IEC 61400-24

Edition 1.0 2010-06

INTERNATIONAL STANDARD

Wind turbines –
Part 24: Lightning protection

IEC 61400-24:2010(E)

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

- Catalogue of IEC publications: www.iec.ch/searchpub
The IEC on-line Catalogue enables you to search by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, withdrawn and replaced publications.

- IEC Just Published: www.iec.ch/online_news/justpub
Stay up to date on all new IEC publications. Just Published details twice a month all new publications released. Available on-line and also by email.

- Electropedia: www.electropedia.org
The world's leading online dictionary of electronic and electrical terms containing more than 20 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary online.

- Customer Service Centre: www.iec.ch/webstore/custserv
If you wish to give us your feedback on this publication or need further assistance, please visit the Customer Service Centre FAQ or contact us:

Email: csc@iec.ch
Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00

IEC 61400-24

Edition 1.0 2010-06

INTERNATIONAL STANDARD

Wind turbines –
Part 24: Lightning protection

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE **XG**

ICS 27.180

ISBN 978-2-88910-969-2

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND TURBINES –

Part 24: Lightning protection

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

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

This first edition replaces IEC/TR 61400-24, published in 2002. It constitutes a technical revision. It is restructured with a main normative part, while informative information is placed in annexes.

The text of this standard is based on the following documents:

FDIS	Report on voting
88/366/FDIS	88/369/RVD

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

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

A list of all parts of the IEC 61400 series, under the general title: *Wind turbines*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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

A bilingual version of this publication may be issued at a later date.

WIND TURBINES –

Part 24: Lightning protection

1 Scope

This International Standard applies to lightning protection of wind turbine generators and wind power systems.

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).

This standard defines the lightning environment for wind turbines and application of the environment for risk assessment for the wind turbine. 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 recommended.

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.

2 Normative references

The following referenced documents are indispensable for the application 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 60060-1:1989, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60068 (all parts), *Environmental testing*

IEC 60071 (all parts), *Insulation Co-ordination*

IEC 60071-2:1996, *Insulation Co-ordination – Part 2: Application guide*

IEC 60099-4, *Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems*

IEC 60099-5, *Surge arresters – Part 5: Selection and application recommendations*

IEC 60204-1, *Safety of machinery – Electrical equipment of machines – Part 1: General requirements*

IEC 60204-11, *Safety of machinery – Electrical equipment of machines – Part 11: Requirements for HV equipment for voltages above 1 000 V a.c. or 1 500 V d.c. and not exceeding 36 kV*

IEC 60243-1, *Electrical strength of insulating materials – Test methods – Part 1: Tests at power frequencies*

IEC 60243-3, *Electric strength of solid insulating materials – Test methods – Part 3: Additional requirements for 1,2/50μs impulse tests*

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

IEC 60364-5-53:2001, *Electrical installations of buildings – Part 5-53: Selection and erection of electrical equipment – Isolation, switching and control*
Amendment 1(2002)[1)]

IEC 60464-2, *Varnishes used for electrical insulation – Part 2: Methods of test*

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

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

IEC 60587, *Electrical insulating materials used under severe ambient conditions – Test methods for evaluating resistance to tracking and erosion*

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

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

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

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

IEC 61643-1, *Low-voltage surge protective devices – Part 1: Surge protective devices connected to low-voltage power distribution systems – Requirements and tests*

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 62153-4-3, *Metallic communication cable test methods – Part 4-3: Electromagnetic compatibility (EMC) – Surface transfer impedance – Triaxial method*

IEC 62305-1:2006, *Protection against lightning – Part 1: General principles*

---

1) There exists a consolidated edition 3.1 (2002) that comprises IEC 60364-5-53 (2001) ant its Amendment 1 (2002).

IEC 62305-2:2006, *Protection against lightning – Part 2: Risk management*

IEC 62305-3:2006, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC 62305-4:2006, *Protection against lightning – Part 4: Electrical and electronic systems within structures*

EN 50164-1, *Lightning Protection Components (LPC) – Part 1: Requirements for connection components*

CLC HD 637 S1, *Power installations exceeding 1kV A.C.*

ITU-T K.2, *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*

ITU-T K.46, *Protection of telecommunication lines using metallic symmetric conductors against lightning-induced surges*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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 of the front of short stroke current
average rate of change of current within a time interval $\Delta t = t_2 - t_1$

NOTE It is expressed by the difference $\Delta i = i(t_2) - i(t_1)$ of the values of the current at the start and at the end of this interval, divided by the time interval $\Delta t = t_2 - t_1$ (see Figure A.3).

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

3.4
collection area
A_d
for a structure, area of ground surface which 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 which, in general, do not occur simultaneously

3.7
coordinated SPD protection
set of SPD properly selected, coordinated and installed to reduce failures of electrical and electronic systems

NOTE Coordination of SPD protection must include 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 A downward flash consists of a first short stroke, which can be followed by subsequent short strokes and may include a long stroke.

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

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

3.12
effective height
H
for a wind turbine, the highest point the blades reach, i.e. hub height plus rotor radius

3.13
external lightning protection system
part of the LPS consisting of an air-termination system, a down-conductor system and an earth-termination system

NOTE The down conductor is often placed inside wind turbine blades.

3.14
flash charge
Q_{flash}
time integral of the lightning current for the entire lightning flash duration

3.15
foundation earth electrode
reinforcement steel of foundation or additional conductor embedded in the concrete foundation of a structure and used as an earth electrode

3.16
ground flash density
N_g
the number of lightning flashes per square kilometre per year in the region where the structure is located

3.17
internal lightning protection system
part of the LPS consisting of lightning equipotential bonding and/or electrical insulation of external LPS

NOTE 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.

3.18
interception efficiency
probability with which the air-termination system of an LPS intercepts a lightning flash

3.19
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

3.20
LEMP protection measures system
LPMS
complete system of protection measures for internal systems against LEMP

3.21
lightning current
i
current flowing at the point of strike

3.22
lightning electromagnetic impulse
LEMP
electromagnetic effects of lightning current

NOTE It includes conducted surges as well as radiated impulse electromagnetic field effects.

3.23
lightning equipotential bonding
bonding to LPS of separated metallic parts by direct conductive connections or via surge protective devices to reduce potential differences caused by lightning current

3.24
lightning flash to a structure
lightning flash striking a structure to be protected

3.25
lightning flash to earth
electric discharge of atmospheric origin between cloud and earth consisting of one or more strokes

NOTE 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.

3.26
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 Lightning protection level is used to design protection measures according to the relevant set of lightning current parameters.

3.27
lightning protection system
LPS
complete system used to reduce physical damage due to lightning flashes to a structure

NOTE It consists of both external and internal lightning protection systems.

3.28
lightning protection zone
LPZ
zone where the lightning electromagnetic environment is defined

NOTE The zone boundaries of an LPZ are not necessarily physical boundaries (e.g. walls, floor and ceiling).

3.29
lightning stroke
single discharge in a lightning flash to earth

3.30
long stroke
part of the lightning flash which corresponds to a continuing current

NOTE The duration time T_{long} (time from the 10 % value on the front to the 10 % value on the tail) of this continuing current is typically more than 2 ms and less than 1 s (see Figure A.4).

3.31
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 The protection effect of a magnetic shield is achieved through attenuation of the magnetic field.

3.32
metal installations
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

3.33
multiple strokes
lightning flash consisting on average of 3 or 4 strokes

The typical time interval between the strokes is about 50 ms.

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

3.34
natural component of LPS
conductive component installed not specifically for lightning protection which 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 Examples of the use of this term include:

– natural air termination;

– natural down conductor;

– natural earthing electrode.

3.35
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

3.36
peak value
I
maximum value of the lightning current

3.37
point of strike
point where a lightning flash strikes the earth or a protruding structure (e.g. structure, LPS, service line, tree, etc.)

NOTE A lightning flash may have more than one point of strike.

3.38
receptor
a form of air termination on wind turbine blades, for example discrete metal studs through the blade surface connected to a down conductor system

3.39
risk
R
value of probable average annual loss (humans and goods) due to lightning, relative to the total value (humans and goods) of the structure to be protected

3.40
separation distance
distance between two conductive parts at which no dangerous sparking can occur

3.41
service line
power line or telecommunication line connected to the structure to be protected

3.42
short stroke
part of the lightning flash which corresponds to an impulse current

NOTE This current has a time to half value T_2 typically less than 2 ms (see Figure A.3).

3.43
SPD tested with I_{imp}
SPDs which withstand the partial lightning current with a typical waveform 10/350 µs require a corresponding impulse test current I_{imp}

NOTE For power lines, a suitable test current I_{imp} is defined in the Class I test procedure of IEC 61643-1.

3.44
SPD tested with I_n
SPDs which withstand induced surge currents with a typical waveform 8/20 µs require a corresponding impulse test current I_n

NOTE For power lines, a suitable test current I_n is defined in the Class II test procedure of IEC 61643-1.

3.45
specific energy
W/R
time integral of the square of the lightning current for the entire flash duration

NOTE It represents the energy dissipated by the lightning current in a unit resistance.

3.46
surge
transient wave appearing as overvoltage and/or overcurrent caused by LEMP

NOTE 1 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 Surges may arise from other sources such as switching operations or fuses operating.

3.47
surge protective device
SPD
device intended to limit transient overvoltages and divert surge currents

It contains at least one non-linear component.

3.48
thunderstorm days
T_d
number of thunderstorm days per year obtained from isokeraunic maps

3.49
tolerable risk R_T
maximum value of the risk which can be tolerated for the structure to be protected

3.50
upward flash
lightning flash initiated by an upward leader from an earthed structure to cloud

NOTE An upward flash consists of a first long stroke with or without multiple superimposed short strokes. One or more short strokes may be followed by a long stroke.

3.51
voltage protection level
U_P
parameter that characterises the performance of the SPD in limiting the voltage across its terminals, which is selected from a list of preferred values

This value shall be greater than the highest value of the measured limiting voltages.

4 Symbols and units

A_d	Collection area of lightning flashes to an isolated structure
A_i	Collection area of lightning flashes to a service line
A_l	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_t	Correction factor for a HV/LV transformer on the service line
D1	Injury to living beings
D2	Physical damage
D3	Failure of electrical and electronic systems
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
$\mathrm{d}i/\mathrm{d}t$	Time derivative of current, average steepness
$\mathrm{d}i/\mathrm{d}t_{30/90\%}$	Current steepness between points of 30 % and 90 % peak amplitude on front
L_A	Loss related to injury to living beings
L_B	Loss in a structure related to physical damage (lightning flashes to structure)
L_C	Loss related to failure of internal systems (lightning flashes to service line)
L_M	Loss related to failure of internal systems (lightning flashes near structure)
L_U	Loss related to injury of living beings (lightning flashes to service line)
L_V	Loss in a structure due to physical damage (lightning flashes to service line)
L_W	Loss related to failure of internal systems (lightning flashes to service line)
L_f	Loss due to injury due to touch and step voltage
L_o	Loss due to physical damage
L_t	Loss due to failure of internal systems
L_x	Amount of consequent loss for component x
L_Z	Loss related to failure of internal systems (lightning flashes near a service line)
L1	Loss of human life in a structure
L2	Loss of service to the public in a structure
L3	Loss of cultural heritage in a structure
L4	Loss of economic value in a structure
n_p	Number of possible endangered persons (victims)
n_t	Exposed total number of persons present in structure
N_D	Number of dangerous events due to lightning flashes to a structure per annum
N_x	Number of dangerous events for component x per annum
N_d	Number of lightning flashes to a structure per annum
N_M	Number of lightning flashes near a structure per annum
N_L	Number of lightning flashes to a service line per annum
N_l	Number of lightning flashes near a service line per annum
$N_{d,x}$	Number of lightning flashes to a structure at the ”x” end of a service line per annum
N_g	Ground flash density per annum
P_A	Probability that lightning flashes to structure will cause shock to living beings
P_B	Probability that lightning flashes to a structure will cause physical damage
P_C	Probability of failure of internal systems caused by lightning flashes to the 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 that lightning flashes near a structure will cause failure of internal systems
P_{SPD}	Probability failure of internal systems given that SPD protection is applied
P_U	Probability that lightning flashes to a service line will cause injury to living beings
P_V	Probability that lightning flashes to a service line will cause physical damage
P_V	Probability that lightning flashes to a service line will cause failure of internal systems
P_x	Probability of damage for a structure x
P_Z	Probability that lightning flashes near a service line will cause failure of internal systems
r_a	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_u	Factor reducing the loss of human life depending on type of floor
R	Risk
R	Rolling sphere radius
R_S	Cable shield resistance per unit length
R_T	Tolerable risk
R_x	Risk component x
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
T_d	Thunderstorm days
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
kA	Kiloampere
C	Coulomb
°C	degrees Celsius
H	Henry
K	Kelvin

S	Siemens
G	Gram
kg	Kilogram
MJ	Megajoule
μm	Micrometre
mm	Millimetre
cm	Centimetre
m	Metre
km	Kilometre
ms	Millisecond
Ω	Ohm
S	Second
μs	Microsecond
V	Volt
Wb	Weber

5 Abbreviations

LPS	Lightning protection system
LPL	Lightning protection level
LPZ	Lightning protection zone
LEMP	Lightning electromagnetic impulse
LPMS	Lightning protection measures system
SEMP	Switching electromagnetic impulse
SPD	Surge protective device
PE	Protective earth
OCPD	Overcurrent protection device
QA	Quality assurance system
GFRP	Glass fibre reinforced plastic
CFRP	Carbon fibre reinforced plastic
CFC	Carbon fibre composite

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 $\mathrm{d}i/\mathrm{d}t$, but quadratic for W/R). The time parameters are unchanged.

Table 1 – Maximum values of lightning parameters according to LPL (Table 5 in IEC 62305-1)

First short positive stroke			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Peak current	I	kA	200	150	100	
Short stroke 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 short negative stroke [a]			**LPL**			
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 [a]			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
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			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Long stroke charge	Q_{long}	C	200	150	100	
Time parameter	T_{long}	s	0,5			
Flash			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Flash charge	Q_{flash}	C	300	225	150	
[a] The use of this wave shape 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).

NOTE 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.

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 0_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 0_B.

Table 2 – Minimum values of lightning parameters and related rolling sphere radius corresponding to LPL (Table 6 in 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

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 should 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.

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 involve loss of human life or permanent injuries is 10^{-5} year^{-1}.

NOTE Values for tolerable risk are given in IEC 62305-2, Table 7.

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. However, as the procedures described therein are quite elaborate, guidance is given here on how to make a simple lightning exposure assessment for individual wind turbines, and how to extend it to groups of wind turbines and wind farms.

Information about local lightning conditions should be collected whenever possible (for example at high latitudes where winter lightning may pose a special threat).

As a word of caution, it should be mentioned that 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 for example for comparison of risks for different wind turbine projects. Further details are provided in Annex B.

7.2 Assessing the frequency of lightning affecting a wind turbine

The first stage in the lightning risk analysis is the estimation of the frequency of lightning flashes to the wind turbine. IEC 62305-2 gives guidance on how this number can be estimated. When assessing the frequency of lightning flashes to a structure, the collection of data detailing the local ground flash density (N_g) is necessary. National organisations such as weather bureaus are likely to be able to provide this information. If the ground flash density is not available, it may be estimated using the following relationship:

$$N_g \approx 0{,}1 \cdot T_d \tag{1}$$

where

N_g [km^{-2}·year^{-1}] is the annual average ground flash density;

T_d [year^{-1}] is the number of thunder storm days per year obtained from isokeraunic maps (typically available from the national weather bureau).

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

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

N_M [year^{-1}] due to lightning flashes near the wind turbine (within 250 m);

N_L [year^{-1}] 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;

N_I [year^{-1}] 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;

$N_{D,b}$ [year^{-1}] due to lightning flashes to a wind turbine or another structure at the (other) ”b” end of the service lines connecting the wind turbine in question.

The average annual frequency of lightning flashes attaching to the wind turbine can be assessed as:

$$N_D = N_g \cdot A_d \cdot C_d \cdot 10^{-6} \tag{2}$$

where

A_d [m^2] is the collection area of lightning flashes to the structure;

C_d is the environmental factor.

Appropriate values are C_d = 1 for wind turbines on flat land and C_d = 2 for wind turbines on a hill or a mountain ridge.

NOTE 1 Wind turbines placed at locations known to be very exposed to lightning in general or to winter lightning in particular may be assigned a higher environmental factor C_d to consider upward lightning being triggered under such conditions.

NOTE 2 Wind turbines placed off shore may have to be assigned an environmental factor C_d of 3 to 5 to get a realistic estimate of the frequency of lightning attachment.

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 border line 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.

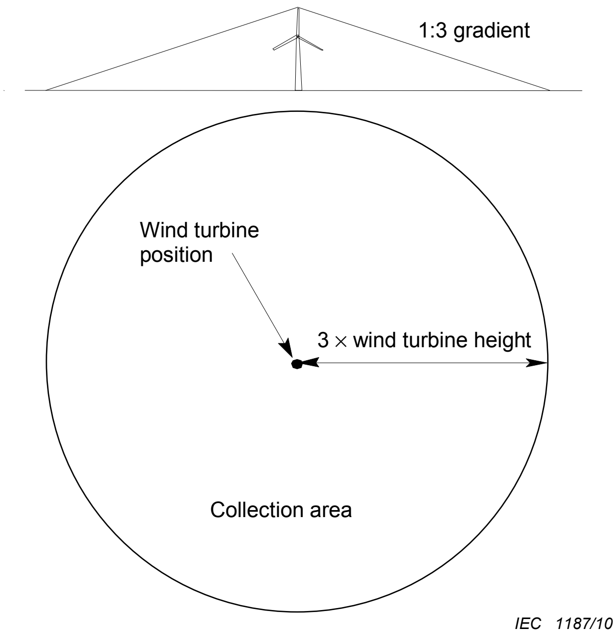


Figure 1 – Collection area of the wind turbine

The following equation can therefore be used when estimating the annual number of lightning flashes to a wind turbine placed on flat ground.

$$N_d = N_g \cdot A_d \cdot 10^{-6} = N_g \cdot 9\pi \cdot H^2 \cdot 10^{-6} \tag{3}$$

where

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

In more complex terrain, it is appropriate to consider the effective height of the wind turbine including the height of the wind turbine position, e.g. if placed exposed on hills or ridges (see Figure 2). IEC 62305-2 provides guidance for structures in complex terrain or in proximity to other structures.

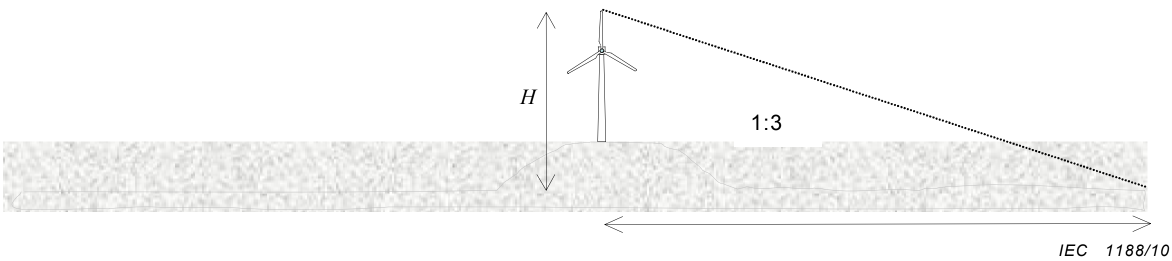


Figure 2 – Effective height, H, of wind turbine exposed on a hill

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

$$N_M = N_g \cdot (A_m - A_d C_d) \cdot 10^{-6} \tag{4}$$

where

A_m [m²] is the collection area for lightning flashes near the structure which is the area within a distance of 250 m.

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.

