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Wind energy generation systems

Part 24: Lightning protection

National foreword

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(IEC 61400-24:2019)**

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(IEC 61400-24:2019)

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European foreword

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IEC 60060-1:2010	NOTE	Harmonized as EN 60060-1:2010 (not modified)
IEC 60071 (series)	NOTE	Harmonized as EN 60071 (series)
IEC 60071-2:2018	NOTE	Harmonized as EN IEC 60071-2:2018 (not modified)
IEC 60099-4	NOTE	Harmonized as EN 60099-4
IEC 60099-5	NOTE	Harmonized as EN IEC 60099-5
IEC 60204-1	NOTE	Harmonized as EN 60204-1
IEC 60204-11	NOTE	Harmonized as EN IEC 60204-11
IEC 60243 (series)	NOTE	Harmonized as EN 60243 (series)
IEC 60243-1	NOTE	Harmonized as EN 60243-1
IEC 60243-3	NOTE	Harmonized as EN 60243-3
IEC 60464-2	NOTE	Harmonized as EN 60464-2
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Annex ZA

(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 60364-4-44	-	Low-voltage electrical installations - Part 4-44: Protection for safety - Protection against voltage disturbances and electromagnetic disturbances	IEC 60364-4-442	-
IEC 60364-5-53	-	Low-voltage electrical installations -- Part-5-53: Selection and erection of electrical equipment - Protection, isolation, switching, control and monitoring		-
IEC 60364-5-54	-	Low-voltage electrical installations - Part 5-54: Selection and erection of electrical equipment - Earthing arrangements and protective conductors	IEC 60364-5-54	-
IEC 60364-6	-	Low voltage electrical installations - Part 6: Verification	IEC 60364-6	-
IEC 60664-1	-	Insulation coordination for equipment within low-voltage systems - Part 1: Principles, requirements and tests	IEC 60664-1	-
IEC 61000-1	series	Electromagnetic compatibility (EMC) - Part 1-2: General - Methodology for the achievement of functional safety of electrical and electronic systems including equipment with regard to electromagnetic phenomena	IEC 61000-1	series
IEC 61000-4-5	-	Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test	IEC 61000-4-5	-
IEC 61000-4-9	-	Electromagnetic compatibility (EMC) – Part 4-9: Testing and measurement techniques – Impulse magnetic field immunity test	IEC 61000-4-9	-
IEC 61000-4-10	-	Electromagnetic compatibility (EMC) – Part 4-10: Testing and measurement techniques – Damped oscillatory magnetic field immunity test	IEC 61000-4-10	-

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 61400-23	-	Wind turbines - Part 23: Full-scale structural testing of rotor blades	EN 61400-23	-
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	EN 61587-3	-
IEC 61643-11	-	Low-voltage surge protective devices - Part 11: Surge protective devices connected to low-voltage power systems - Requirements and test methods	EN 61643-11	-
IEC 61643-12	-	Low-voltage surge protective devices - Part 12: Surge protective devices connected to low-voltage power distribution systems - Selection and application principles	CLC/TS 61643-12	-
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	CLC/TS 61643-22	-
IEC 61936-1	-	Power installations exceeding 1 kV a.c. - Part 1: Common rules	EN 61936-1	-
IEC 62305-1 mod) 2010		Protection against lightning - Part 1: General principles	EN 62305-1	2011
IEC 62305-2 mod) 2010		Protection against lightning - Part 2: Risk management	EN 62305-2	2012
IEC 62305-3 mod) 2010		Protection against lightning - Part 3: Physical damage to structures and life hazard	EN 62305-3	2011
IEC 62305-4 mod) 2010		Protection against lightning - Part 4: Electrical and electronic systems within structures	EN 62305-4	2011
IEC/TR 60479-4	-	Effects of current on human beings and livestock -- Part 4: Effects of lightning strokes on human beings and livestock		-
IEC/TR 61000-5-2	-	Electromagnetic compatibility (EMC) - Part 5: Installation and mitigation guidelines - Section 2: Earthing and cabling		-
IEC/TS 60479-1	-	Effects of current on human beings and livestock - Part 1: General aspects		-
IEC/TS 61936-2	-	Power installations exceeding 1 kV a.c.- and 1,5 kV d.c. - Part 2: d.c.		-
ITU-T K.20	-	Resistibility of telecommunication-equipment installed in a telecommunication centre to overvoltages and overcurrents		-

EN IEC 61400-24:2019+A1:2024 (E)

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
ITU-T K.21	-	Resistibility of telecommunication-equipment installed in customer premises to overvoltages and overcurrents		-
IECRE OD-501	-	Type and Component Certification Scheme - (wind turbines)		-

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 24: Lightning protection

FOREWORD

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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.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
88/709/FDIS	88/713/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

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 will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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.

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)*

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*

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

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 laboratory 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

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.

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.

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.

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.

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

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)

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

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

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	$\mu\text{s} / \mu\text{s}$	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	$\mu\text{s} / \mu\text{s}$	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	$\mu\text{s} / \mu\text{s}$	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.

^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).

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, $Q_{\text{flash}} = 300 \text{ C}$, 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 $Q_{\text{flash}} = 600 \text{ C}$ 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.

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 $10^{-5} \text{ year}^{-1}$.

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.

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:

$$N_{SG} = 2N_G \quad (1)$$

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:

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

Where

- N_{SG} is the lightning ground strike-point density per km² per year;
- A_D is the equivalent collection area of the structure [m²];
- 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.

