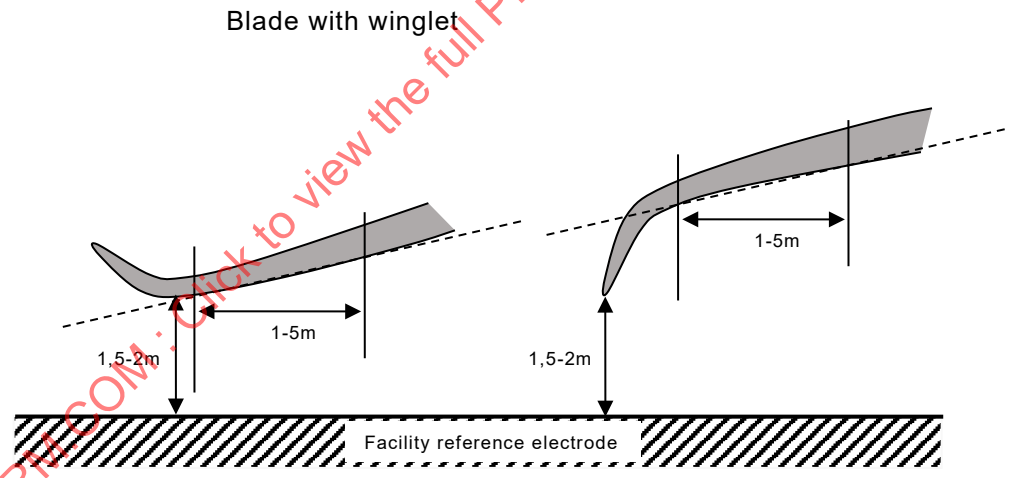

Figure D.4 – Example of the application of angles during the HV test

In the case of blades with winglets, the gap distance to non-conducting parts may be adjusted depending on the winglet design, provided the distance to the air-termination and conducting parts is minimum 1,5 m, and the minimum air-gap distance to non-conducting parts is 0,5 m.

Two conditions shall apply for a valid test when test setup A is used:

a) Connection of the streamers shall occur in the lower part of the air gap between the energised blade and the ground plane, i.e. more than half the flashover distance away from the blade specimen. This is confirmed by photographs of the flashovers. The leader connection point is shown in Figure D.5. If this is not achieved, the uniformity of the plane surface shall be improved, or the distance between blade and plane increased. If the connection has occurred closer to the blade than half way between the blade and the

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ground plane and the test has resulted in successful attachment to a designated protection device or design, the test should be considered successful. But if a puncture of the blade has occurred, the test shall not be considered successful, and the specific test is disregarded and an additional test may be applied.

b) The streamer from the ground plane shall not originate from the edge of the ground plane. In such a case, the size of the ground plane may be increased. But note that increasing the diameter of the HV electrode may not stop flashovers from originating at the edge of the HV electrode and bypassing the test specimen.

If the flashover originated at the ground plane, and the test has resulted in successful attachment to a designated protection device or design, the test should be considered successful. But if a puncture of the blade has occurred, the test shall not be considered successful, and the specific test is disregarded and an additional test may be applied.

Conditions a) and b) are typically met by keeping the following dimensions:

1) The ground plane should be at least 2 m from the closest conductive element (inside or outside the test specimen);
2) The ground plane should be at least 1,5 m from the nearest test specimen skin;
3) The smallest dimension of the ground plane should be at least 5 times the minimum gap length between the blade and the ground plane.