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 according to IEC 62305-2, Annex A as:

$$N_L = C_d \cdot C_t \cdot N_g \cdot A_l \cdot 10^{-6} \tag{5}$$

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

$$N_I = C_e \cdot C_t \cdot N_g \cdot A_i \cdot 10^{-6} \tag{6}$$

where

C_d is a location factor: say 1 in flat areas and 2 in hilly terrain;

C_e is an environmental factor, which is 1 for rural areas;

C_t is a transformer factor;

A_l [m²] is the collection area of lightning flashes to the service line – see Table 3;

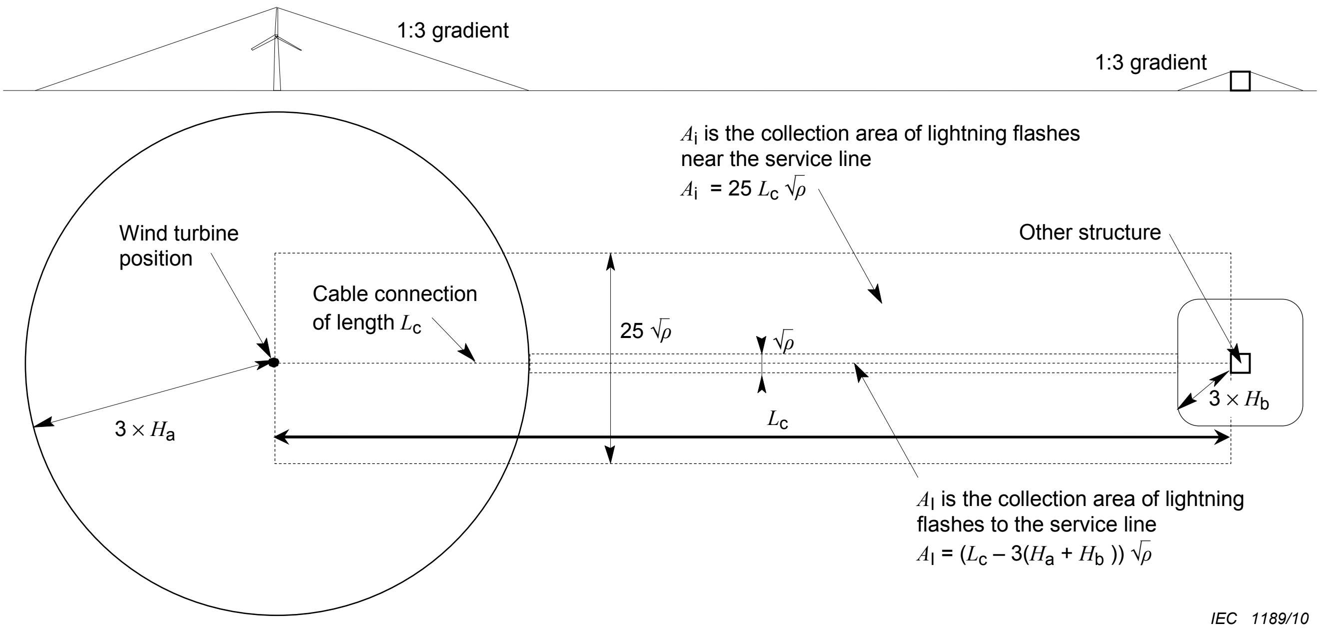
A_i [m²] is the collection area of lightning flashes near the service line – see Table 3.

The transformer 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, Annex A).

NOTE 3 C_d=0 for submarine service lines (submarine high-voltage cables and communication cables).

Table 3 – Collection areas A_l and A_i of service line depending on whether aerial or buried (corresponds to Table A.3 in IEC 62305-2)

	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 [m]	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.	
H_a [m]	is the height of the wind turbine connected at the "a" end of the service line.	
H_b [m]	is the height of the wind turbine (or other structure) connected at the "b" end of the service line.	
H_c [m]	is the height of the service line conductors above ground.	
ρ [Ωm]	is the resistivity of the soil where the service line is buried. A maximum value ρ = 500 Ωm should be assumed.	



Lightning flashes inside the narrow area A_l along the cable route may penetrate to and affect the cable directly, while lightning flashes inside the wider area A_i may induce transients and cause pin-hole punctures of the cable insulation.

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 may often overlap. 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.

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

$$R_X = N_X \cdot P_X \cdot L_X \tag{7}$$

where

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

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

L_X is the 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).

In case the risk is found to be too high, protection measures have to be applied as necessary to reduce the risk to less than the tolerable risk R_T.

$$R_X \leq R_T \tag{8}$$

NOTE The tolerable risk R_T may be stipulated by authorities.

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 relationship apply:

– component related to injury to living beings (D1)

$$R_A = N_D \cdot P_A \cdot L_A \tag{9}$$

– component related to physical damage (D2)

$$R_B = N_D \cdot P_B \cdot L_B \tag{10}$$

– component related to failure of internal systems (D3)

$$R_C = N_D \cdot P_C \cdot L_C \tag{11}$$

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

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 injury to failure of internal systems (D3)

$$R_M = N_M \cdot P_M \cdot L_M \tag{12}$$

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 relationship apply:

– component related to injury to living beings (D1)

$$R_U = (N_L + N_{D,b}) \cdot P_U \cdot L_U \tag{13}$$

– component related to physical damage (D2)

$$R_V = (N_L + N_{D,b}) \cdot P_V \cdot L_V \tag{14}$$

– component related to failure of internal systems (D3)

$$R_W = (N_L + N_{D,b}) \cdot P_W \cdot L_W \tag{15}$$

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 apply:

– component related to failure of internal systems (D3)

$$R_Z = (N_I - N_L) \cdot P_Z \cdot L_Z \tag{16}$$

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 Table 8 in 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)
	Probability that a flash to the wind turbine will cause
P_A	shock to living beings
P_B	physical damage
P_C	failure of internal systems
	Probability that a flash near the wind turbine will cause
P_M	failure of internal systems
	Probability that a flash to a service line will cause
P_U	injury to living beings
P_V	physical damage
P_W	failure of internal systems
	Probability that a flash near a service line will cause
P_Z	failure of internal systems
	Loss due to
$L_A = L_U = r_a \cdot L_t$	injury to living beings
$L_B = L_V = r_p \cdot r_f \cdot h_z \cdot L_f$	physical damage
$L_C = L_M = L_W = L_Z = L_o$	failure of internal systems
NOTE Values of loss L_t; L_f; L_o; factors r_p, r_a, r_u, r_f reducing the loss and factor h_z increasing the loss are given in Annex B.	

8 Lightning protection of subcomponents

8.1 General

Unless otherwise shown by risk analysis, all subcomponents should be protected according to LPL-I.

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.

NOTE A detailed risk assessment may reveal that a protection level less than LPL-I is economically optimal for some wind turbines or wind farms, just as it may be advantageous to differentiate so that for example 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.

8.2 Blades

8.2.1 General

Wind turbine blades are the most exposed parts of the turbine, and would 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 described in Annex A.

Wind turbine blades are placed in lightning protection zone 0_A according to IEC 62305-1 and shall be protected accordingly.

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 accept LPL I lightning flashes (unless a risk analysis shows that LPL-II or LPL-III is sufficient) without structural damage that would impair the functioning of the blade.

Lightning damage shall be limited to that which can be tolerated until the next scheduled maintenance and inspection.

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 verified by one 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 previously verified blade type, or a blade type with documented successful lightning protection;
c) using analysis tools previously verified by comparison with test results or with blade protection designs that have had successful service experience.

To claim verification by similarity, the blades must exhibit the same material composition, the same system of lightning protection and have the same structural characteristic dimensions. Significant changes which would affect lightning susceptibility should not be allowed without verification. However, assessments that would be identical to those performed on a previously verified blade design would not have to be repeated.

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

8.2.4 Protection design considerations

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

8.2.4.1 Air-termination system

The lightning air-termination systems are placed in the surface areas on the blade where connection 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.

The air-termination system positioning tools (rolling sphere, protective angle, etc.) described in IEC 62305-3 do not apply to wind turbine blades. Therefore, the air-termination system design shall be verified according to 8.2.3.

The manufacturer shall ensure that the air termination system is properly fixed in its mountings, and he shall design the air termination system so that it can withstand the expected wear due to wind, moisture, particles, etc. As part of such verification, the lightning protection components shall be present in the final blade design, preceding fatigue tests and other mechanical tests.

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 manufacturer shall design the air-termination system so that service personnel can repair or replace parts of it that may be damaged or degraded by lightning or other environmental effects. The air terminations will wear over time due 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 maximised through suitable selection of material and design. The manufacturer shall provide guidance on how to inspect and maintain the air-termination system.

If the air-termination system is covered by, for example, a coating, the function and the reparability over the lifetime of the blade must be maintained. Recommended tests for determining the effectiveness of air terminations are described in Annex D.

The manufacturer shall define a procedure for regular inspection of the air-termination systems so that the estimated design life-time and service/replacement intervals can be established and verified.

Verification of the air-termination system efficiency shall be done as described in 8.2.3.

8.2.4.2 The down conductor system and its connection components

The down conductor system and its connection components is the system for conducting the lightning current from the air-termination system to the termination in the root end of the blade.

The connections to the down conductor system shall be firm and permanent and ensure that the entire system can withstand the combined impact of the electrical, thermal, and electrodynamic effects of the lightning current. The ability of the lightning protection systems to withstand the mechanical stresses in the blades shall be verified, preferably by installing the system in a blade which is subjected to the tests in IEC/TS 61400-23.

The cross section of the down conductor and natural conductive parts of the blade used as down conductor shall be able to conduct lightning current corresponding to the chosen LPL. Metal conductors shall in general be selected according to IEC 62305-3.

Testing of connection components shall be done in accordance with EN 50164-1 without the conditioning/aging applied. 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 amplitudes 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. This aims at impeding 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.

Externally mounted down conductors are defined as air-termination systems, hence the requirements in 8.2.4.1 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 condition and estimated design life time and service intervals of these parts can be verified.

Recommended tests for determining 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.

8.2.4.3 Additional conductive components

In case additional conductive components (conductive structural components, CFC, weights, tip brake cables, electrical cables for sensors, warning lights, etc.) are present within the blade, these parts shall in general be bonded to the lightning protection system, be designed to conduct their share(s) of lightning current and be designed to prevent flashover between conductive parts.

Alternatively, it shall be documented by testing corresponding to the LPL and/or analysis whether additional conductive components, CFC structures etc. shall be bonded together and to the lightning protection system or not.

Bonding methods for these additional conductive components shall be proven by high-current testing as described in 8.2.5.2.

In case conductors form parallel current paths within the blade, such conductors shall be interconnected according to IEC 62305-1, and attention must be paid to the effects of electrodynamic forces.

8.2.4.4 Electrical field stress impact on composite material design

Due 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 composite materials. Therefore, the lightning protection systems should be designed considering high voltage insulation design principles.

8.2.5 Test methods

The following test methods apply to entire blade designs or sub-sections such as blade tips or laminate coupons.

8.2.5.1 High-voltage tests

Interception effectiveness of the air termination systems on the blade can be evaluated using the initial leader attachment test described in Annex D, Subclause D.2.1.

Development of specific design details surrounding tip receptors, side receptors or similar can gain from the initial leader attachment test described in Annex D, Subclause D.2.1.

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. The breakdown field strength of insulating composites and coating layers can be evaluated according to IEC 60060-1, IEC 60243-1 (a.c.), IEC 60243-3 (impulse voltage) and IEC 60464-2 (coating).

When electrical activity occurs on insulating surfaces (streamers, surface flashovers, etc.), the surface may deteriorate experienced as tracking and electrical erosion. The impact, in connection with moisture, may change the properties of the insulating surface towards a more conductive nature, and hence 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.

8.2.5.2 High-current tests

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

Connection components and parts of the down conductor can be tested by the high-current physical damage test in Annex D, Clause D.3, or the EN 50164-1 without the conditioning/aging applied.

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.

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 themselves as much as possible for lightning air termination, equipotentialisation, 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 air craft warning lights on the nacelle, down conductors and bonding connections shall be made and dimensioned according to IEC 62305-3. The wind turbine should be divided into lightning protection zones, LPZ (see Annex E).

8.3.2 Hub

The hub for large wind turbines is a hollow cast iron sphere of 2 m to 3 m 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 should 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 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.

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, the efficiency of such discrete brushes may be low, as it is very difficult to construct the 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.

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. 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.

8.3.6 Testing methods

Preliminary testing methods are included in Annex D.

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 bearings are operated without protection, it shall be demonstrated that the bearing itself can operate for the whole design lifetime, after being exposed to the expected number of lightning current penetrations. If the bearing is not able to operate for the whole design life time, protection shall be applied (see 8.4.4).

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.

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 must in order to be effective have less impedance than the direct natural current path through the component.

Spark gaps and sliding contacts shall be able to conduct the lightning current it may be exposed to at the place of use in the wind turbine.

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 must be considered to be wear parts and the service lifetime of these devices shall be calculated and documented. Spark gaps and sliding contacts shall be inspected regularly in accordance with the service and maintenance manuals.

8.4.5 Testing

All systems for protection of bearings and actuator systems shall have a documented functionality. It is recommended to perform tests with impulse current representing the natural lightning current.

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 that the protection system can withstand the damaging effect of the first lightning stroke combined with the long stroke current.

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 scaled models, but calculations shall demonstrate the scaling factors and effects.

Informative testing methods are included in Annex D, Sublause D.3.4.

8.5 Electrical low-voltage systems and electronic systems and installations

8.5.1 General

This clause deals with the protection of the electrical and control systems of a wind turbine against the effects of

- 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).

NOTE 1 Transient overvoltages and surges caused by switching operations in electrical systems (switching electromagnetic impulse, SEMP) must be considered as well. However, it is outside the scope of this standard. For general information, the reader is referred to IEC 62305-2 Annex F for discussion of switching overvoltages. Subclause 8.5.6.9 and Clause F.7 of this standard give some information on the selection of SPDs with regard to overvoltages created within wind turbines.

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

NOTE 2 The general requirements for electrical equipment on machines described in IEC 60204-1 should be observed.

8.5.2 LEMP protection measures (LPMS)

Electrical and control systems are subject to damage from the LEMP. Therefore LEMP protection measures (LPMS) shall be provided to avoid failure of these systems. The effective protection of the electrical and control system of a wind turbine against LEMP requires the systematic approach of the lightning protection zones (LPZ) concept according to IEC 62305-4. LPMS is part of the lightning protection zone (LPZ) concept for the complete wind turbine, described in 8.5.3. Examples of the application of the lightning protection zones (LPZ) concept in a wind turbine are given in Annex E.

The wind turbine manufacturer shall provide a LEMP protection measures system (LPMS) according to IEC 62305-4 for the complete electrical system.

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

Basic protection measures in an LPMS according to IEC 62305-4 include:

- bonding – see Subclause 8.5.4;
- magnetic and electrical shielding of cables and line routing (system installation) – see Subclause 8.5.5;

- coordinated SPD protection – see Subclause 8.5.6;
- earthing – see Clause 9.

Additional methods include:

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

For the LPMS, 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.5 and E.6 provide basic examples of such documentation.

8.5.3 Lightning protection zones (LPZ)

A wind turbine can be divided into physical areas which roughly define the level of the influence of a lightning flash on components in that zone. The 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 Table E.1). Lightning protection methods are then applied to ensure that components, for example machinery, electrical systems or control systems, can withstand the magnetic and electrical fields and lightning current that may enter the zone in which the components are placed. For instance, protection against overvoltages 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, Clause 4 "Design and installation of a LEMP protection measures system (LPMS)", and it is discussed in Annex E.

Further guidance on how to fulfil these requirements is given in Annex E.

8.5.4 Equipotential bonding within the wind turbine

Equipotential bonding according to IEC 62305-4 shall be used within a wind turbine to ensure that potentially dangerous sparking cannot take place between conducting parts of the wind turbine. These equipotential bonds provide protection against touch and step voltages during a 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. 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.

8.5.5 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 according to IEC 62305-4, Clause 4 should be used, and the general guidelines on EMC-correct installation practices described in IEC/TR 61000-5-2 should be followed.

When lightning currents flow through a wind turbine, large magnetic fields are produced. If these changing magnetic fields pass through a loop formed by wiring or formed by wiring and the wind turbine structure, they will induce surge voltages and currents within that loop. The magnitude of the surges is related to the rate of change of the magnetic field and the area of the loop in question. The designer shall consider the magnitude of induced voltages and make sure that such surges do not exceed the withstand level of the cabling and connected equipment.

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

Some further considerations about the shielding required in a wind turbine are discussed in Annex G.

8.5.6 Coordinated SPD protection

8.5.6.1 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 must include 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. The recommendations for coordinated SPD protection within wind turbines are given in Annex F.

8.5.6.2 Location of SPDs

According to IEC 62305-4, in an LPMS, 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 61643-1, 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 61643-1, shall be installed.

NOTE If the length of the circuit between the SPD and the equipment is too long (i.e. in general when longer than 10 m), propagation of surges can lead to an oscillation phenomenon – see IEC 62305-4, Subclause D.2.3 and D.2.4.

8.5.6.3 Selection of SPDs

SPDs which 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 61643-1.

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 61643-1.

SPDs shall comply with

- IEC 61643-1 for power systems;
- IEC 61643-21 for telecommunication and signalling systems.

8.5.6.4 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 LPMS. For the SPDs installed at the different LPZ boundaries and possible surge protection components installed inside equipment, the requirements for energy coordination according to 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 8.5.4 and 8.5.5 and exemplified in Annex G.

8.5.6.5 Environmental stresses

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

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

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.

8.5.6.6 Maintenance

Maintenance and replacement of SPDs shall be done according to a maintenance plan.

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

NOTE The SPD manufacturer can provide information on SPD service life time.

8.5.6.7 SPD monitoring

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

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

In order to identify the required protection level U_p in an LPZ, it is necessary to establish the immunity levels of the equipment in the LPZ, e.g. of

- power lines and equipment terminals according to IEC 61000-4-5 and IEC 60664-1;
- telecom lines and equipment terminals according to IEC 61000-4-5, ITU-T K.20 and ITU-T K.21;
- other lines and equipment terminals according to information obtained from the manufacturer.

Manufacturers of electrical and electronic components should be able to supply the necessary immunity level information according to the EMC standards. Otherwise the wind turbine manufacturer should have tests performed to establish the immunity level.

The established immunity level of components in an LPZ directly defines the necessary protection level to be achieved at the LPZ boundaries.

System immunity shall be verified including all SPDs installed and equipment to be protected, if applicable. Possible testing methods are described in Annex H.

8.5.6.9 Overvoltages created within wind turbines

Specific requirements might apply to SPDs due 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. Examples hereof are given in Annex F.

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

8.5.6.10 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 according to 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 rating as compared to the levels 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.

8.5.6.11 Selection of SPDs with regard to short-circuit current, the follow current interrupt rating and duty cycle (service lifetime) of the SPDs

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 interrupting 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 interrupting 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.

NOTE The SPD manufacturer can provide information on SPD service life time.

8.5.6.12 Behaviour of SPDs in case of multiple lightning flashes

Due 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.

8.5.7 Testing methods for system immunity tests

Preliminary testing methods are included in Annex H.

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 may be placed in the back of 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 (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 according to IEC 60071 series. In case such studies are not performed, HV surge arresters are advisable as a general precaution.

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.

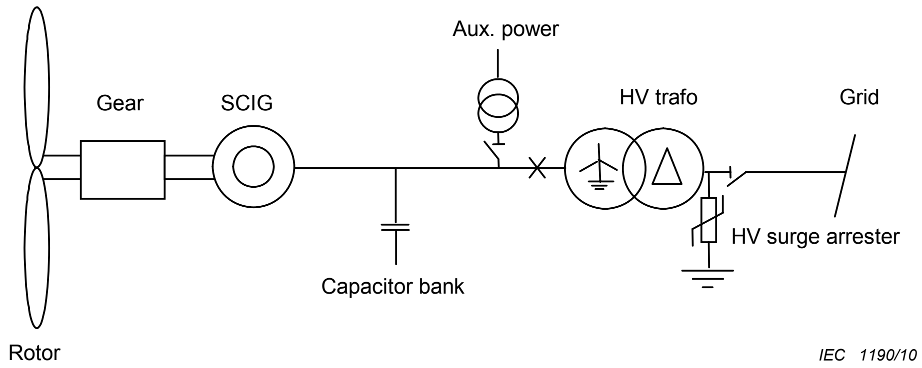


Figure 4a – Squirel cage induction generator (SCIG)

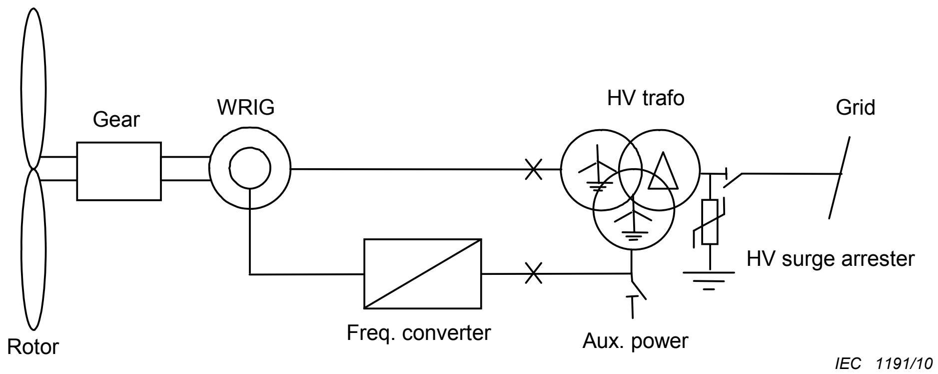


Figure 4b – Wound rotor induction generator (WRIG)

Figure 4 – 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 4 thereby providing maximum protection for the transformer. However, it may be convenient to place surge arresters at the switchgear. I general, a distance of 10 m to 40 m between arrester and component to be protected is possible depending on the insulation level of the component, if the distance is larger, a closer study 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 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, 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 The general requirements for high-voltage systems on machinery in IEC 60204-11 should be observed.