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 km² 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:

$$N_{G\text{corrected}} = \frac{N_{G\text{LLS}}}{DE} \quad (4)$$

where

- $N_{G\text{corrected}}$ is the corrected annual average ground flash density considering detection efficiency of the LLS [km⁻²·year⁻¹];
- $N_{G\text{LLS}}$ 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 LSS; 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.

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.

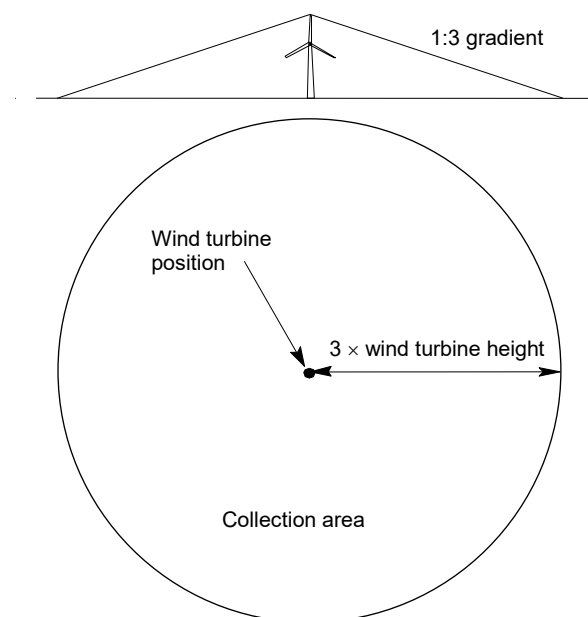


Figure 1 – Collection area of the wind turbine

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:

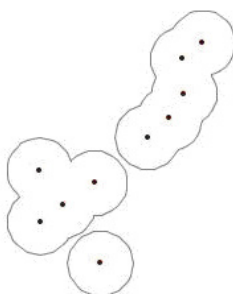


Figure 2 – Example of collection area for a complete wind farm (A_{DWF}) with 10 wind turbines (black points) considering overlapping

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 km² per year;

A_M is the equivalent collection area of flashes striking near the structure (m²).

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.

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 km² per year;
- A_L is the collection area of lightning flashes to the service line [m²] – 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 km² 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 [m²] – 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).

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

	Aerial	Buried
A_L	$(L_c - 3(H_a + H_b)) \sqrt{\rho}$	$(L_c - 3(H_a + H_b)) \sqrt{\rho}$
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 [Ω m]. A maximum value $\rho = 500$ Ω m should be assumed.

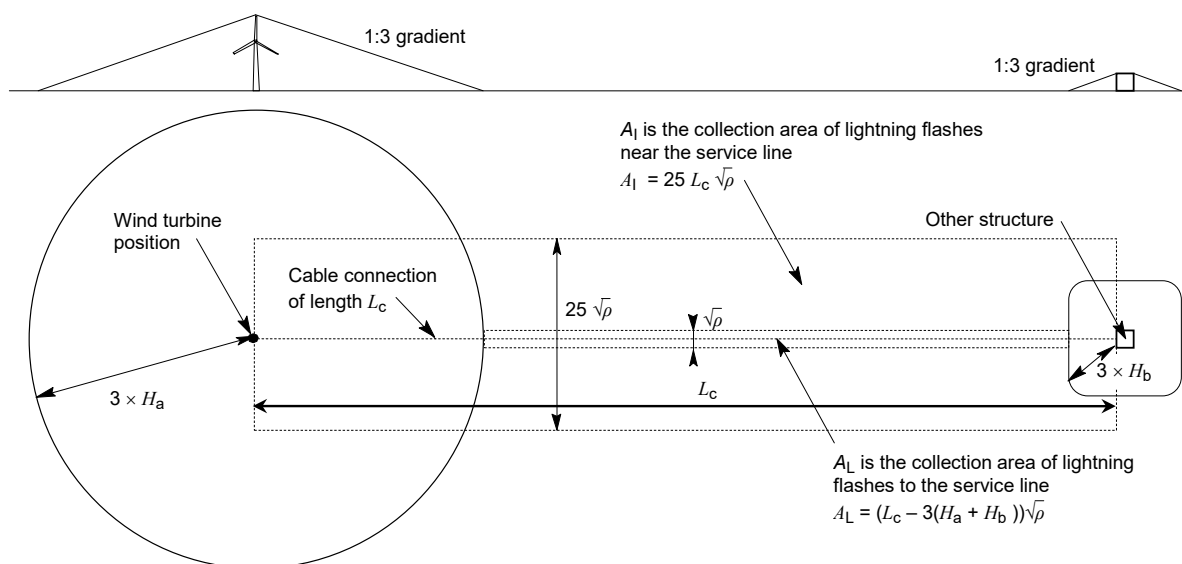


Figure 3 – Collection area of wind turbine of height H_a and another structure of height H_b connected by underground cable of length L_c

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.

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 .

$$R > R_T \quad (10)$$

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 customer.

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})

$$R_{AT} = N_D \cdot P_{AT} \cdot P_P \cdot L_{AT} \quad (11)$$

$$R_{AD} = N_D \cdot P_{AD} \cdot P_P \cdot L_{AD} \quad (12)$$

- component related to physical damage to the structure

$$R_B = N_D \cdot P_B \cdot P_P \cdot L_B \quad (13)$$

- component related to failure of internal systems

$$R_C = N_D \cdot P_C \cdot P_P \cdot P_E \cdot L_C \quad (14)$$

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

$$R_M = N_M \cdot P_M \cdot P_P \cdot P_E \cdot L_M \quad (15)$$

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

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.

**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_U ; L_V ; 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.

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;

- 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.

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.

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.

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.

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.