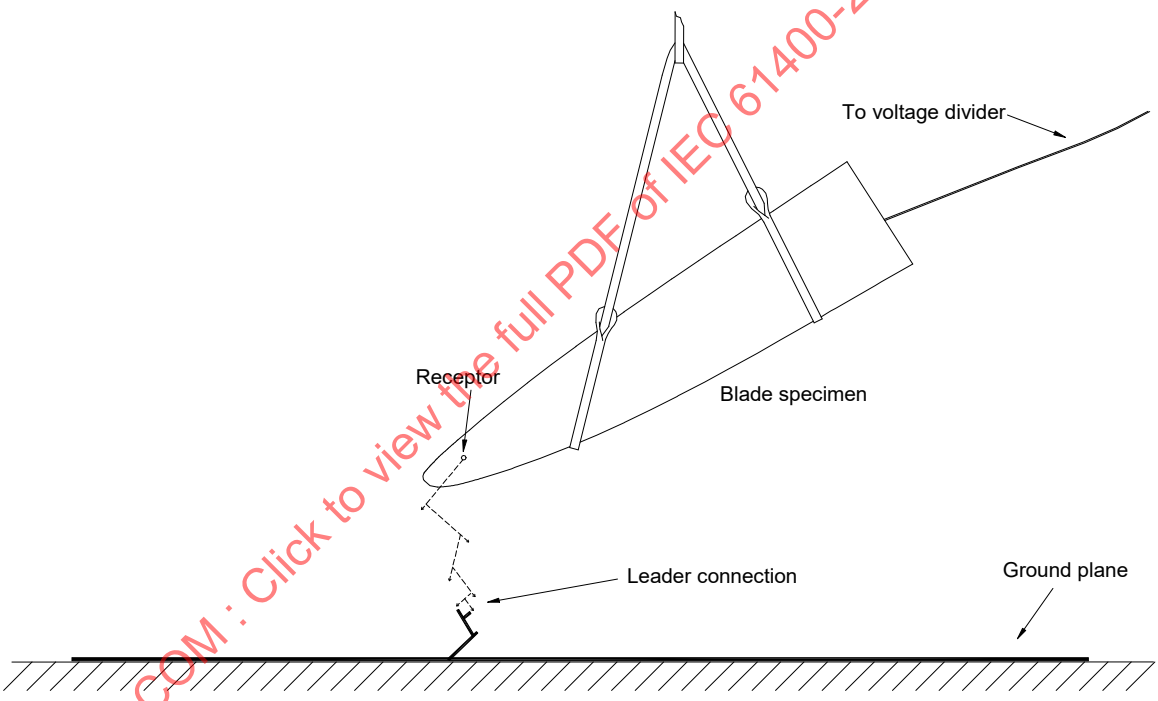

Figure D.5 – Example of leader connection point away from test specimen

Specific dimensions and test specimen orientations shall be described in the test plan.

D.2.2.3.3 Test setup B

The general test arrangement for test setup B is illustrated in Figure D.6.

The specimen should be tested in several positions representing different directions of the approaching leader, as specified in Figure D.2 for test setup A.

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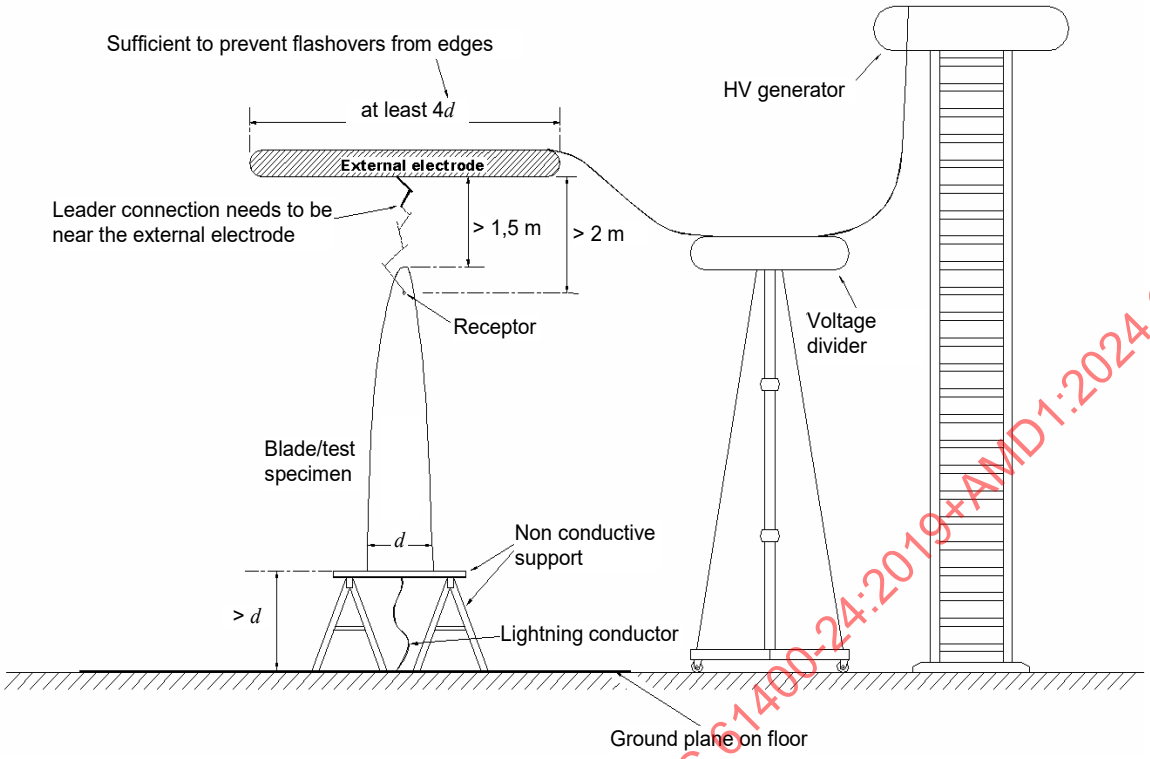