9 Earthing of wind turbines and wind farms

9.1 General

To disperse lightning currents and prevent damage to a wind turbine, an efficient earthing system for the machine 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 must 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 CENELEC HD637 S1 or relevant national standards. In relation to human safety, please refer to IEC/TS 60479-1 and IEC 60479-4.

9.1.1 Basic requirements

The earthing system of the wind turbine shall be designed to provide sufficient protection against damage due to lightning flashes that 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;

b) prevent damage to equipment;

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

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

9.1.2 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;

NOTE For further information on type A arrangements, see IEC 62305-3, Subclause 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.

9.1.3 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 impulse impedance as possible to reduce the total voltage drop (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 embedded depth and the type of the earth electrodes shall minimise the effects of corrosion, soil drying and freezing and thereby stabilise the conventional earthing resistance. It is recommended that the first metre of a vertical earth electrode should not be regarded as being effective under frost conditions.

The earthing system components shall be able to withstand lightning currents as well as power system fault currents. This is ensured by selecting earthing system components according to IEC 62305-3. The earthing system shall be constructed to disperse the lightning current into earth without thermal or electrodynamic damage, and the length of the conductors shall be as short as possible.

Additional information is included in Annex I, Subclause 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 Table 5.

The minimum values of the cross section of the bonding conductors connecting internal metal installations to the bonding bars/points are listed in Table 6.

Table 5 – Minimum dimensions of conductors connecting different bonding bars/points or connecting bonding bars/points to the earth termination system (Table 8 in IEC 62305-3)

Class of LPS	Material	Cross section mm^2
I to IV	Copper	14
	Aluminium	22
	Steel	50

Table 6 – Minimum dimensions of conductors connecting internal metal installations to the bonding bar/point (Table 9 in IEC 62305-3)

Class of LPS	Material	Cross section mm^2
I to IV	Copper	5
	Aluminium	8
	Steel	16

9.2.3 Electrically insulated LPS

It is not recommended to use an insulated external LPS for wind turbines.

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 must 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 along it without obstacle.

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 must be expected and thus considered in the design of the tower (see IEC 62305-3, Subclause E.4.3).

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 according to 9.3.6.

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.

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 be defined as one or more lightning protection zones (LPZ) 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, for every 20 m and at every platform.

Rails, guides for hoists, hydraulic piping, wires for personal protection and other components passing through a tower shall be bonded at each end. In addition, for lattice towers, bonding should be made for every 20 m, if possible.

The HV transformer earthing system should be bonded 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.

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

It is recommended to use at least two concentric ring electrodes for step and touch voltage protection, which may be combined with vertical electrodes drilled into the rock.

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. 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 collection system cable shields 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:

$$r_e \geq l_1 \tag{17}$$

Where l_1 is represented in Annex I, 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 shall be added with individual lengths l_r (horizontal) and l_v (vertical) given by the following equations:

$$l_r = l_1 - r_e \tag{18}$$

$$l_v = (l_1 - r_e)/2 \tag{19}$$

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 Wind farms

A wind farm typically consists of a number of structures such as wind turbines, buildings, cable or overhead line infrastructure, high voltage substations and signal cables.

Each wind turbine shall have its own earthing system. The earthing systems of the individual wind turbines and the high voltage sub-station shall preferably be connected with horizontal earthing conductors, to form an overall wind farm earthing system. This is particularly beneficial in case good earthing resistance is difficult to obtain at each individual wind turbine position.

NOTE 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-resistance earthing system reduces the potential difference between the different structures of the wind farm and so reduces the interference injected into the electrical links.

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.

9.6 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 may 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.

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.

Weather bureaus usually provide reasonably accurate thunderstorm forecasts and even provide warning services by telephone, fax 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 manufactures.

Some lightning warning systems may not provide warning of all lightning flashes, especially of the first lightning flash in a developing storm. 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.

NOTE 1 People should be instructed to stand or sit on the platforms and avoid touching electrically conducting systems extending vertically in the tower such as electrical systems.

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).

NOTE 2 The wind turbine documentation should define safe locations in the wind turbine including necessary safety distances and other precautions to be taken by people while at the safe location. IEC 62305-3 provides guidance on how to make a detailed evaluation of the safety distance.

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 single document, or references to the standard documentation.

11.2 Documentation necessary during assessment for design evaluation

General documents (11.2.1) shall have the focus on the wind turbine as a whole 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 (11.2.2 through 11.2.6).

11.2.1 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;

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.

c) Personnel Safety procedures with regards to lightning.

11.2.2 Documentation for rotor blades

a) Drawing of the rotor blades containing:
   1) down conductor cross sectional areas;
   2) any additional conductive components;
   3) bonding details.
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.
c) Documentation of method of verification showing the ability of the air-termination system to sufficiently intercept lightning strikes and conduct lightning currents.

11.2.3 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 showing 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 being operated for the design life time.

11.2.4 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 in the LPZs;
d) maintenance Plan for SPD's;
e) analysis defining the need for high voltage arresters.

11.2.5 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) description of QA control to be made to connections.

11.2.6 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;
4) metal nets or closed metal conduits, where applicable;
5) the shielding measures for the hub and nacelle.

b) Testing reports, 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

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.

11.4 Documentation to be provided for LPS inspections

a) description of the LPS;
b) description of earthing system;
c) reports of previous inspections, if relevant.

11.4.1 Visual LPS inspection report

11.4.2 Complete LPS inspection report

11.5 Manuals

The following manuals shall cover relevant issues with regards to lightning protection and earthing systems:

a) quality manuals;
b) foundation installation manual;
c) foundation maintenance manual;
d) wind turbine erection manual;
e) wind turbine 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 established. The objective of the inspections is to ensure that:

- the LPS continues to conform to the original design based on this standard;
- 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.

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 7);
- 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.

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;
- corrosion of earth electrodes (only periodic inspection).

With certain intervals (given in Table 7), 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.

Continuity measurements can be performed as measurements with DC current or similar methods. The main goal is to ensure 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 measurement limits shall be well defined in the service and maintenance manual.

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.

Table 7 – 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 secured 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 secured that the wind turbine is inspected at least with the frequencies given in Table 7.

12.3 Maintenance

Regular inspections 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 secured 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.

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 about the lightning phenomenon relevant for understanding the lightning phenomenon and the processes involved when lightning interact with wind turbines. More comprehensive information is available in the literature [1][2].

A.1.2 The properties of lightning

A 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 maximum recorded value of lightning current produced by a single stroke is in the region of 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 must 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 and 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. [1]). A lightning 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.

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

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, which are more commonly known as continuing currents.

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 $\mathrm{d}i/\mathrm{d}t$).

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 [2] [3]. 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). 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 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.1.4.1 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.

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 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.

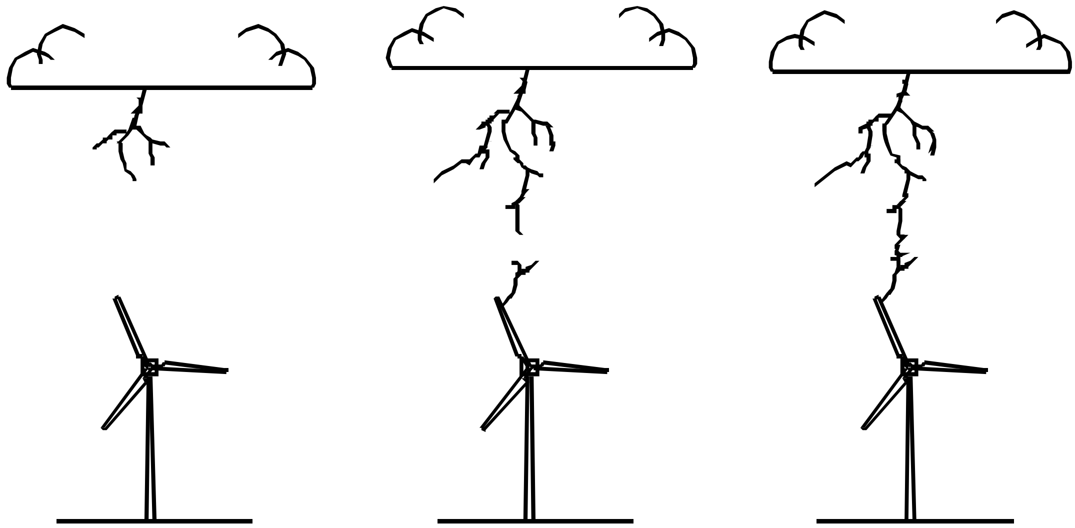


Figure A.1 – Processes involved in the formation of a cloud-to-ground flash

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.

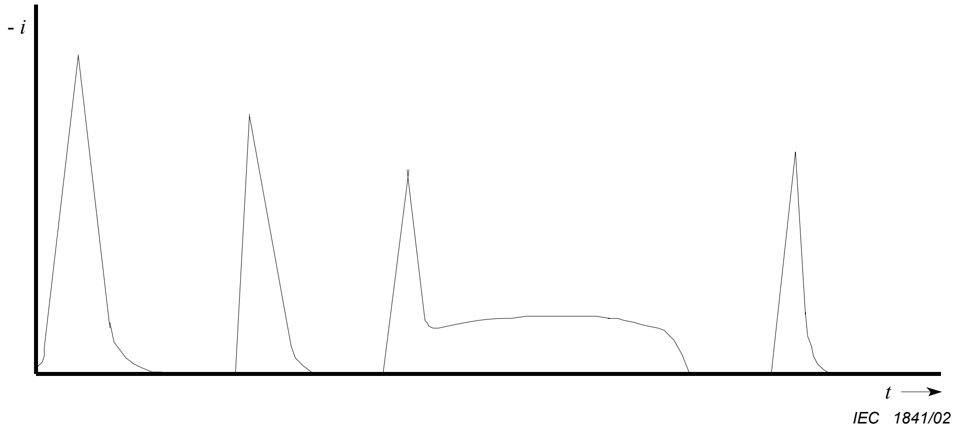
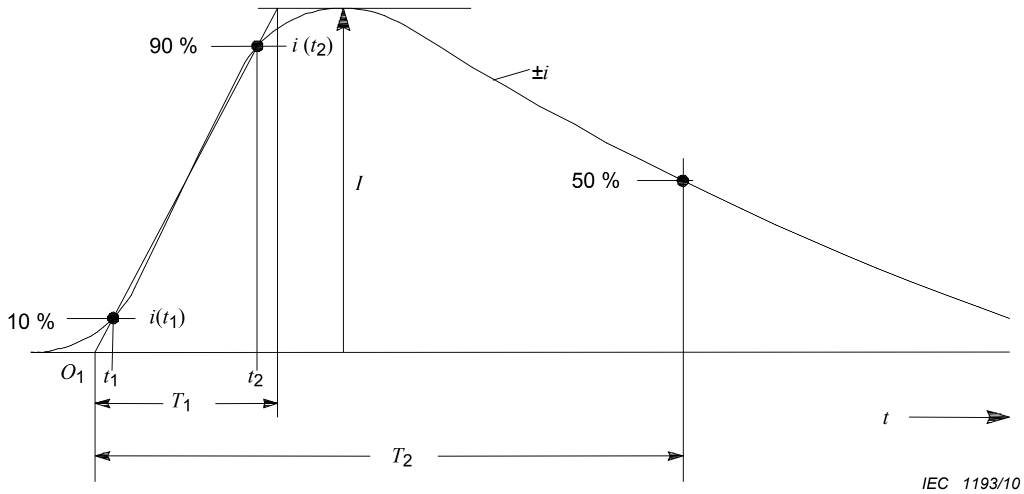


Figure A.2 – Typical profile of a negative cloud-to-ground flash (not to scale)

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

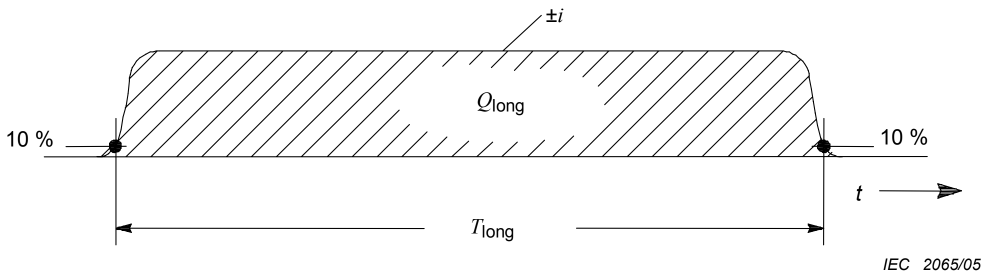
i current

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)



Key

T_{long} duration time

Q_{long} long stroke charge

Figure A.4 – Definitions of long stroke parameters (typically 2 ms < T_{long} < 1 s) (Figure A.2 in IEC 62305-1)

Table A.1 – Cloud-to-ground lightning current parameters (adapted from Table A.1 in IEC 62305-1)

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
NOTE The values of I = 4 kA and I = 20 kA correspond to a probability of 98 % and 80 %, respectively.					

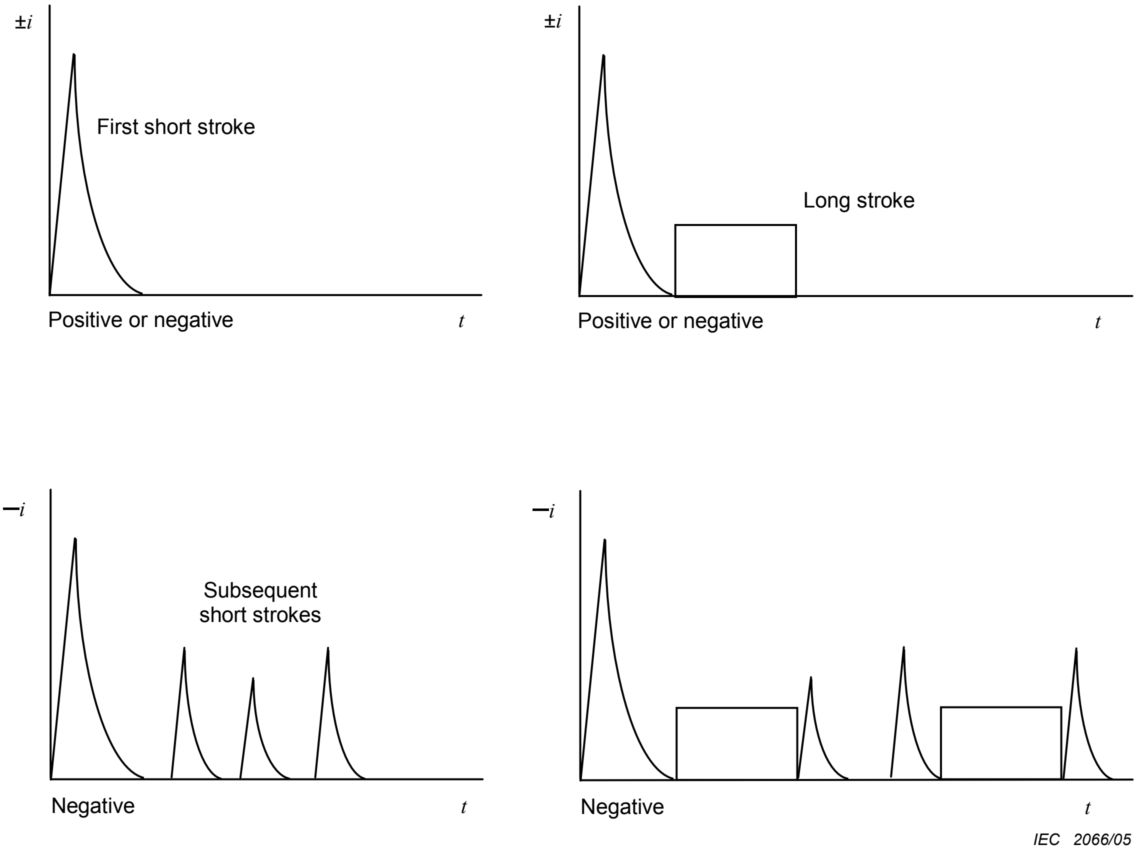


Figure A.5 – Possible components of downward flashes (typical in flat territory and to lower structures) (Figure A.3 in IEC 62305-1)

A.1.4.2 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 [2] [3].

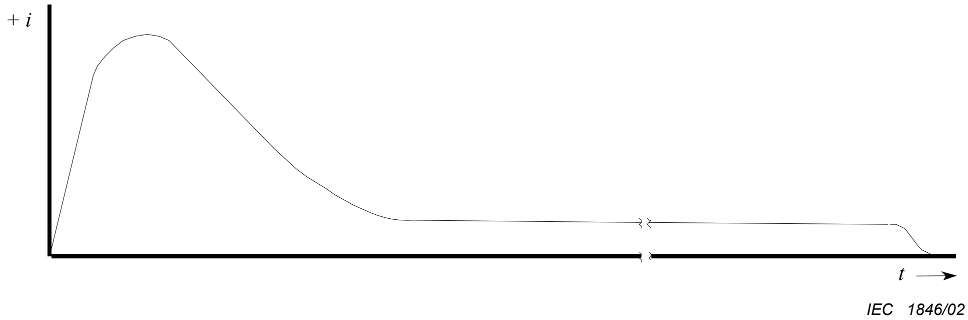


Figure A.6 – Typical profile of a positive cloud-to-ground flash

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. 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.

An upward initiated flash starts with a continuing current phase. On the continuing current impulse, currents can be superimposed (Figure A.7). 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.

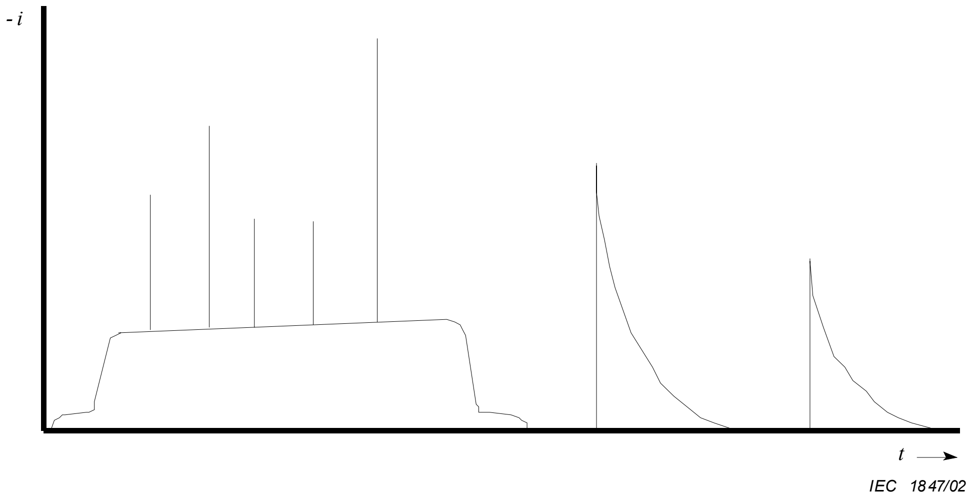


Figure A.7 – Typical profile of a negative upward initiated flash

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 [1]. In recent years, upward flashes have also been studied by measurements on wind turbines [4].

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 [1]. Upward initiated flashes, too, may be composed of various combinations of the different current components mentioned above, as demonstrated in Figure A.8.

In general, upward initiated flashes have lower current parameter values as 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 when 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 due 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.

Table A.2 – Upward initiated lightning current parameters

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

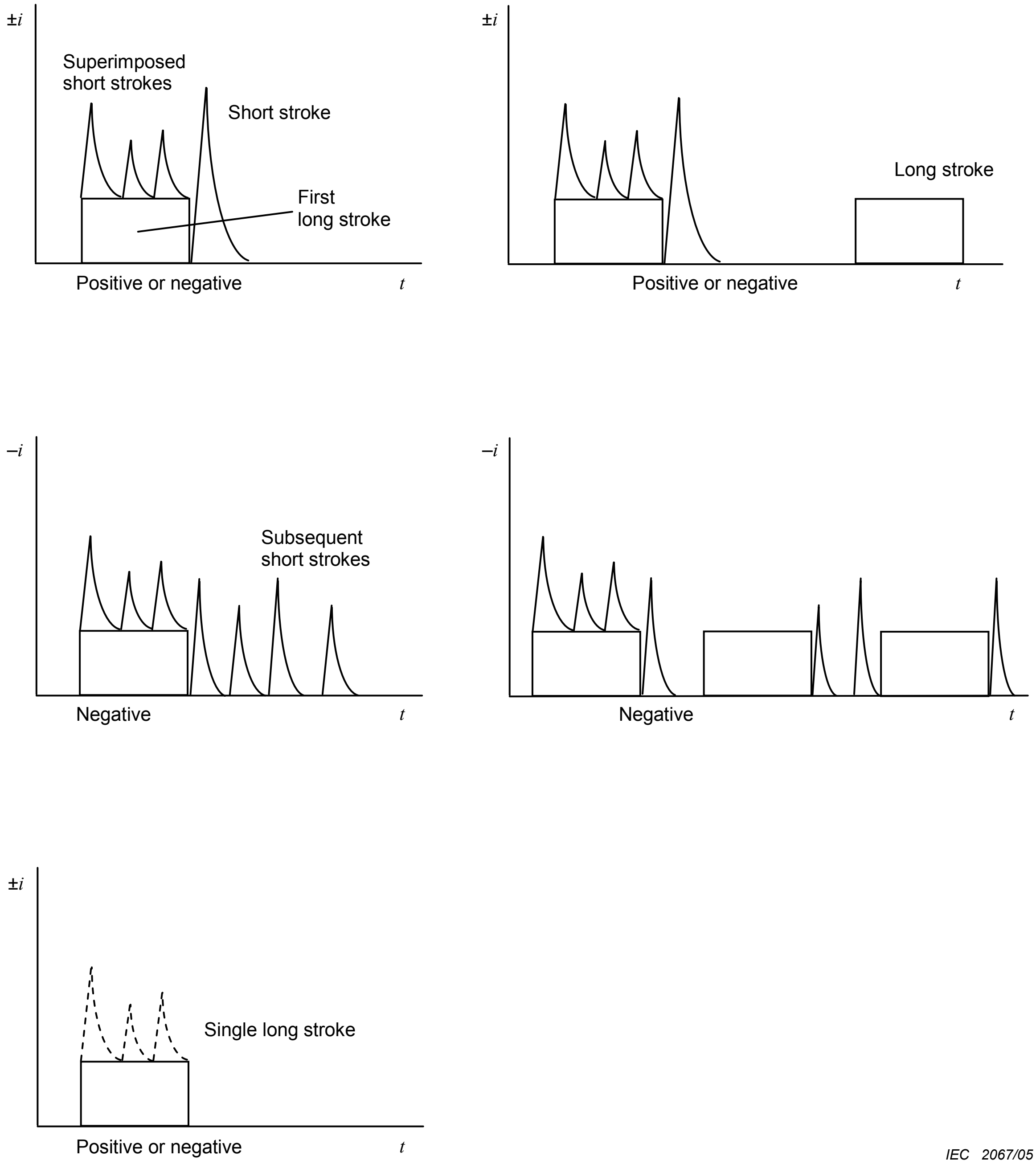


Figure A.8 – Possible components of upward flashes (typical to exposed and/or higher structures) (Figure A.4 in IEC 62305-1)

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

The lightning current parameters playing a role in 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 (Table D.1 in IEC 62305-1)

Component	Main problem	Lightning threat parameters					Notes
Air termination	Erosion at attachment point (e.g. thin metal sheets)	LPL	Q_{long} C	T			
		I II III-IV	200 150 100	< 1 s (apply Q_{long} in a single shot)			
Air termination and down conductor	Ohmic heating	LPL	W/R kJ/Ω	T			Dimensioning with IEC 62305-3 renders testing superfluous
		I II III-IV	10 000 5 600 2 500	Apply W/R in an adiabatic configuration			
	Mechanical effects	LPL	I kA	W/R kJ/Ω			
		I II III-IV	200 150 100	10 000 5 600 2 500			
Connecting components	Combined effects (thermal, mechanical, and arcing)	LPL	I kA	W/R kJ/Ω	T		
		I II III-IV	200 150 100	10 000 5 600 2 500	< 2 ms (apply I and W/R in a single impulse)		
Earth terminations	Erosion at attachment point	LPL	Q_{long} C	T			Dimensioning usually determined by mechanical/ chemical aspects (corrosion, etc.)
		I II III-IV	200 150 100	< 1 s (apply Q_{long} in a single shot)			
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 II III-IV	200 150 100	100 75 50	10 000 5 600 2 500	200 150 100	
SPDs containing metal-oxide resistor blocks	Energy effects (overload)	LPL	Q_{short} C				Both aspects need to be checked
		I II III-IV	100 75 50				
	Dielectric effect (flashover/cracking)	LPL	I kA	T			Separate tests can be considered
		I II III-IV	200 150 100	< 2 ms (apply I in a single impulse)			

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.

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. This kind 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).

Annex B
(informative)

Lightning exposure assessment

B.1 General

In Clause B.2 of this annex, the terms used for damage and loss (B.2.1), for risk and risk components (B.2.2), for composition of risk components related to a wind turbine (B.2.3), for composition of risk components related to a service (B.2.4) are explained.

In Clause B.3, the values of the probabilities, P_X, for various types of damage are assessed according to IEC 62305-2, Annex B, and commented with regard to relevance for application to wind turbines.

In Clause B.4, the amount of loss, L_X, is assessed according to IEC 62305-2, Annex C, and commented with regard to relevance for application to wind turbines

In Clause B.5, the assessment of probability P'_X, of damage to a service is assessed according to IEC 62305-2, Annex D, and commented with regard to relevance for application to wind turbines

In Clause B.6, the assessment of the amount of loss L'_X in a service is assessed according to IEC 62305-2, Annex E.

In Clause B.7, the evaluation of costs of loss is assessed according to IEC 62305-2, Annex G.

B.2 Explanation of terms

B.2.1 Damage and loss

Terms covering the topics damages and loss are defined in IEC 62305-2. Here is 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 (see Table B.1):

S1: lightning striking the wind turbine;

S2: lightning striking near a wind turbine;

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

S4: lightning striking near a service.

NOTE 1 S2 Lightning striking near a wind turbine is not considered a threat when protection against direct lightning is provided.

NOTE 2 S4 Lightning striking near a service is not considered a threat when protection against direct lightning is provided.

Three basic types of damage caused by lightning are considered (see Table B.2):

D1: injury to living beings;

D2: physical damage;

D3: failure of electrical and electronic systems.

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

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

Each type of damage, alone or in combination with others, may produce a consequential loss in the wind turbine. The types of loss considered relevant for wind turbines are:

L1: loss of human life;

L4: loss of economic value (repair costs damages to the wind turbine and loss of revenue).

NOTE 3 L2 loss of service to the public and L3 loss of cultural heritage are not considered relevant for wind turbines.

The types of loss considered relevant for a service (e.g. power cable and communication cable) are:

L´4: Loss of economic value (repair cost of damages to the service and loss of revenue).

NOTE 4 L´2 loss of service to the public is not considered relevant.

Table B.1 – Sources of damage, types of damage and types of loss according to point of strike (corresponds to Table 1 in IEC 62305-2)

		Wind turbine		Service	
Point of strike	**Source of damage**	**Type of damage**	**Type of loss**	**Type of damage**	**Type of loss**
Striking wind turbine	S1	D1 D2 D3	L1, L4[b] L1, L4 L1[a], L4	 D2 D3	 L´4 L´4
Striking near to wind turbine	S2	D3	L1[a], L4		
Striking service line	S3	D1 D2 D3	L1, L4[b] L1, L4 L1[a], L4	 D2 D3	 L´4 L´4
Striking near to service line	S4	D3	L1[a], L4	D3	L´4

[a] only if failures of internal systems immediately endangers human life

[b] only where animals may be lost (e.g. if livestock can be within 3 m from wind turbine tower)

Table B.2 – Risk in a wind turbine for each type of damage and of loss (corresponds to Table 2 in IEC 62305-2)

Loss Damage	L1 Loss of human life	L4 Loss of economic value
D1 **Injury to living beings**	R_S	R_S [b]
D2 **Physical damage**	R_F	R_F
D3 **Failure of electric or electronic systems**	R_O [a]	R_O

[a] Only if failures of internal systems immediately endangers human life.

[b] Only where animals may be lost (e.g. if cattle can be within 3 m from wind turbine tower).

B.2.2 Risk and risk components

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

The risks to be evaluated in a wind turbine may be as follows:

R_1: risk of loss of human life;

R_4: risk of loss of economic value.

The risk to be evaluated for a service may be as follows:

R'_4: risk of loss of economic value.

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

Risk components for a wind turbine due to lightning striking the wind turbine are:

R_A: Component related to injury to persons inside the wind turbines and injury to living beings caused by touch and step voltages in the zones up to 3 m outside the wind turbine tower. Loss of type L1 and in the case of livestock also L4 may arise.

R_B: Component related to physical damage caused by dangerous sparking inside the structure triggering fire. Loss of type L1 and L4 may arise.

R_C: Component related to failure of internal systems caused by lightning electromagnetic pulse, LEMP. Loss of type L4 may arise or L1 in case failure of internal systems immediately endangers human life.

Risk components for a wind turbine due to lightning striking a service connected to the wind turbine are:

R_U: Component related to injury to persons caused by touch voltage inside the wind turbine, due to lightning current injected in a line entering the wind turbine. Loss of type L1 may arise.

R_V: Component related to physical damage (fire triggered by dangerous sparking between external installations and metallic parts generally at the entrance point of the line into the wind turbine) due to a lightning current transmitted through or along the incoming service. Loss of type L1 and L4 may arise.

R_W: Component related to failure of internal systems caused by overvoltages induced in incoming lines and transmitted to the wind turbine. Loss of type L4 could occur or L1 in case failure of internal systems immediately endangers human life.

Risk component for a wind turbine due to lightning striking near a service connected to the wind turbine:

R_Z: Component related to failure of internal systems caused by overvoltages induced in incoming lines and transmitted to the wind turbine. Loss of type L4 could occur or L1 in case failure of internal systems immediately endangers human life.

Risk components for a service to lightning striking the service connected to the wind turbine are:

R'_V: Component related to physical damage due to mechanical and thermal effects of lightning current. Loss of type L'4 may arise.

R'_W: Component related to failure of lines and connected equipment caused by overvoltages induced on lines. Loss of type L´4 may arise.

Risk component for a service due to lightning striking near the service connected to the wind turbine:

R'_Z: Component related to failure of lines and connected equipment caused by overvoltages induced on lines. Loss of type L´4 could occur.

Risk components for a service due to lightning striking the wind turbine to which the service is connected are:

R'_B: Component related to physical damage due to mechanical and thermal effects of lightning current flowing along the line. Loss of type L'4 may arise.

R'_C: Component related to failure of connected equipment due to overvoltages by resistive coupling. Loss of type L´4 may arise.

B.2.3 Composition of risk components related to a wind turbine

Risk components to be considered for each type of loss in a wind turbine are listed below:

R_1: Risk of loss of human life:

$$R_1 = R_A + R_B + R_C{}^{3)} + R_U + R_V + R_W{}^{3)} + R_Z{}^{3)} \tag{B.1}$$

R_4: Risk of loss of economic value:

$$R_4 = R_A{}^{4)} + R_B + R_C + R_U{}^{4)} + R_V + R_W + R_Z \tag{B.2}$$

Composition of risk components with reference to the source of damage:

$$R = R_D + R_I \tag{B.3}$$

where

3) Only in case failure of internal systems immediately endangers human life.

4) Only for wind turbines where animals may be lost (e.g. if livestock can be within 3 m from wind turbine tower).

R_D is the risk due to lightning striking the wind turbine (source S1) which is defined as the sum:

$$R_D = R_A + R_B + R_C \tag{B.4}$$

R_I is the risk due to lightning influencing the wind turbine but not striking the wind turbine (sources: S3 and S4) which is defined as the sum:

$$R_I = R_U + R_V + R_W + R_Z \tag{B.5}$$

Composition of risk components with reference to type of damage:

$$R = R_S + R_F + R_O \tag{B.6}$$

where

R_S is the risk of injury to living beings (D1) which is defined as the sum:

$$R_S = R_A + R_U \tag{B.7}$$

R_F is the risk of physical damage (D2) which is defined as the sum:

$$R_F = R_B + R_V \tag{B.8}$$

R_O is the risk due to failure of internal systems (D3) which is defined as the sum:

$$R_O = R_C + R_W + R_Z \tag{B.9}$$

B.2.4 Composition of risk components related to a service

Risk components to be considered for each type of loss in a service line are listed below.

R'_4: risk of loss of economic value:

$$R'_4 = R'_V + R'_W + R'_Z + R'_B + R'_C \tag{B.10}$$

Composition of risk components with reference to source of damage:

$$R' = R'_D + R'_I \tag{B.11}$$

where

R'_D is the risk due to flashes striking the service line (source S3); defined as the sum:

$$R'_D = R'_V + R'_W \tag{B.12}$$

R'_I is the risk due to flashes influencing the service line without striking it (sources S1 and S4); defined as the sum:

$$R'_I = R'_B + R'_C + R'_Z \tag{B.13}$$

Composition of risk components with reference to the type of damage:

$$R' = R'_F + R'_O \tag{B.14}$$

where

R'_F is the risk due to physical damage (D2); defined as the sum:

$$R'_F = R'_V + R'_B \tag{B.15}$$

R'_O is the risk due to failure of internal systems (D3); defined as the sum:

$$R'_O = R'_W + R'_Z + R'_C \tag{B.16}$$

B.3 Assessing the probability of damage to the wind turbine

B.3.1 Probability, P_A, that a lightning flash to the wind turbine will cause injury to living beings

The values of probability, P_A, of shock to living beings due to touch and step voltage from a lightning flash to the structure (i.e. the wind turbine), as a function of typical protection measures are as given in Table B.3. If more than one of the protection measures is taken, the value of P_A is the product of the corresponding P_A values.

Table B.3 – Values of probability, P_A, that a lightning flash to a wind turbine will cause shock to living beings due to dangerous touch and step voltages (corresponds to Table B.1 in IEC 62305-2)

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

B.3.2 Probability, P_B, that a lightning flash to the wind turbine will cause physical damage

The values of probability, P_B, of physical damage caused by a lightning flash to the wind turbine as a function of lightning protection level (LPL) are given in Table B.4.

Table B.4 – Values of probability, P_B, depending on the protection measures to reduce physical damage (corresponds to Table B.2 in IEC 62305-2)

Characteristics of wind turbine	Class of LPS	P_B
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 and the tower acting as a continuous natural down conductor		0,01
Wind turbine with lightning protection of blades, metal roof nacelle (or equivalent metal mesh) with complete protection of any nacelle roof installations against direct lightning attachment and the tower acting as a continuous natural down conductor		0,001

NOTE Values of P_B other than those in Table B.4 are possible if based on a detailed investigation – refer to IEC 62305-2, Clause B.2.

B.3.3 Probability, P_C, that a lightning flash to the wind turbine will cause failure of internal systems

The values of probability, P_C, of failure of internal systems caused by a lightning flash to the wind turbine depend on the adopted coordinated SPD protection:

$$P_C = P_{SPD} \tag{B.17}$$

Values of P_{SPD} depend on the lightning protection level (LPL) for which the SPDs are designed as shown in Table B.5.

Table B.5 – Values of probability P_{SPD} as a function of the LPL for which the SPDs are designed (Table B.3 in IEC 62305-2)

LPL	P_{SPD}
No coordinated SPD protection	1
III-IV	0,03
II	0,02
I	0,01
See Note 3	0,005 to 0,001

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.

NOTE 3 Smaller values of P_{SPD} are possible in case SPDs have better protection characteristics (higher current withstand capability, lower protective levels, etc.) compared with the requirements defined for LPL I at the relevant installation locations.

B.3.4 Probability, P_M, that a lightning flash near the wind turbine will cause failure of internal systems

Due to the height of 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.

B.3.5 Probability, P_U, that a lightning flash to a service line will cause injury to living beings

The values of probability, P_U, of injury to living beings due 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.3) and the SPDs provided at the entrance of the service line.

When SPDs are not provided for equipotential bonding in accordance with IEC 62305-3, the value of P_U is equal to the value of P_{LD}, where P_{LD} is the probability of failure of internal systems due to a lightning flash to the connected service line.

Values of P_{LD} are given in Table B.6.

When SPDs are provided for equipotential bonding in accordance with IEC 62305-3, the value of P_U is the lower value between P_{SPD} (Table B.5) and P_{LD}.

NOTE Coordinated SPD protection according to IEC 62305-4 is not necessary to reduce P_U in this case. SPDs according to IEC 62305-3 are sufficient.

Table B.6 – Values of probability, P_{LD}, depending on the resistance, R_S, of the cable screen and the impulse withstand voltage, U_W, of the equipment (Table B.6 in IEC 62305-2)

U_W kV	$5 < R_S \leq 20$ Ω/km	$1 < R_S \leq 5$ Ω/km	$R_S \leq 1$ Ω/km
1,5	1	0,8	0,4
2,5	0,95	0,6	0,2
4	0,9	0,3	0,04
6	0,8	0,1	0,02
R_S [Ω/km] is the resistance of the cable shield.			

For unshielded service line, P_{LD} = 1 shall be taken.

When protection measures such as physical restrictions, warning notices, etc. are provided, the probability, P_U, shall be further reduced by multiplying it by the values of probability, P_A, given in Table B.3.

B.3.6 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.

When SPDs are not provided for equipotential bonding according to IEC 62305-3, the value of P_V is equal to the values of P_{LD}, where P_{LD} is the probability of failure of internal systems due to a flash to the connected service line.

Values of P_{LD} are given in Table B.6.

When SPDs are provided for equipotential bonding in accordance with IEC 62305-3, the value of P_V is the lower value between P_{SPD} (Table B.5) and P_{LD}.

NOTE Coordinated SPD protection according to IEC 62305-4 is not necessary to reduce P_U in this case. SPDs according to IEC 62305-3 are sufficient.

B.3.7 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 SPDs provided.

When coordinated SPD protection conforming to IEC 62305-4 is not provided, the value of P_W is equal to the value of P_{LD}, where P_{LD} is the probability of failure of internal systems due to a lightning flash to the connected service line.

Values of P_{LD} are given in Table B.6.

When coordinated SPD protection conforming to IEC 62305-4 is provided, the value of P_W is the lower value between P_{SPD} (see Table B.5) and P_{LD}.

B.3.8 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.

When coordinated SPD protection conforming to IEC 62305-4 is not provided, the value of P_Z is equal to the value of P_{LI}, where P_{LI} is the probability of failure of internal systems due to a lightning flash near the connected service line.

Values of P_{LI} are given in Table B.7.

When coordinated SPD protection conforming to IEC 62305-4 is provided, the value of P_Z is the lower value between P_{SPD} (see Table B.5) and P_{LI}.

Table B.7 – Values of probability, P_{LI}, depending on the resistance, R_S, of the cable screen and the impulse withstand voltage, U_W, of the equipment (Table B.7 in IEC 62305-2)

U_W kV	No shield	Shield not bonded to equipotential bonding bar to which equipment is connected	Shield bonded to equipotential bonding bar and equipment connected to the same bonding bar		
			$5 < R_S \leq 20$ Ω/km	$1 < R_S \leq 5$ Ω/km	$R_S \leq 1$ Ω/km
1,5	1	0,5	0,15	0,04	0,02
2,5	0,4	0,2	0,06	0,02	0,008
4	0,2	0,1	0,03	0,008	0,004
6	0,1	0,05	0,02	0,004	0,002

R_S (Ω/km) is the resistance of the cable shield.

NOTE More precise evaluation of K_S for shielded and unshielded sections can be found in ITU Recommendation K.46.

B.4 Assessing the amount of loss, L_X, in a wind turbine

B.4.1 General

The values of the amount of loss, L_X, should be evaluated and fixed by the lightning protection designer (or the owner of the wind turbine). The typical mean values given here are merely values proposed by the IEC. Different values may be assigned by each national committee (or agreed between purchaser and customer).

B.4.2 Average relative amount of loss per year

The loss, L_X, refers to the mean relative amount of a particular type of damage which may be caused by a lightning flash considering both its extent and effects.

Its value depends on:

- the number of persons and the time for which they remain in the hazardous place;
- the value of lost production;

- the value of wind turbine components affected by the damage.

The loss, L_X, varies with the type of loss (L1, L2, L3 and L4) considered and, for each type of loss, with the type of damage (D1, D2 and D3) causing the loss. The following symbols are used:

- L_t is the loss due to injury from touch and step voltage;
- L_f is the loss due to physical damage;
- L_o is the loss due to failure of internal systems.

B.4.3 Loss of human life

The value of L_t, L_f and L_o may be determined in terms of the relative number of victims from the following approximate relationship:

$$L_X = (n_p / n_t) \cdot (t_p / 8760) \tag{B.18}$$

where

n_p is the number of possible endangered persons (victims);

n_t is the expected total number of persons (in the wind turbine);

t_p is the time in hours per year for which the persons are present in a dangerous place, outside the wind turbine (L_t only) or inside the wind turbine (L_t, L_f and L_o).

Loss of human life is affected by the characteristics of the wind turbine structure. These are taken into account by increasing (h_Z) and decreasing (r_f, r_p, r_a, r_u) factors as follows:

$$L_A = r_a \cdot L_t \tag{B.19}$$

$$L_U = r_u \cdot L_t \tag{B.20}$$

$$L_B = L_V = r_p \cdot h_Z \cdot r_f \cdot L_f \tag{B.21}$$

$$L_C = L_M = L_W = L_Z = L_O \tag{B.22}$$

where

L_A is loss related to injury to living beings;

L_B is loss in a structure related to physical damage (flashes to structure);

L_C is loss related to failure of internal systems (flashes to service line);

L_M is loss related to failure of internal systems (flashes near structure);

L_U is loss related to injury of living beings (flashes to service line);

L_V is loss in a structure due to physical damage (flashes to service line);

r_a is a factor reducing the loss of human life depending on the type of soil (see Table B.8);

r_u is a factor reducing the loss of human life depending on the type of floor (see Table B.8);

r_p is a factor reducing the loss due to physical damage depending on the provisions made to reduce the consequences of fire (see Table B.9);

r_f is a factor reducing the loss due to physical damage depending on the risk of fire in the wind turbine (see Table B.10);

h_Z is a factor increasing the loss due to physical damage when a special hazard is present (see Table B.11).