Figure D.6 – Initial leader attachment test setup B

The distances shown in Figure D.6 are indicative only. The minimum air-gap distance to conductive parts shall be 1,5 m.

Test setup B is applicable for blades as an alternative to test setup A, but also suitable for test specimens where elevation in the test facility is impractical, such as meteorological instrument booms, hubs, spinners. This arrangement has the disadvantage that the ground plane on the test facility floor may distort the electric field near the test specimen. The minimum clearance to extraneous structures is specified, in IEC 60060-1, as 1,5 times the minimum flashover distance between the two opposite electrodes. To minimise the distortion on the electric field present in the gap, the ground plane and other conductive structures shall be at least 1,5 times the gap length away, i.e. 3 m with the gap length of 2 m in Figure D.6.

The test specimen is elevated above the ground plane on supports by a distance greater than 1,5 times the distance between air termination on the test specimen and the external electrode to minimise influence of the ground plane on test results. The external electrode is suspended above the test specimen and at high potential when the test is applied. The external electrode shall be of sufficient size to avoid edge effects, i.e. to avoid having flashovers terminating on the edge of the external electrode. The test specimen should normally be tested with two or more orientations, to represent the possible electric field directions that this part of the blade or other structures may experience in service. One pitfall with Setup B is that when the external electrode is at positive polarity, flashovers can originate at the edges of this electrode and terminate on the ground plane and bypass the test specimen.

Three conditions should apply to a valid test when test setup B is used:

a) Connection of the streamers should occur in the upper part of the air gap between the energised external electrode and the test specimen, i.e. more than half the flashover distance away from the test specimen. This is confirmed by photographs of the flashovers.

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The leader connection point is shown in Figure D.6. If this is not achieved, the uniformity of the plane surface should be improved, or the distance between the blade and the plane increased.

b) The streamer from the external electrode should not originate from the edge of this electrode. In such a case, the size of the external electrode may be increased. But note that increasing the diameter of the HV electrode may not stop flashovers from originating at the edge of the HV electrode and bypassing the test specimen. In this case, the only solution is to use test setup A.

c) The end termination of the LPS or other conductive elements within the specimen should be elevated above the ground plane by a distance larger than 1,5 times the distance between air termination on the test specimen and the external electrode.

Conditions a) and b) are typically met by keeping the following dimensions:

1) The external electrode should be at least 2 m from the closest conductive element (inside or outside the test specimen).
2) The external electrode should be at least 1,5 m from the nearest test specimen skin.
3) The smallest dimension of the external electrode should be at least 5 times the minimum gap length between the blade and the ground plane.

Specific dimensions and test specimen orientations should be described in the test plan.

D.2.2.4 Test voltage waveform

The voltage waveform used is a slowly rising voltage waveform reaching flashover to the specimen before the prospective voltage peak. This voltage waveform is selected since it is the most representative of the electric field in the vicinity of a structure during an initial leader attachment.

On rare occasions, the flashover can happen after the peak of the voltage waveform. Such tests are regarded valid and are accounted for in the overall evaluation provided it does not happen in more than 10 % of all flashovers throughout the test sequence. But if a puncture of the blade has occurred, the test shall not be considered successful, and the specific test is disregarded and an additional test may be applied.

Such waveforms might be achieved by using the switching impulse voltage in IEC 60060-1 with time to peak of 250 μs ± 50 μs (i.e. 250 μs ± 20 %) and decay time to half value of 2 500 μs ± 1 500 μs (i.e. 2 500 μs ± 60 %). Since the voltage is applied as a rise to flashover, the decay time of the full waveform is not of particular interest.

A typical test voltage waveform is shown in Figure D.7.

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