Table B.8 – Values of reduction factors r_a and r_u as a function of the type of surface of soil or floor (corresponds to Table C.2 in IEC 62305-2)

Type of surface	Contact resistance kΩ [a]	r_a and r_u
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.

Table B.9 – Values of reduction factor r_p as a function of provisions taken to reduce the consequences of fire (Table C.3 in IEC 62305-2)

Provisions	r_p
No provisions	1
One of the following provisions: extinguishers; fixed manually operated extinguishing installations; 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 [a]	0,2

[a] Only if protected against overvoltages and other damage and if firemen can arrive within less than 10 min.

If more than one provision has been taken, the value of r_p shall be taken as the lowest of the relevant values.

NOTE 1 Risk of explosion is not considered relevant for wind turbines.

Table B.10 – Values of reduction factor r_f as a function of risk of fire of the wind turbine (corresponds to Table C.4 in 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 may 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.

NOTE 3 Structures considered as having an ordinary risk of fire may 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 may 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.

Table B.11 – Values of factor h_z increasing the relative amount of loss in presence of a special hazard (corresponds to Table C.5 in IEC 62305-2)

Kind of special hazard	h_z
No special hazard	1
Low level of panic (few and professional persons)	2
Difficulty of evacuation	5

NOTE 6 Loss of service to the public is not considered relevant for wind turbines, as loss of revenue from produced electricity should be considered economically only.

NOTE 7 Loss of irreplaceable cultural heritage is not considered relevant for wind turbines.

B.4.4 Economic loss

The value of L_t, L_f and L_o can be determined in terms of the relative amount of possible loss from the following approximate relationship:

$$L_X = c \ / c_t \tag{B.23}$$

where

c is the mean value of possible loss of the wind turbine (including its content, earning of revenue and consequences) in currency;

c_t is the total value of the wind turbine (including its content and earning of revenue) in currency.

Typical mean values of L_t, L_f and L_o for use when the determination of *c* and c_t is uncertain or difficult are given in Table B.12.

Table B.12 – Typical mean values of L_t, L_f and L_o (corresponds to Table C.7 in IEC 62305-2)

Wind turbine	Value
L_t Inside	10^{-4}
L_t Outside	10^{-2}
L_f	10^{-1}
L_o	10^{-4}

Loss of economical value is affected by the characteristics of the structure. These are taken into account by increasing (h_Z) and decreasing (r_p , r_a , r_f , r_u) factors as follows:

$$L_A = r_a \cdot L_t \tag{B.24}$$

$$L_U = r_u \cdot L_t \tag{B.25}$$

$$L_B = L_V = r_p \cdot h_Z \cdot r_f \cdot L_f \tag{B.26}$$

$$L_C = L_M = L_W = L_Z = L_O \tag{B.27}$$

where

L_A is loss related to injury to living beings;

L_B is loss in a structure related to physical damage (flashes to structure);

L_C is loss related to failure of internal systems (flashes to service line);

L_M is loss related to failure of internal systems (flashes near structure);

L_U is loss related to injury of living beings (flashes to service line);

L_V is loss in a structure due to physical damage (flashes to service line);

r_a is a factor reducing the loss of human life depending on the type of soil (see Table B.8);

r_u is a factor reducing the loss of human life depending on the type of floor (see Table B.8);

r_p is a factor reducing the loss due to physical damage depending on the provisions made to reduce the consequences of fire (see Table B.9);

r_f is a factor reducing the loss due to physical damage depending on the risk of fire in the wind turbine (see Table B.10);

h_Z is a factor increasing the loss due to physical damage when a special hazard is present (see Table B.11).

B.5 Assessment of probability P'_X of damage to a service

B.5.1 Service line with metallic conductors

B.5.1.1 Probability P'_B and P'_C that a flash to the wind turbine to which a service line is connected will cause damage

The probability P'_B that a flash to a wind turbine to which a service line is connected will cause physical damages, and the probability P'_C that a flash to the wind turbine to which the service line is connected will cause failures of the service line equipment are related to the failure current I_a. I_a is dependent on the characteristics of the service line, the number of incoming service lines to the wind turbine and the adopted protection measures.

For unshielded service lines, I_a= 0 kA must be assumed.

For shielded service lines, the failure current I_a(kA) shall be evaluated according to:

$$I_a. = 25\ n \cdot U_W / (R_s \cdot K_d \cdot K_p) \tag{B.28}$$

where

K_d is a factor depending on characteristics of the service line (see Table B.13);

K_p is a factor taking into account the effects of adopted protection measures (see Table B.14);

U_W [kV] is the impulse withstand voltage (see Table B.15 for cables and Table B.16 for apparatus);

R_S [Ω/km] is the shield resistance of the cable;

n is the number of service lines incoming to the wind turbine.

NOTE SPDs at entrance point into the wind turbine increase the failure current I_a and may have a positive protection effect

Table B.13 – Values of factor K_d as a function of the characteristics of the shielded service line (corresponds to Table D.1 in IEC 62305-2)

Service line	K_d
With shield in contact with the soil	1
With shield not in contact with soil	0,4

Table B.14 – Values of factor K_p as a function of the protection measures (Table D.2 in IEC 62305-2)

Protection measure	K_p
No protection measure	1
Additional shielding wires – One conductor[a]	0,6
Additional shielding wires – Two conductors[a]	0,4
Lightning protective cable duct	0,1
Lightning protective cable	0,02
Additional shielding wires – steel tube	0,01
[a] The shielding wire is installed about 30 cm above the cable; two shielding wires are located 30 cm above the cable symmetrically disposed in respect of the axis of the cable.	

Table B.15 – Impulse withstand voltage U_W as a function of the type of cable (Table D.3 in IEC 62305-2)

Type of cable	U_n kV	U_W kV
TLC – Paper insulated	–	1,5
TLC – PVC, PE insulated	–	5
Power	≤ 1	15
Power	3	45
Power	6	60
Power	10	75
Power	15	95
Power	20	125

Table B.16 – Impulse withstand voltage U_W as a function of the type of apparatus (Table D.4 in IEC 62305-2)

Type of apparatus	U_W kV
Electronic	1,5
Electronic user apparatus (U_n < 1 kV)	2,5
Electrical network apparatus (U_n < 1 kV)	6

The values of P'_B and P'_C as function of the failure current I_a are given in Table B.17.

Table B.17 – Values of probability P'_B, P'_C, P'_V and P'_W as function of the failure current I_a (Table D.5 in IEC 62305-2)

I_a kA	P'_B, P'_C, P'_V, P'_W
0	1
3	0,99
5	0,95
10	0,9
20	0,8
30	0,6
40	0,4
50	0,3
60	0,2
80	0,1
100	0,05
150	0,02
200	0,01
300	0,005
400	0,002
600	0,001

B.5.1.2 Probabilities P'_V and P'_W that a flash to a service line will cause damages

The probability P'_V that a flash to a service line will cause physical damage, and the probability P'_W that a flash to a service line will cause failure of service line equipment is related to the failure current I_a which, in turn, depends on the characteristics of the service line and on the protective measures adopted.

For unshielded service lines I_a = 0 kA must be assumed.

For shielded service lines, the failure current I_a.(kA) shall be evaluated according to:

$$I_a. = 25 \cdot U_W / (R_s \cdot K_d \cdot K_p) \quad \text{(B.29)}$$

where

K_d is a factor depending on characteristics of the service line (see Table B.13);

K_p is a factor taking into account the effects of adopted protection measures (see Table B.14);

U_W [kV] is the impulse withstand voltage (see Table B.15 for cables and Table B.16 for apparatus);

R_S [Ω/km] is the shield resistance of the cable.

When evaluating P'_V for telecommunication lines, the maximum values of failure current I_a to be assumed are as follows:

I_a = 40 kA for cables with lead shield;

I_a = 20 kA for cables with an aluminium shield.

NOTE These values are a rough estimation of the test current (I_t) damaging typical telecommunication cables at the lightning striking point. If any evidence exists that these values are not applicable for a given cable design, other values may be used. In this case, tests should be used for the evaluation of the failure current.

The values of P'_V and P'_W as a function of values of the failure current I_a are given in Table B.17.

B.5.1.3 Probability P'_Z that a flash near the service line will cause damage

The probability P'_Z that a flash near the service line will cause failure of connected apparatus depends on the characteristics of the service line and on the protection measures adopted.

When SPDs conforming to IEC 62305-4 are not provided, the value of P'_Z is equal to the value of P_{LI}.

Values of P_{LI} are reported in Table B.7.

When SPDs conforming to IEC 62305-4 are provided, the values of P'_Z are the lower values between P_{SPD} (see Table B.5) and P_{LI}.

B.5.1.4 Fibre optic lines

Under consideration.

B.6 Assessment of the amount of loss L'_X in a service

B.6.1 General

The loss L'_X refers to the mean relative amount of a particular type of damage which may occur as the result of a flash to a service, considering both the extent and consequential effects.

Its value depends on:

– the type and importance of the service provided to the public;
– the value of the goods affected by the damage.

The loss L'_X varies with the type of loss (L'_1, L'_2 and L'_4) considered and, for each type of loss, with the type of damage (D2 and D3) causing the loss. The following symbols are used:

L'_f loss due to physical damage;

L'_o loss due to failure of internal systems.

NOTE Loss of service to the public is not considered relevant for wind turbines, hence the loss L'_X in a service is only considered as an economic loss.

B.6.2 Economic loss

The value of L'_f and L'_o can be determined in terms of the relative amount of possible loss from the approximate relationship:

$$L'_X = c \,/\, c_t \tag{B.30}$$

where

c is the mean value of possible loss of the wind turbine, its content and relevant activities, in currency;

c_t is the total values of L'_f and L'_o, for use for all types of service lines when the determination of c and c_t is uncertain or difficult, are as follows:

$$L'_f = 10^{-1}$$

$$L'_o = 10^{-3}$$

The loss of economic values is affected by service characteristics as follows:

$$L'_B = L'_V = L'_f \tag{B.31}$$

$$L'_C = L'_W = L'_Z = L'_o \tag{B.32}$$

B.7 Evaluation of costs of loss

The cost of total loss C_L may be calculated by the following equation:

$$C_L = (R_A + R_U)\cdot C_A + (R_B + R_V)\cdot(C_A + C_B + C_S + C_C) + (R_C + R_M + R_W + R_Z)\cdot C_S \tag{B.33}$$

where

R_A and R_U are the risk components related to loss of animals, without protection measures;

R_B and R_V are the risk components related to physical damage, without protection measures;

R_C, R_M, R_W, R_Z are the risk components related to failure of electrical and electronic systems, without protection measures;

C_A is the cost of the animals;

C_B is the cost of systems in the wind turbine;

C_S is the cost of the wind turbine;

C_C is the cost of the contents of the wind turbine.

The total cost C_{RL} of residual loss in spite of protection measures may be calculated by the means of the formula:

$$C_{RL} = (R'_A + R'_U)\cdot C_A + (R'_B + R'_V)\cdot(C_A + C_B + C_S + C_C) + (R'_C + R'_M + R'_W + R'_Z)\cdot C_S \tag{B.34}$$

where

R'_A and R'_U are the risk components related to loss of animals, with protection measures;

R'_B and R'_V are the risk components related to physical damage, with protection measures;

R'_C, R'_M, R'_W, R'_Z are the risk components related to failure of electrical and electronic systems, with protection measures.

The annual cost C_{PM} of protection measures may be calculated by means of the equation:

$$C_{PM} = C_P \cdot (i + a + m) \tag{B.35}$$

*w*here

C_P is the cost of production measures;

i is the interest rate;

a is the amortisation rate;

m is the maintenance rate.

The annual saving S of money is:

$$S = C_L - (C_{PM} + C_{RL}) \tag{B.36}$$

Protection is convenient if the annual savings $S > 0$.

B.8 Case studies

Under consideration.

Annex C
(informative)

Protection methods for blades

C.1 General

C.1.1 Types of blades and types of protection methods for blades

Modern 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, bearings, wires, electrical wiring, springs and fixtures are made of metal. At some point in time, hopes were high that lightning would not strike blades made of non-conducting material only, but practical experiences have clearly demonstrated that this is not the case. Lightning does in fact strike blades without any 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 and stretching the entire length of the blade. Alternatively, the blade skins also supply the mechanical strength of the blade in which the load carrying spar is avoided. Finally, blades may be cast in one piece and hence such blades are 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 steel flap 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.

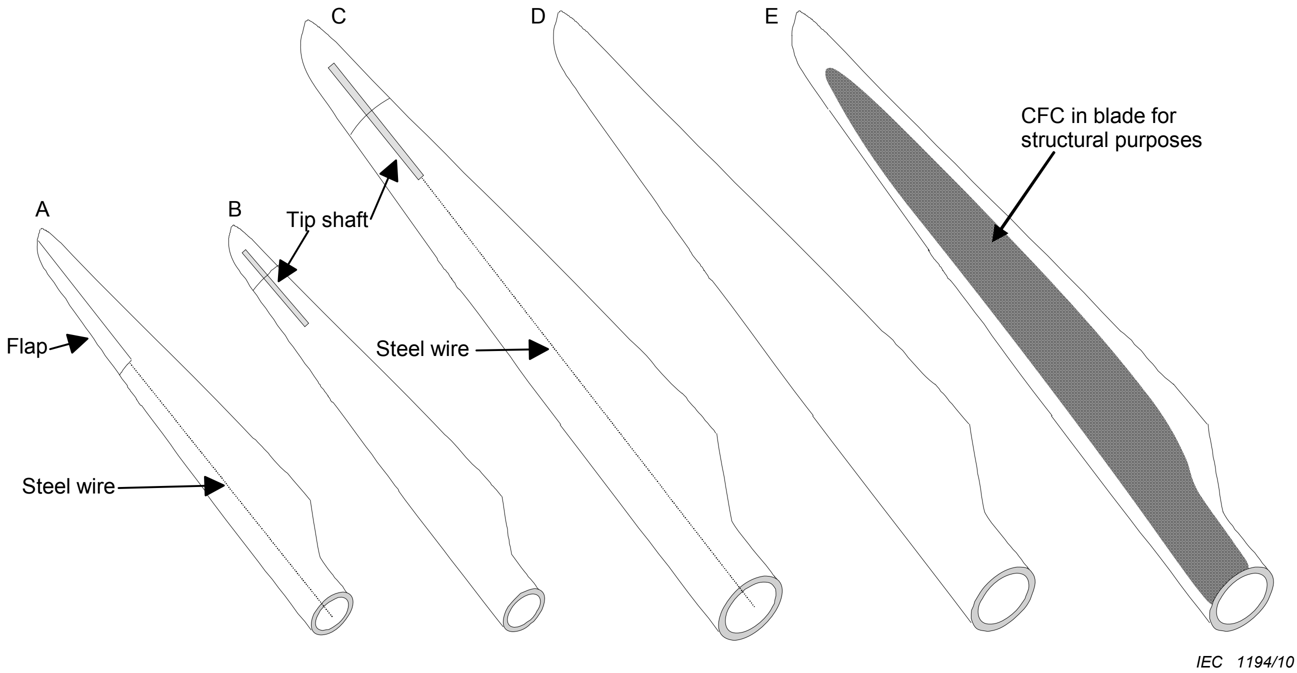


Figure C.1 – Types of wind turbine blades

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 replaced with carbon fibre composite (CFC), since it has desirable mechanical properties. Depending on the specific design, CFC can be used as reinforcement of the blade skin, as well as for load carrying structural components, as the centre spar and main laminate. Due to its electrical properties, it might be integrated into the lightning protection system forming parts of the down conductor. The issues of lightning protection of wind turbine blades containing CFC 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 [9]. 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 CFC (type E) is quite common and hence lightning protection is needed.

NOTE References to the literature are numbered [X] in this Annex and are listed in the Bibliography.

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 is seen 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 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, 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 may 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 commented 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 to the hub, 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 conducting to carry the lightning current safely to the blade root. Variations of both these methods are used with wind turbine blades (see Figure C.2).

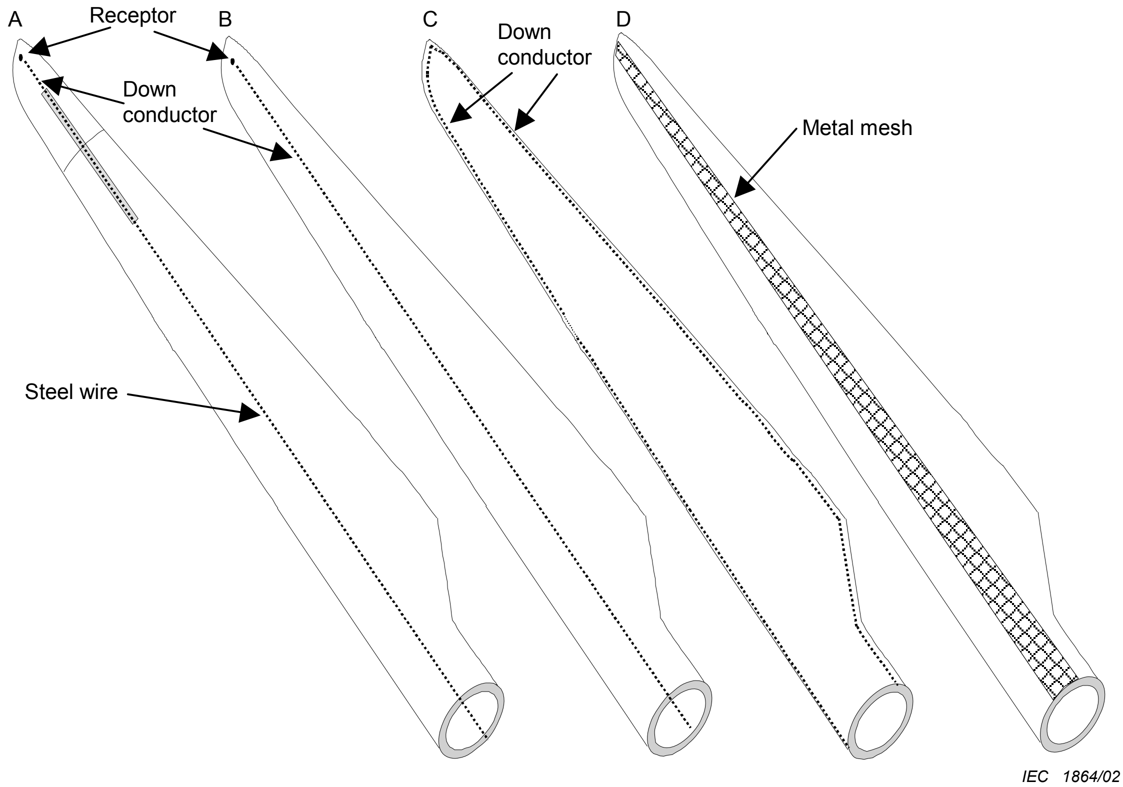


Figure C.2 – Lightning protection concepts for large modern wind turbine blades

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 must 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 [10] [11].

For lightning conductors embedded in the blade, wires or braids of either aluminium or copper are used. In the literature, several protection systems are described where a metallic conductor connected to the blade root is placed either on the blade surface along the trailing edge of the blade 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 positions along the blade, each of these being connected to conductors placed along the blade edges [11] [12] [13] [14] [15].

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 [12] [16]. 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 [10]. This may lead to structural damage.

Some promising experiments with segmented diverter strips have been performed in the past [17] [18]. Such segmented strips are used on aircraft radomes because they do not interfere with the radar signal. The use of long-lasting segmented diverter strips as part of the lightning protection for a wind turbine blade containing CFC has been described in literature [26].

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 solution to the problems with conductors placed on the blade surface is to have the lightning conductors placed 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 [10].

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).

Several 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 [19]. 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 equally fast as the ones incepted from the receptors. 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 will 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 [27] [28].

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 may 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 meshes of metal placed just beneath the surface [10] [15]

[21] and [20]. 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 either made of metal or covered with a metal sheet [12] [13] [14] [15] [22] and [23].

The advantage of using metal meshes or other thin conducting surfaces for lightning down conductors is that possible interior conductive elements (CFC) 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 due to skin effects must also be considered.

C.3 CFC structural components

Carbon fibre composites (CFC) have been used for tip shafts for small blades and are now a commonly used material for reinforcement of large blades. The material is used either for the load carrying centre spar or directly in the blade skins due to its superior mechanical properties. The use of CFC for structural components is expected to increase even further as the size of blades increases.

The main issue with CFC is how it reacts to the impact from the lightning current possibly entering and flowing within the material. Here two electrical properties of CFC make it remarkably different than isotropic conductor materials like metals, the DC conductivity and the degree of anisotropy.

The d.c. conductivity of CFC is typically assigned a value which is a 1 000 times lower than that of aluminium, i.e. $3{,}5 \cdot 10^4$ S/m. This is an approximate value found for biaxial woven CFC plates used for small aircraft skins, measured parallel with the surface of the sample [25] [21].

Depending on the actual construction and weaving technique, the conductivity of CFC exhibit a very high degree of anisotropy. For CFC coupons used for lightning tests in the avionics industry, the conductivity has been measured and varies within four orders of magnitude for different current directions [29].

Therefore, the resistive heating of CFC 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 matrix (approximately 200 °C). When the matrix evaporates, the pressure from evolving gases can cause rupture and delamination of the CFC layers. The CFC may even incinerate, in particular at the lightning attachment point [21].

Where CFC is used in aircrafts, it is considered mandatory that lightning protection is provided for CFC components that may be struck by lightning or may conduct lightning current [10].

There are examples of CFC tip shafts for wind turbine blades having been damaged by lightning. Some laboratory experiments have also demonstrated problems with CFC shafts conducting lightning current [24]. Laboratory tests of blades with CFC skin have shown surface delamination and incineration at the lightning attachment point [9] [26]. Protection of the CFC surfaces against direct lightning attachments is therefore required, either by means of encapsulation by a sufficient layer of insulation material or shielding by external lightning capturing devices.

Since the conductive CFC is most often a parallel path to the lightning current, relative to the down conductor, proper bonding between CFC and other conducting components must be made. For each specific blade design, it should be determined whether the spacing between equipotential bondings is small enough to avoid the development of critical voltages between the CFC and the down conductor. Critical voltages in this context are voltages that can potentially puncture the insulation layer between the CFC and the down conductor, affecting the mechanical strength of the structure.

Once the lightning current has been distributed over a wide cross sectional area of the CFC, such structures may be able to conduct lightning current without being damaged.

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 the possible CFC described in Clause C.3.

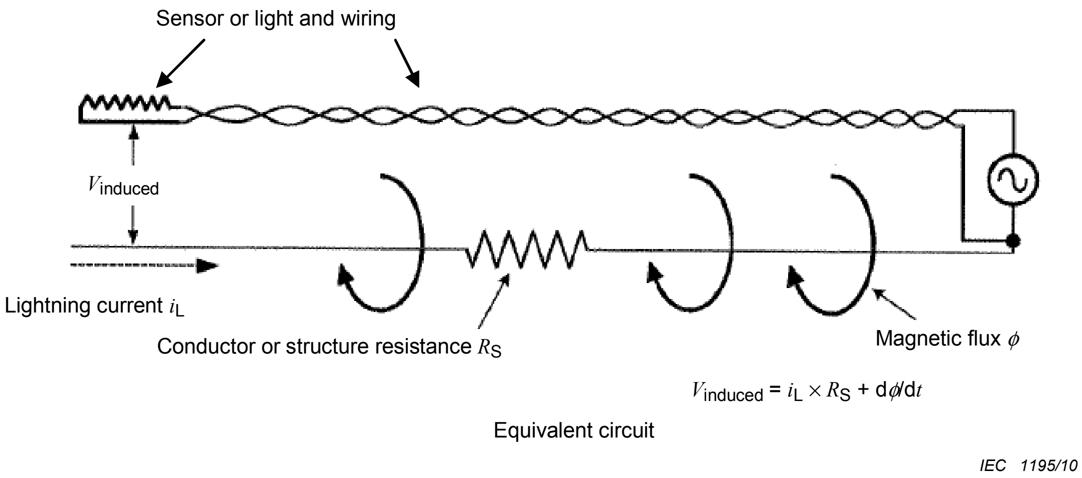


Figure C.3 – Lightning induced voltages between lightning conductor or structure and sensor wiring

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. If not, both sensors and wiring must be protected by appropriate equipotential bonding to the down conductor system and shielded or covered by the external lightning receptors. Having well exposed external lightning receptors 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 may 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 which 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 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. must be treated similarly. All conductive parts in the blade must be designed to minimise electric field enhancement and be connected by equipotential bonding 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, i.e. blade tip navigation light, lightning sensors, condition monitoring equipment, etc., it must 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 an issue with the lightning protection methods using discrete air-termination systems placed on the blade surface. Any air terminations and extensions of air terminations (solid conductors and segmented diverters on the surface) must be placed in such a way that the likelihood of lightning puncturing a non-conducting surface 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 must be expected. Furthermore, the interception efficiency of segmented diverters and of discrete receptors will be influenced by the presence of conducting materials inside the blade [10].

For blades up to 20 m long, receptors at the tip of the blade have proven to be adequate. Recent publication of lightning attachment distribution for 39 m glass fibre blades shows that the majority of lightning flashes attaches to the tip region of the blade (88 %) whereas the remaining strikes attached to the receptor 5 m inboard the tip [30].

High-voltage strike attachment tests on test specimens representing the design are useful for revealing insufficient receptor protection. However, further studies are needed, particularly of the effects of wet, polluted and aged blades.

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 [32] [33]. Once the potential and use of these models are fully understood, they can be used to estimate the surfaces where lightning may possibly strike if these surfaces were conductive or had receptors. 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 due to the complexity of most blade structures, and the dynamics of multiple streamer origination and growth. Thus the numerical methods may become useful design tools, but high-voltage attachment tests, as described in Clause D.2, of candidate designs should be used to provide additional assurance of protection effectiveness.

C.6 Dimensioning of lightning protection systems

The materials used for lightning protection of wind turbine blades must 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 and down conductors (corresponds to Table 6 in IEC 62305-3, future edition 2[5)])

Material	Configuration	Nominal cross-sectional area mm²	Comments[i,j]
Copper	Solid tape	50[h]	2 mm thickness
	Solid round[g]	50[h]	8 mm diameter
	Stranded	50[h]	1,7 mm diameter of each strand
	Solid round[c, d]	200	15 mm diameter
Tin plated copper[a]	Solid tape	50[h]	2 mm thickness
	Solid round[g]	50[h]	8 mm diameter
	Stranded	50[h]	1,7 mm diameter of each strand
Aluminium	Solid tape	70	3 mm thickness
	Solid round	50[h]	8 mm diameter
	Stranded	50[h]	1,7 mm min. diameter of each strand
Aluminium alloy	Solid tape	50[h]	2,5 mm thickness
	Solid round	50	8 mm diameter
	Stranded	50[h]	1,7 mm diameter of each strand
	Solid round[c]	200	15 mm diameter
	Copper coated solid round	50	250 μm min. radial copper coating 99,9 % copper content
Hot-dip galvanised steel[b]	Solid tape	50[h]	2,5 mm thickness
	Solid round	50	8 mm diameter
	Stranded	50[h]	1,7 mm diameter of each strand
	Solid round[c, d]	200	15 mm diameter
Stainless steel[e]	Solid tape[f]	50[h]	2 mm thickness
	Solid round[f]	50	8 mm diameter
	Stranded	70[h]	1,7 mm diameter of each strand
	Solid round[c, d]	200	15 mm diameter
Steel	Copper coated solid round	50	250 μm min. radial copper coating 99,9% copper content

[a] Hot dipped or electroplated minimum thickness coating of 1 μm.

[b] The coating should be smooth, continuous and free from flux stains with a minimum weight of coating of 350 g/m² for solid round conductors and 500 g/m² for solid tape conductors.

[c] Applicable for air termination rods only. For applications where mechanical stress such as wind loading is not critical, a 10 mm diameter, 1 m long maximum air termination rod with an additional fixing may be used.

[d] Applicable to earth lead-in rods only.

[e] Chromium ≥ 16 %, nickel ≥ 8 %, carbon ≤ 0,07 %.

[f] For stainless steel embedded in concrete, and/or in direct contact with flammable material, the minimum sizes should be increased to 78 mm² (10 mm diameter) for solid round and 75 mm² (3 mm minimum thickness) for solid tape.

[g] 50 mm² (8 mm diameter) may be reduced to 28 mm² (6 mm diameter) in certain applications where mechanical strength is not an essential requirement. Consideration should, in this case, be given to reducing the spacing of the fasteners.

[h] If thermal and mechanical considerations are important, these dimensions can be increased to 60 mm² for solid tape and to 78 mm² for solid round.

[i] The minimum cross section to avoid melting is 16 mm² (copper), 25 mm² (aluminium), 50 mm² (steel) and 50 mm² (stainless steel) for a specific energy of 10 000 kJ/Ω. For further information, see Annex E of IEC 62305-3.

[j] Allowable tolerances for the cross section area are 3 %.

5) To be published.

The cross-sectional areas given above are meant 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 receptors, connection components, expanded foil, etc., different dimensions can be considered; for such components, the design verification should be based on laboratory tests. 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 constructor must 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 its function immediately after a lightning stroke.

$$\theta - \theta_0 = \frac{1}{\alpha} \cdot \left\{ \exp\left[\frac{(W/R \cdot \alpha \cdot \rho_0}{q^2 \cdot \gamma \cdot c_W} \right] - 1 \right\} \qquad \text{(C.1)}$$

where

$\theta - \theta_0$	[K]	is the temperature rise of the conductors;
α	[1/K]	is the temperature coefficient of the resistance;
W/R	[J/Ω]	is the specific energy of the current impulse;
ρ_0	[Ωm]	is the specific ohmic resistance of the conductor at ambient temperature;
q	[m^2]	is the cross-sectional area of the conductor;
γ	[kg/m^3]	is the material density;
c_w	[J/kgK]	is the thermal capacity.

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 (Table D.2 in IEC 62350-1)

Quantity	Material			
	Aluminium	**Mild steel**	**Copper**	**Stainless steel***
ρ_0 [Ωm]	$29 \cdot 10^{-9}$	$120 \cdot 10^{-9}$	$17{,}8 \cdot 10^{-9}$	$0{,}7 \cdot 10^{-6}$
α [1/K]	$4{,}0 \cdot 10^{-3}$	$6{,}5 \cdot 10^{-3}$	$3{,}92 \cdot 10^{-3}$	$0{,}8 \cdot 10^{-3}$
γ [kg/m^3]	2 700	7 700	8 920	$8{,}0 \cdot 10^3$
θ_s [°C]	658	1 530	1 080	1 500
c_s [J/kg]	$397 \cdot 10^3$	$272 \cdot 10^3$	$209 \cdot 10^3$	–
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.

* Austenitic non-magnetic.

Table C.3 – Temperature rise [K] for different conductors as a function of *W/R* (Table D.3 in IEC 62305-1)

Cross-section mm²	Material											
	Aluminium			Mild steel			Copper			Stainless steel*		
	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	564	–	–	–	–	–	169	542	–	–	–	–
16	146	454	–	1 120	–	–	56	143	309	–	–	–
25	52	132	283	211	913	–	22	51	98	940	–	–
50	12	28	52	37	96	211	5	12	22	190	460	940
100	3	7	12	9	20	37	1	3	5	45	100	190
* Austenitic non-magnetic.												

Considering the impact on the air termination, IEC 62305-1 suggests the use of the anode-or-cathode voltage drop model. The model assumes that all the injected energy in the arc root is used for evaporation of the bulk material, hence neglecting heat diffusion within the metal. The melted volume using this conservative approach can be found using equation C.2.

$$V = \frac{u_{a,c} \cdot Q}{\gamma} \cdot \frac{1}{c_W(\theta_s - \theta_u) + c_s} \tag{C.2}$$

where

V	[m³]	is the volume of metal melted;
$u_{a,c}$	[V]	is the anode-or-cathode voltage drop (assumed as constant);
Q	[C]	is the charge of the lightning current;
γ	[kg/m³]	is the material density;
c_w	[J/kgK]	is the thermal capacity;
θ_s	[°C]	is the melting temperature;
θ_u	[°C]	is the ambient temperature;
c_s	[J/kg]	is the latent heat of melting.

Using a typical anode-or-cathode voltage $u_{a,c}$ drop of a few tens of volts, the model leads to an overestimate of the melted volume.

C.7 Blade-to-hub connection

At the root of the blade, the down conduction system is usually either terminated to the blade mounting flange or to the hub.

If the blade is pitch regulated (type D), the lightning current is either allowed to pass uncontrolled through the pitch bearing or some kind of bonding across the bearing is provided such as a sliding contact or a flexible bonding cable with enough slack to allow for the pitch motion. The flexible bonding across the bearing can be combined 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, must 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. Another approach with a sliding air gap construction has been described [24].

Care must 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 inefficient protection of the cylinder [24].

Annex D
(informative)

Test specifications

D.1 General

This annex describes possible test methods for developing new blade designs or verifying existing 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 spinner, hub, nacelle or parts thereof.

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 nacelles. 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 like connection components, etc. These tests do not give any information about the most likely attachment points.

Pass/fail criteria for each test shall be defined and stated by the manufacturer.

NOTE References to the literature are numbered [X] in this Annex and are listed in the Bibliography.

D.2 High-voltage strike attachment tests

These tests are used to determine lightning attachment points and breakdown paths across or through non-conducting materials.

D.2.1 Initial leader attachment test

D.2.1.1 Test purpose

This test is intended for wind turbine blades, but may be applied to nacelles fabricated of glass fibre or other non-conducting materials. This test can be used to assess:

- location of possible leader attachment points and flashover or puncture paths on blades and other non-conducting structures;
- optimisation of the location of protection devices (air termination systems, receptors);
- flashover or puncture paths along or through dielectric surfaces;
- performance of protection devices.

D.2.1.2 Test specimen

The test specimen should be a full-scale blade or blade section. The section of the blade that needs to be tested depends on the structural details of the blade and on the lightning protection design. Some guidelines for selection of blade specimens are as shown below. The principles are to expose all aspects of the blade and its protection design to the electric fields that precede lightning leader attachment.

- If the blade has the same composite material thicknesses throughout most of the blade length, an outer section of the blade may be tested.
- If the blade lightning protection utilises only one or two discrete air terminations located in the tip area, then an outer section of the blade may be tested, but if the lightning conductor is inside the blade, the tested section must be of sufficient length to verify that punctures will not occur inboard from the tip through the skin to the down conductor system.
- If the blade lightning protection utilises an air termination system consisting of multiple discrete pairs (i.e. terminals on opposite surfaces of the blade) of air terminations spaced x metres apart and the purpose is to determine the maximum distance x, then the test specimen must include at least two pairs of air terminations plus a minimum of one half of the distance to the next inboard air terminations. Specimen lengths that have produced results similar to service experience have ranged from 6 m to 20 m in length.
- If the blade lightning protection utilises other designs of air terminations and down conductors, the size of the specimen should encompass all details to be tested. For externally mounted conductors, the ends of test samples should be rounded off by means of conducting toroids to avoid unintentional field enhancements at these extremities.
- If the test purpose is to investigate and develop a detailed design option that involves only a small portion of a blade (i.e. the blade tip or a mid section of the blade), then smaller specimens, involving the design options may be tested. However, it must be noted that the electric field present between a small test sample and the opposite electrode is different than when the entire blade is present. Due to these differences, field grading toroids or slightly rounded opposite electrodes might be necessary to prevent unrealistic flashovers from the inboard end of such specimens, depending on the actual geometry.
- Specimen lengths that have produced results similar to service experience, with the purpose of optimising blade tip designs, have ranged from 3 m to 6 m in length.

Any surface finishes and paints should be included to ensure realistic test results.

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) should be represented within the test specimen.

These items must be positioned at the same locations within the test specimen as they would be in the blade or nacelle installation. 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.

D.2.1.3 Test setups

There are three test arrangements, designated test setup A, test setup B and test setup C, which can be used. Test setups A and B are most appropriate for tests on complete blades used for design development and verification. Test setup C is most appropriate for developmental tests to evaluate skin panel construction and possible diverter strip 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 geometry 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, B and C are illustrated in Figure D.1, Figure D.3, 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.

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 must be suspended above the test specimen. A large diameter is essential to avoid non-realistic field intensifications due to the edges of the suspended electrode.

Test setup C is most appropriate for developmental tests to evaluate or compare dielectric strengths of candidate skin materials and/or local protection designs. However, tests of panels should not be employed for verification of complete protection designs, since the panel specimens do not represent all significant features of the non-conducting structures being verified.

D.2.1.3.1 Test setup A

The general test arrangement for test setup A is illustrated in Figure D.1.

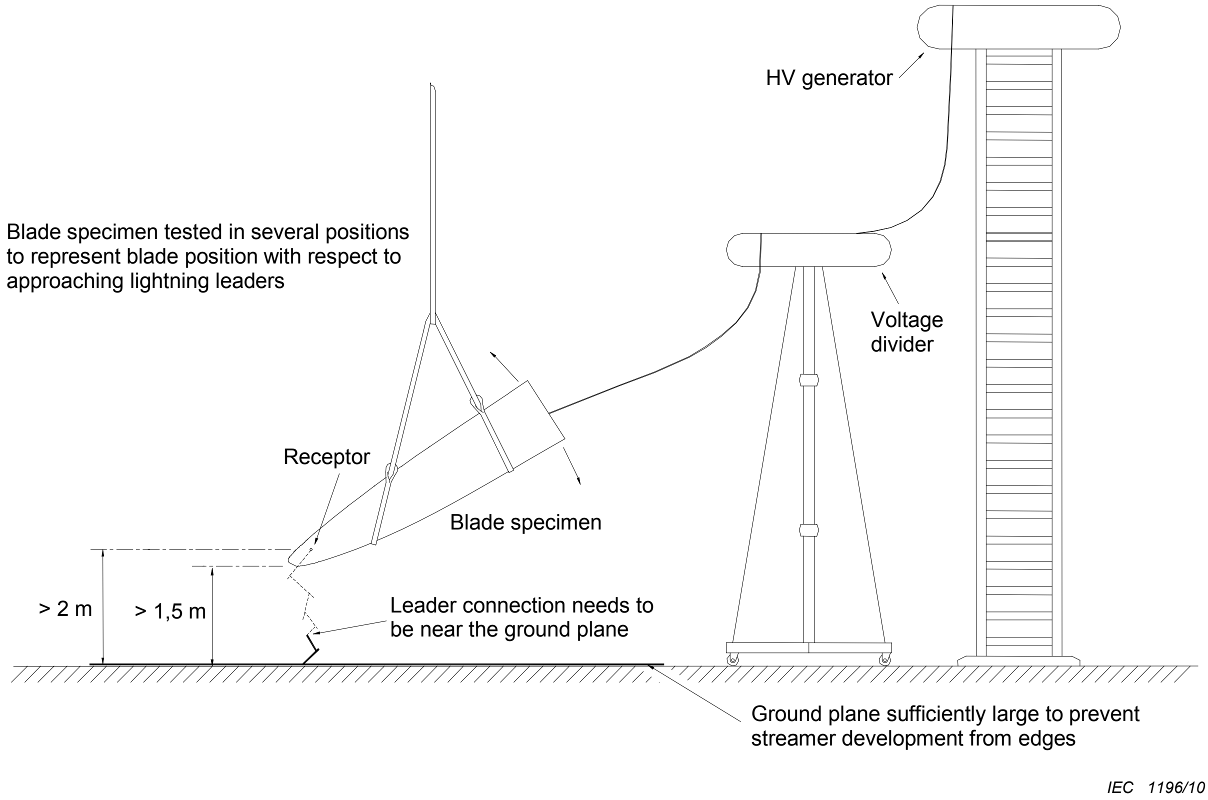


Figure D.1 – Initial leader attachment test setup A (specimen should be tested in several positions representing different directions of the approaching leader)

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 must be of sufficient size to avoid edge effects, i.e. to avoid having flashovers terminating on the edge of the ground plane. The test specimen should normally be tested in several orientations, to represent electric field directions that this part of the test specimen may experience on the turbine.

An example of such orientations is given in Figure D.2. Here three different angles of the blade relative to the ground plane is used (90°, 60° and 30° with horizontal), and four different pitch angles. By applying three discharges of each polarity and at each orientation, the blade will experience 54 impacts.

Long blades should usually be tested with the specimen 5˚ and 10˚ from horizontal, representing the greater possibility of lightning leaders approaching within striking distance of a location inboard of the blade tip while when the blade happens to be in the horizontal position.

Practical limitations of vertical space and overhead crane availabilities may necessitate that tests in the 60˚ and 90˚ positions be applied to shorter blade specimens, perhaps 2 m to 4 m long.

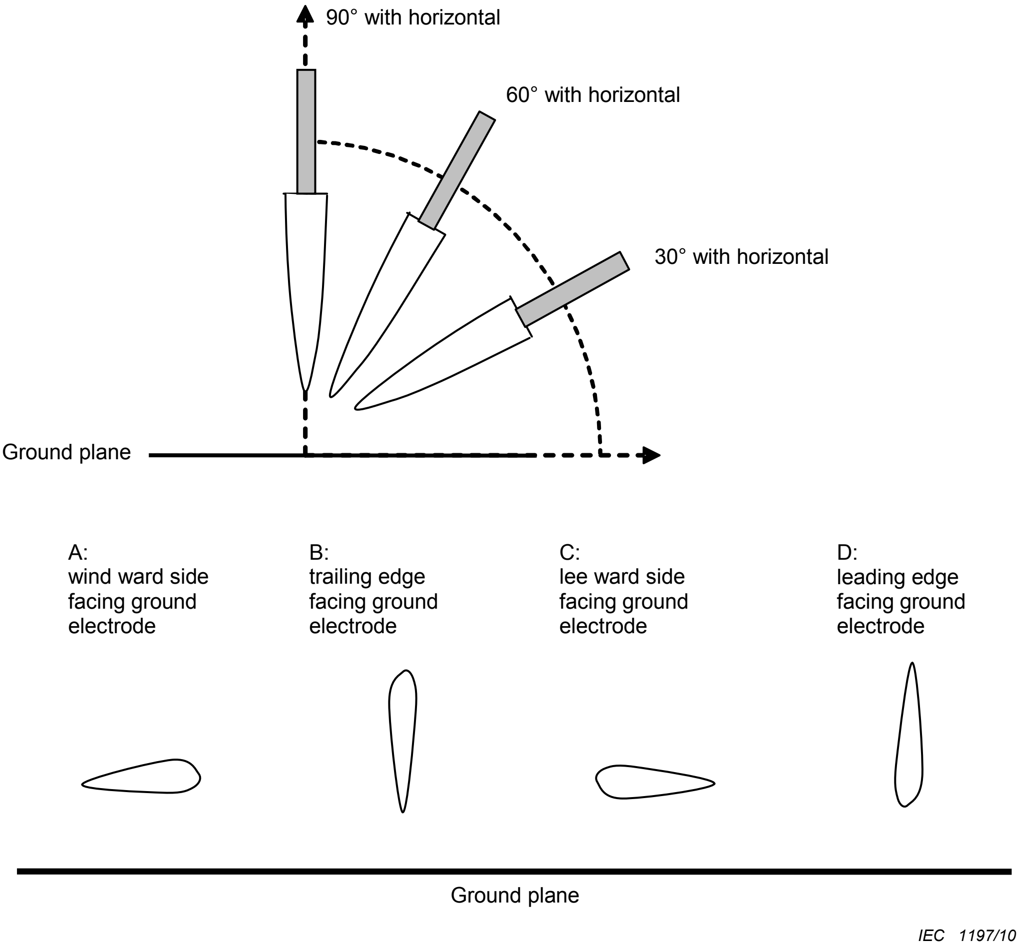


Figure D.2 – Possible orientations for the initial leader attachment test setup A

Two conditions should apply for a valid test when test setup A is used:

a) Connection of the streamers should 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 can be confirmed by photographs of the flashovers. The leader connection point is shown in Figure D.3. The requirement is usually met by keeping the following distances.

   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 but condition (a) prevails.

b) The streamer from the ground plane must not originate from the edge of the ground plane. In such case, the size of the ground plane must be increased.

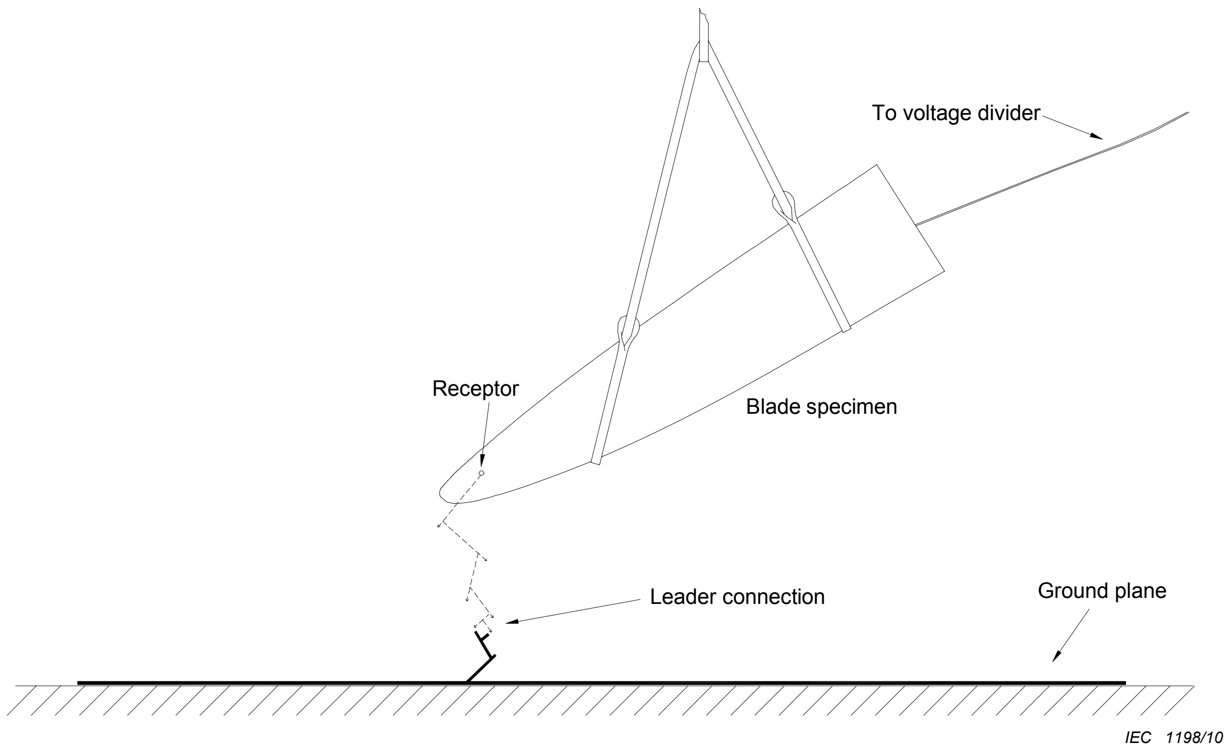


Figure D.3 – Leader connection point must be away from test specimen

Specific dimensions and test specimen orientations should be described in the test plan.

D.2.1.3.2 Test setup B

The general test arrangement for test setup B is illustrated in Figure D.4.

Specimen should be tested in several positions representing different directions of the approaching leader.

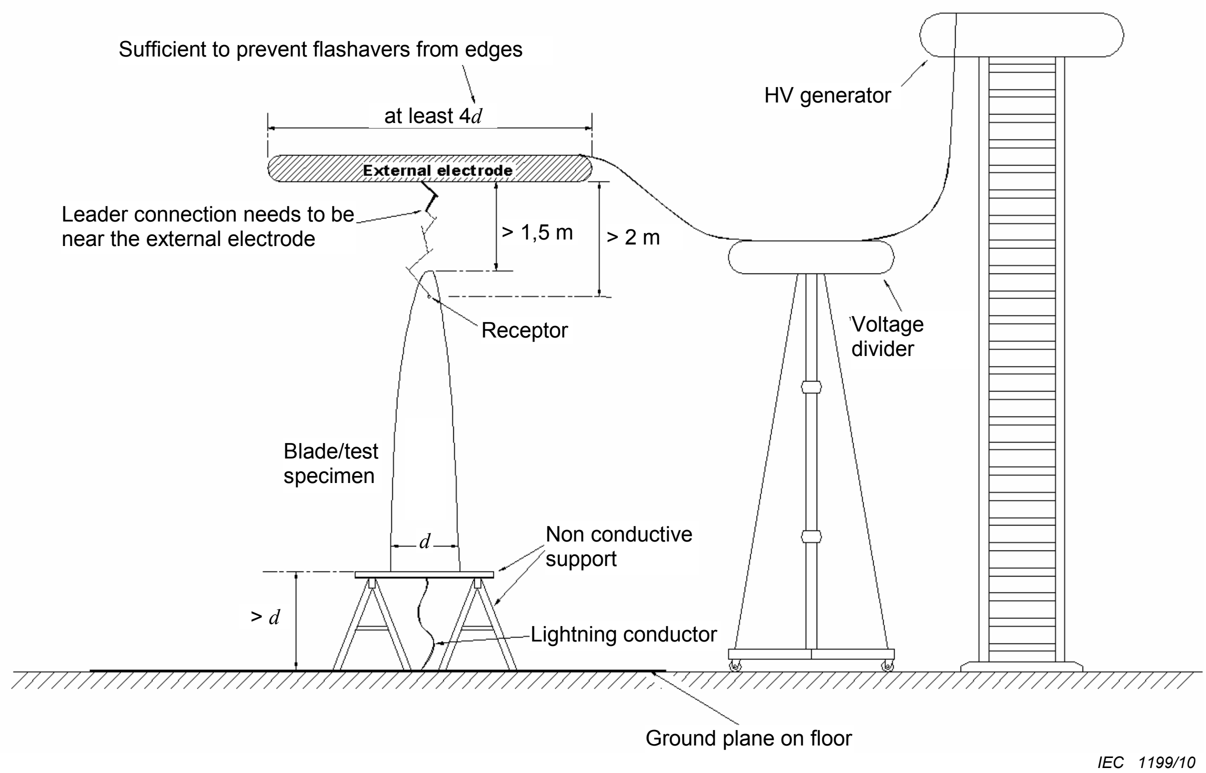


Figure D.4 – Initial leader attachment test setup B

Test setup B is suitable for test specimens too large to elevate in the test facility such as meteorological instrument booms, hubs, spinners, etc. 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 in IEC 60060-1 specified 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 must then be at least 1,5 times the gap length away, i.e. 3 m with the gap length of 2 m on Figure D.4.

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 must 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.

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 can be confirmed by photographs of the flashovers. The leader connection point is shown in Figure D.4. The requirement is usually met by keeping the following distances.
   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 test specimen skin, but condition (a) prevails.

b) The streamer from the external electrode must not originate from the edge of this electrode.

c) The end termination of the protection device or other conductive elements within the specimen must 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.

Specific dimensions and test specimen orientations should be described in the test plan.

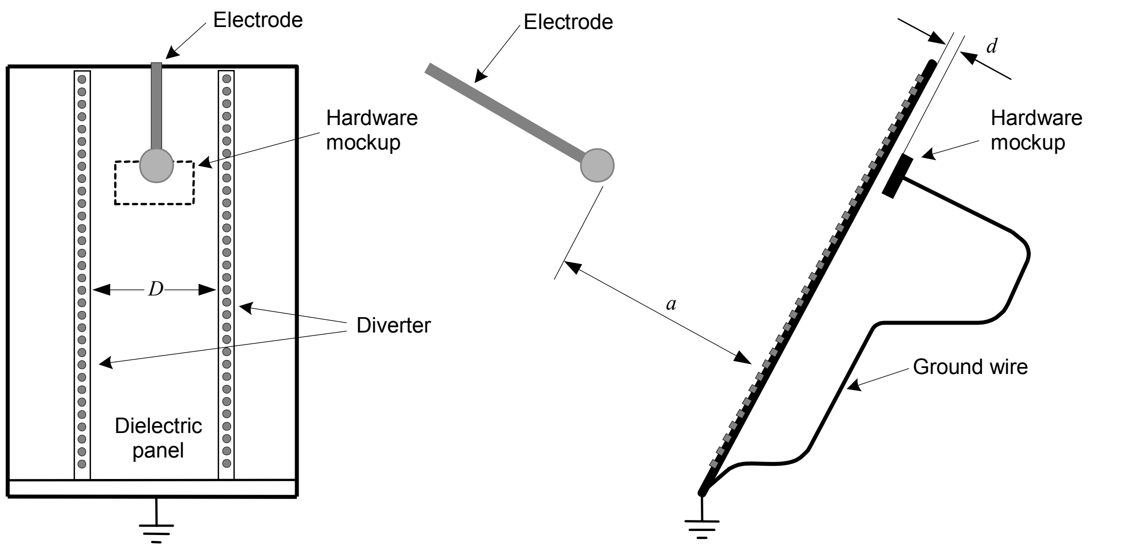
D.2.1.3.3 Test setup C

The general test arrangement for test setup C is illustrated in Figure D.5.

In this arrangement, candidate protective devices and device locations on a non-conductive skin specimen can be evaluated prior to establishing a protection design and installing such devices on a larger, more complete test specimen.

A typical skin panel would be a square of 1 m^2 to 2 m^2, although other sizes and shapes may be acceptable, sufficient to accommodate a full-scale arrangement of protection devices. Production-like skin materials, surface finishes and paints should be applied. A typical use of this test is to determine the spacing (D) of diverter strips to be installed on a blade or nacelle surface.

A mock-up of any conductive items behind the protective surface should be placed at an appropriate position behind the skin at the distance (d). The protection devices are normally at test facility ground potential and the electrode is at high potential. In order to apply a realistic test condition, experience has shown that the electrode should be positioned midway between the diverter strips, as in the example of Figure D.5, to prevent attachment around the edge of the specimen or an unrealistic result. The electrode should be elevated above the panel surface by a distance equal to the dimension of the panel if square, or the smaller dimension of a rectangular panel. The diverter strips may be repositioned at a larger or smaller spacing to optimise the design and prevent puncture.



Determining distance D as a function of proximity d to an internal conductor

Distance a is the shorter dimension of the panel's width or height

IEC 1200/10

Figure D.5 – Arrangement for local protection device (e.g. diverter) – Evaluations test setup C

The arrangement of Figure D.5 is not equivalent to the verification test arrangement of test setups A and B, but experience has shown that diverter spacing determined from development tests as illustrated in Figure D.5 have proved successful in subsequent verification tests of local protection arrangements such as diverter extension of air termination systems on blade skins, employing similar diverter spacing. A verification test should be made using test setup A or B.

D.2.1.4 Test voltage waveform

The voltage waveform used should be a double exponential switching type impulse voltage with time to peak 250 µs ± 20 % and decay time to half value of 2 500 µs ± 60 %. 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. For the initial leader attachment test, the voltage will be applied as a rise to flashover occurring before the crest of the voltage waveform. The time between initiation of the voltage waveform and the flashover to the structure must be at least 50 µs.

Such waveforms might be achieved by using the switching type impulse voltage in IEC 60060-1. Since the voltage is applied as a rise to flashover, the decay times are not of particular interest. A typical test voltage waveform is shown in Figure D.6.

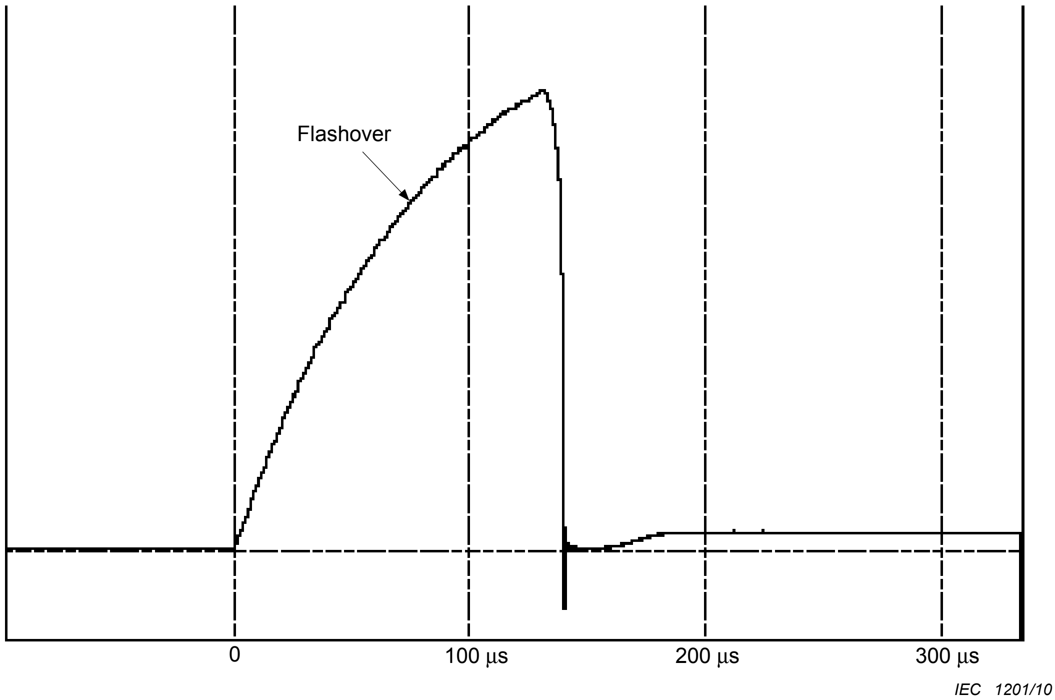


Figure D.6 – Typical switching impulse voltage rise to flashover (100 µs per division)

At least three discharges of each polarity and each orientation of the test specimen with respect to the opposite electrode should be applied [30] and [34]. Testing with several different orientations of the test specimen with respect to the opposite electrode ensures a significant possibility of failure in case of improper blade design.

In case punctures of the blade skin occur during tests, the damage may be cleaned and repaired using suitable polymer resin. However, experience has shown that specimens subjected to a large number of impacts will degrade electrically over time; a situation not only affecting the repaired punctures but also the main laminate. Hence the manufacturer must be aware that the number of discharges to each test sample should not exceed approximately

100 discharges to avoid damage due to electrical aging. The test procedures in D.2.1.6 are defined to minimise the impact of electrical aging throughout the test.

The matter of electrical aging of blade laminates due to the impact of lightning is not fully understood at the time of publication. Sections considering these issues will hopefully be improved in future editions.

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.

D.2.1.5 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. These should have complete coverage of the tested areas of the specimen. One camera should enable immediate preliminary analysis of the test to be made so that any punctures are identified immediately. An extra camera looking into the interior of the blade sample might be useful in order to monitor 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.

D.2.1.6 Test procedure

This test procedure is applicable to all test setups (A, B, and C).

a) Measure laboratory environmental conditions.

b) Review and implement safety procedures. Some areas of concern are as follows. Test areas must be safe and clear of personnel prior to charging of test equipment. Capacitor banks must be shorted out after tests and prior to re-entry of personnel into the test area. Eye and ear protection must be appropriate.

c) Calibrate the HV generator and instrumentation as follows:

   1) 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.

   2) Cover the surfaces that are towards the opposite electrode (i.e. ground plane) with a conductive foil and connect this to the blade lightning down conductor.

   3) Select the initial polarity and initiate a test to the foil while measuring the applied voltage. It is advisable for 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 protective devices progress further into the air gap before being joined by opposing streamers from the negative electrode.

   4) 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 specimen and opposite electrode as necessary to obtain the specified waveform and flashover.

5) Repeat steps 3) through 4) as necessary to obtain the required conditions.

6) Remove the foil from the test specimen.

d) Clean the test specimen with appropriate technique to remove moisture, dust, debris, and other contaminants which could affect test results.

e) Apply a discharge to the test specimen, while measuring the applied voltage and taking photographic evidence of the path of the flashover. Ensure that the flashover still occurs on the rising wave front before the crest of the voltage waveform.

f) Inspect the test specimen and document the results.

g) If puncture has occurred, perform an assessment to determine if the test specimen has failed the test. If it is deemed to have failed, then the test sequence may need to be terminated, or repairs of test damage or modifications to the blade lightning protection system made before continuing with the tests.

h) Repeat steps e) through h) until three discharges of positive polarity have been applied under the same conditions.

i) 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).

j) Calibrate the HV generator and instrumentation as follows:

   1) Drape the test specimen with a conductive foil.

   2) Initiate a test to the foil while measuring the applied voltage.

   3) 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 specimen and external electrode as necessary to obtain the specified waveform and flashover.

   4) Repeat steps 2) through 3) as necessary to obtain the required conditions.

   5) Remove the foil from the test specimen.

k) Repeat steps e) through i) until three discharges of negative polarity have been applied under the same conditions.

l) Reposition the test specimen (test setup A) or the external electrode (test setup B) as required by the test procedure.

m) Repeat steps c) through m) as required by the test procedure.

Initial leader attachment tests may be conducted on polluted and wetted blade specimens.

Since flashovers occur more readily across wet or contaminated surfaces, thereby making punctures less likely, it may not be important to apply contamination to external surfaces. However, wetted or contaminated interior surfaces may more rapidly guide streamers to blade edge bonds, where punctures are known to have occurred. Thus, tests of blade specimens with wetted and/or contaminated interior surfaces may be appropriate if such conditions are believed to exist within a blade under service due to environments.

NOTE Since a wind turbine is usually designed to operate for 20 years with only a minimum of maintenance, it is important that the number of discharges is comparable with the expected threat for the actual wind turbine location. Therefore a minimum of 3 discharges for each polarity and orientation should be applied for proof and demonstration purposes, whereas a higher number of tests could be conducted during development of new designs.

D.2.1.7 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 Swept channel attachment test

D.2.2.1 Test purpose

This test is normally applicable to surfaces of a wind turbine blade that are exposed to initial leader attachment when the blade is rotating, so that a leader may “sweep” along the surface a short distance prior to first stroke arrival. This test can be used to assess:

- possible puncture locations on non-conducting (i.e. dielectric) surfaces;
- flashover paths over non-conducting surfaces; or
- the performance of protection devices, such as diverter strips.

D.2.2.2 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 lightning receptor or other protection device. Any surface finishes, including surface fillers or paints should be provided to ensure realistic surface flashover characteristics. If the blade protection design includes a lightning conductor that is inside the blade, the test specimen should also enclose such a conductor.

D.2.2.3 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.7. Tests should usually be applied from several electrode positions, representing the possible directions of leader sweep.
- 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.
- The receptor(s) and any associated lightning protection conductors must be at ground potential.
- Connect the output terminal of the HV generator to the high-voltage electrode. The electrode should be spherical with a radius between 25 mm and 50 mm. The surface of the HV electrode should be placed 50 mm away from the surface on the test specimen to be stressed to represent the voltage applied by a lightning channel sweeping over the surface of the test specimen.
- Set up equipment to measure and record the applied test voltage.

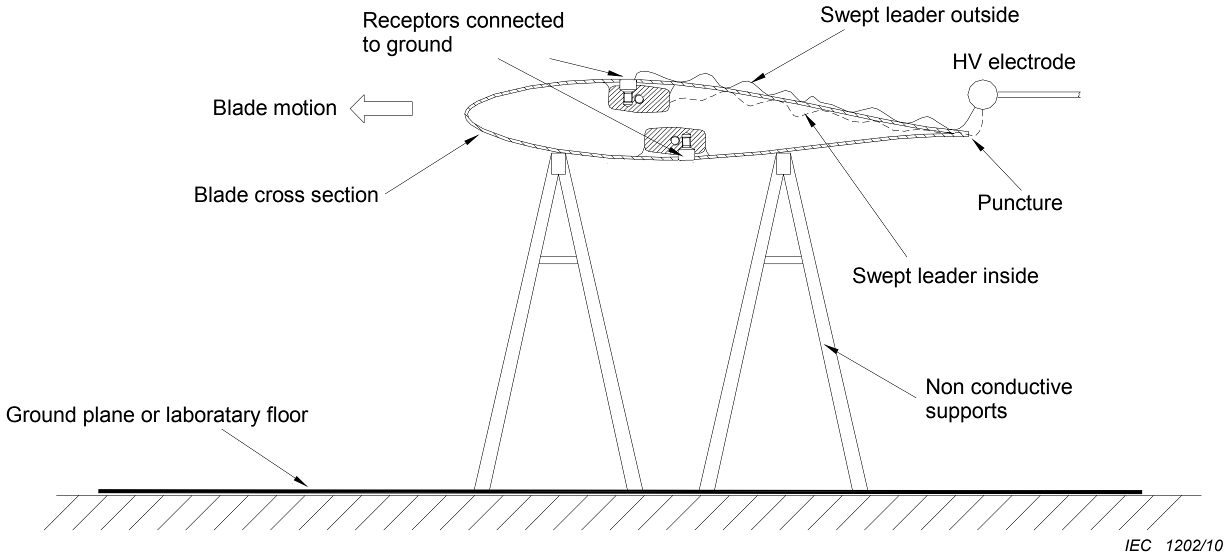


Figure D.7 – Swept channel test arrangement

D.2.2.4 Test voltage waveform

The electric field associated with a swept leader attachment is due primarily to impulses of electric charge flowing in the leader channel. These 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 time to crest 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.8.

This waveform is applied with a virtual peak voltage that is higher than required to ionise the air gap between the test electrode and the specimen surface so that flashover occurs on the wave front as shown in Figure D.9.

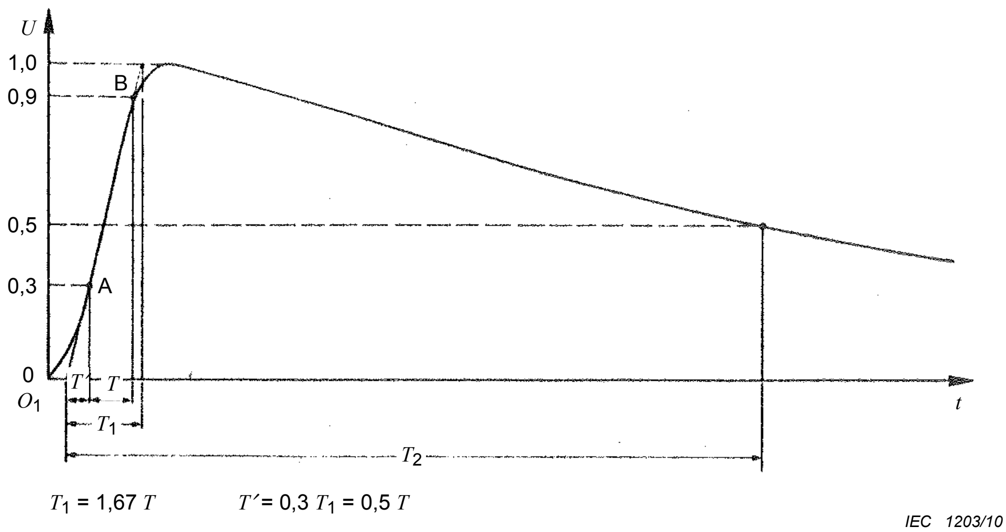


Figure D.8 – Lightning impulse voltage waveform (Figure 6 in IEC 60060-1)

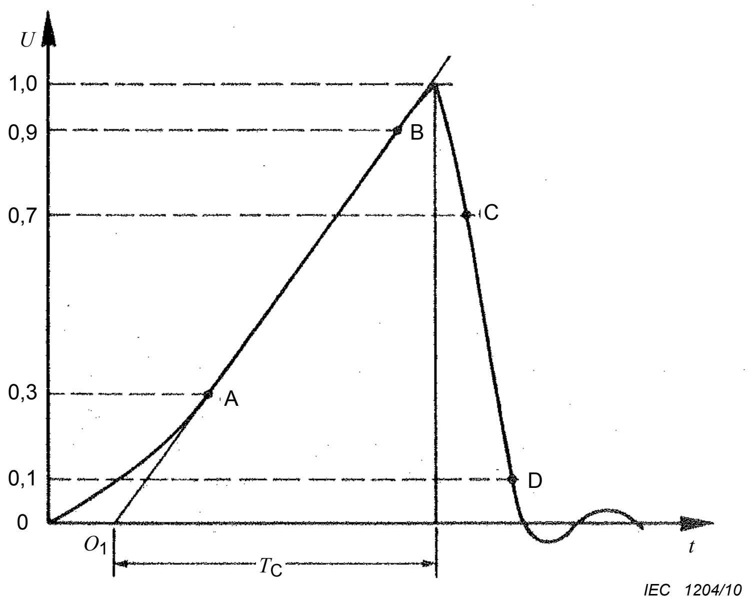


Figure D.9 – Lightning impulse voltage waveform showing flashover on the wave front (Figure 7 in IEC 60060-1)

D.2.2.5 Measurements and data recording

The following measurements and data recordings should be made.

- 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 streamer/leader behaviour during tests.
- 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.
- Records of any deviations from the test procedure.
- Records of the results of each test showing voltage polarity, amplitude and waveform.

D.2.2.6 Test procedure

The test procedure is as follows.

a) Measure laboratory environmental conditions.
b) Review and implement safety procedures. Some areas of concern are as follows: Test areas must be safe and clear of personnel prior to charging of test equipment. Capacitor banks must be shorted out after test and prior to re-entry of personnel into the test area. Eye and ear protection may be required.
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 as follows.
   1) Drape the test specimen with a conductive foil.

2) Tests should be conducted with the electrode at both positive and negative polarity. Select the initial polarity and initiate a test discharge to the foil while measuring the applied voltage. It is advisable for the initial electrode polarity to be negative (–). This places the test specimen at positive polarity. Experience has shown that this condition results in a lower probability of puncture of non-conducting materials since streamers originating from protective devices on the test specimen progress further into the air gap before being joined by opposing streamers from the negative electrode.

3) If the required waveform is not correct, adjust the generator parameters or electrode spacing as necessary to obtain the specified waveform.

4) Remove the foil.

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 the flashover.

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 e) through i) for each of the tests, electrode polarities and electrode positions called for in the test procedures.

NOTE Since a wind turbine is usually designed to operate for 20 years with only a minimum of maintenance, it is important that the number of discharges is comparable with the expected threat for the actual wind turbine location. Therefore, a minimum of 3 discharges for each polarity and orientation should be applied for proof and demonstration purposes, whereas a higher number of tests could be conducted during development of new designs.

D.2.2.7 Data interpretation

Test specimens should undergo a thorough post-test evaluation to determine the adequacy of the design against the pass/fail criteria.

D.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 taken by the lightning current.

D.3.2 Arc entry test

D.3.2.1 Test purpose

This test is applicable to structures such as wind turbine blades and nacelles that are exposed to direct lightning attachment or conducted lightning currents.

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.

The test can be used to assess:

- arc attachment damage;
- hot spot formation;

- metal erosion at air termination systems;
- adequacy of protection materials and devices;
- magnetic force effects;
- blast and shock wave effects;
- behaviour of joints and hardware assemblies;
- voltages and currents at points of interest throughout a lightning protection system.

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. 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.
- Ground all hardware to the test specimen structure that is normally grounded.
- 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.10. This type of electrode has been shown to best represent the shock wave effects of natural lightning attachments, and minimises the amount of electrode material that is deposited upon the test specimen surface [31].
- Set the generator polarity to negative in order to produce maximum damage since arc roots are more concentrated at the anode.
- A fine metallic wire, not exceeding 0,1 mm diameter, may be used, if desired, to direct the arc to a specific point of interest on the test specimen. 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.
- Set up sensing and recording equipment.

D.3.2.4 Test current waveforms

The test currents to be applied are taken from Clause 8 of IEC 62305-1. These include the first short stroke and the long stroke. These are usually applied in one discharge. The important parameters of these test currents are shown in Table A.1.

The parameters I, W/R and Q_{flash} within their tolerances are to be obtained in the same impulse. This can be achieved by an approximately exponentially decaying current with T_2 in the range of 350 μs accompanied by a continuous current supplying the remaining charge.

The specific test currents to be applied are determined by the protection level (LPL) that has been assigned to the part of the blade or other wind turbine structure that is being tested.

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 camera 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, specific energies and charge transfers at applicable test points.

NOTE Indirect effect measurements are sometimes required for electrical systems such as lights, heaters and control sensors that are to be installed in the part being tested (see Clause 8). If required, some of these measurements can be made during the direct effects tests, as long as key waveform parameters such as peak rate of rise, are correct or otherwise accounted for.

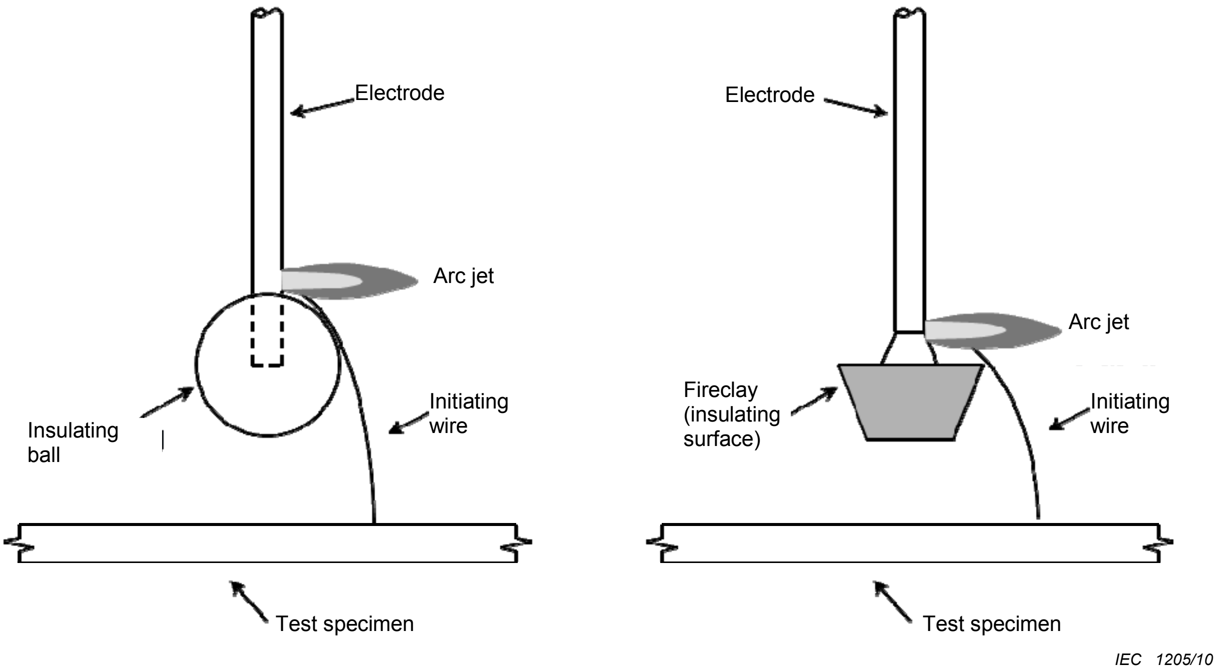


Figure D.10 – Typical jet diverting test electrodes

D.3.2.6 Test procedure

The test procedure is as follows.

a) Measure laboratory environmental conditions.

b) Review and implement safety procedures. Some areas of concern are as follows: Test areas must be safe and clear of personnel prior to charging of test equipment, and capacitor banks must be shorted out prior to entry of personnel into the test area. Eye and ear protection may be required.

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 correct, adjust the generator parameters.
5) Repeat steps 3) through 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) through e).

In general, this test method should at least represent the expected threat from actual lightning attachments to the blade during its service lifetime of e.g. 20 years. Considering the specific energy and the magnetic forces, only the highest current level is of concern, and only a few discharges at this level should be applied (EN 50164-1). 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.

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.3.3 Non-conductive surfaces test

D.3.3.1 Test purpose

This test is applicable to non-conductive surfaces such as wind turbine blade surfaces. This test is used to determine the effects of a lightning channel sweeping over non-conductive surfaces, following correct attachment to the air-termination system.

For non-conductive parts, where a puncture and subsequent attachment to underlying conducting parts could occur (fastening of air termination systems, down conductor systems, etc.), the swept channel attachment test in D.2.2 should also be performed. If puncture occurs during a swept channel attachment test, the design of the structure must be improved to avoid such damage in future tests. This test can be used to assess:

- shock wave and thermal effects to non-conductive surfaces and skins;
- effects of surface arcing on conductive structures embedded in or beneath the blade surface (metallic meshes beneath the surface used as down conductors, CFC located just below the surface, etc.);
- non-conductive surface to frame attachment integrity, in case of structural components supporting the blade skin.

D.3.3.2 Test specimen

Depending on the aim of the test, the test specimen should be a full-scale production item, a representative prototype or a smaller coupon containing the areas of interest. The parts of the blade to be tested would be the areas in the vicinity of air-termination systems (e.g. tip and side receptors), insulating surfaces above CFC and/or conductive metal meshes. The assembly should be sufficiently complete to evaluate possible damage without affecting the test results. If the intent of the test is to compare different designs, all samples should have the same size.

D.3.3.3 Test setup

The test setup is as follows.

- Support the test specimen in a fixture that elevates the specimen to a sufficient distance from other conductive surfaces so that these do not influence the test results. Figure D.11 shows a typical arrangement.

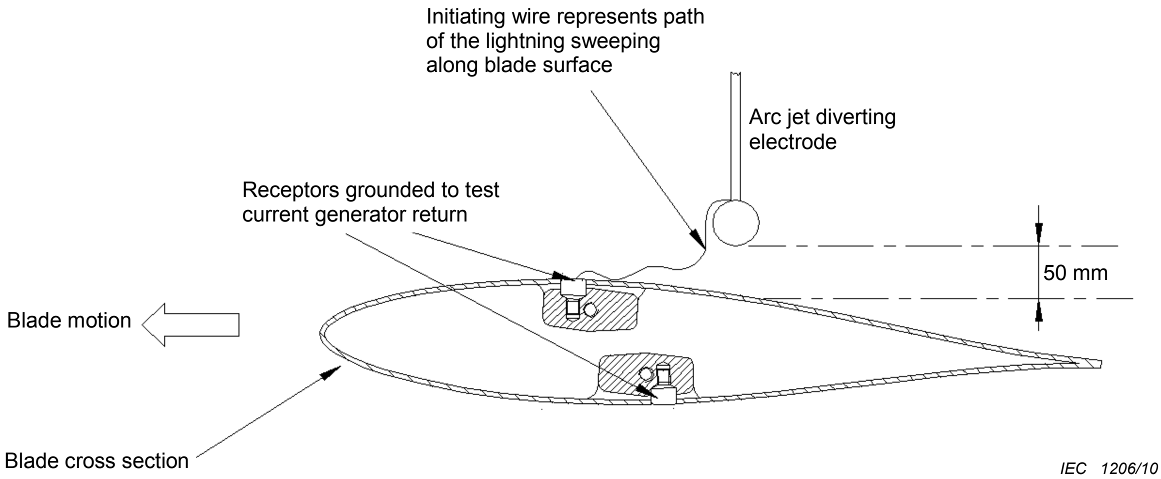


Figure D.11 – High-current test arrangement for non-conductive surfaces

- Ground all hardware to the test specimen structure that is normally grounded.
- Connect the generator return to the test specimen so the lightning currents are conducted away from the test specimen in a manner representative of when the wind turbine blade 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.
- Point a ”jet diverting” electrode (see Figure D.11) 50 mm or more above the area of the test specimen that is to be evaluated.
- Connect the output terminal of the high-current generator to the electrode.
- For this test, either positive or negative polarity can be applied.
- A fine metallic wire, not exceeding 0,1 mm diameter, should be used to direct the arc to a specific point of interest on the test specimen. The initiating wire path should be from the electrode directly across the non-conductive surface along the direction of a swept leader. The initiating wire should be approximately 20 mm above the specimen surface.
- Set up sensing and recording equipment.

D.3.3.4 Test current waveforms

The test currents to be applied are taken from Clause 8 of IEC 62305-1 and are described in D.3.2.4.

D.3.3.5 Measurements 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 camera 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, specific energies and charge transfers at applicable test points.

D.3.3.6 Test procedure

The test procedure is as follows.

a) Measure laboratory environmental conditions.

b) Review and implement safety procedures. Some areas of concern are as follows: Test areas must be safe and clear of personnel prior to charging of test equipment, and capacitor banks must be shorted out prior to entry of personnel into the test area. Eye and ear protection may be required.

c) Calibrate the generator and instrumentation as follows.

   1) Insert a conductive bar over or in place of the test specimen with material properties similar to the test specimen to ensure that a generator discharge will not damage the test specimen.
   2) Connect the bar to the test current generator current return terminal.
   3) Initiate a discharge to the bar while measuring the applied current waveform(s).
   4) If the current level or waveform(s) are not correct, adjust the generator parameters.
   5) Repeat steps 3) through 4) as necessary to obtain the required waveform(s).
   6) Remove the bar.

d) Clean the test specimen to remove dust, debris and other contaminants which could affect test results.

e) Apply the first test to the specimen.

f) Inspect the test specimen and document the results.

g) If required by the test plan, move the electrode to a new position and repeat steps e) and (f).

D.3.3.7 Data interpretation

The test specimen should undergo a thorough post-test evaluation to determine the adequacy of the design with respect to pass/fail criteria. Photographs showing the arc path, entry point(s) and damage areas observed on the test specimen should be reviewed to provide an understanding of damage effects.

D.3.4 Conducted current test

D.3.4.1 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. The test is comparable to the test methods in EN 50164-1 without the conditioning/aging applied. If EN 50164-1 is used for verification of lightning connection components on wind turbines, the current test levels should be selected according to the first short stroke of the selected LPL.

This test can be used to assess:

- lightning current conducting abilities;
- temperature rises in conductors and connections;
- arcing and sparking in bearings, sliding contacts, brushes and general connection components;

- magnetic force effects;
- conducting adequacy of carbon fibre composite materials and interfaces.

D.3.4.2 Test specimen

The test specimen should be a full-scale production item such as sections or sub-sections of lightning conductors or conducting structures that include interfaces between structural members or assemblies, such as 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.

D.3.4.3 Test setup

The test setup is as follows.

- Mount the test specimen in a fixture. Figure D.12 shows a typical arrangement.
- Ground all hardware to the test specimen structure that is normally grounded.
- 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.
- Set up sensing and recording equipment.

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.11 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.3.4.4 Test current waveforms

The test currents to be applied are taken from Clause 8 of IEC 62305-1, and are described in D.3.2.4.

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 cross section of the structure (e.g. two parallel down conductors within a blade)) must be scaled based on the percentage of the specimen cross section to the entire cross section (assuming uniform conductivities). Often this current is increased by up to 50 % to account for possible imbalances in current distribution throughout a structure cross section.

D.3.4.5 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 camera 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, specific energies and charge transfers at applicable test locations.

Other arrangements validated for high current tests, like the crowbar principle, are allowed as well.

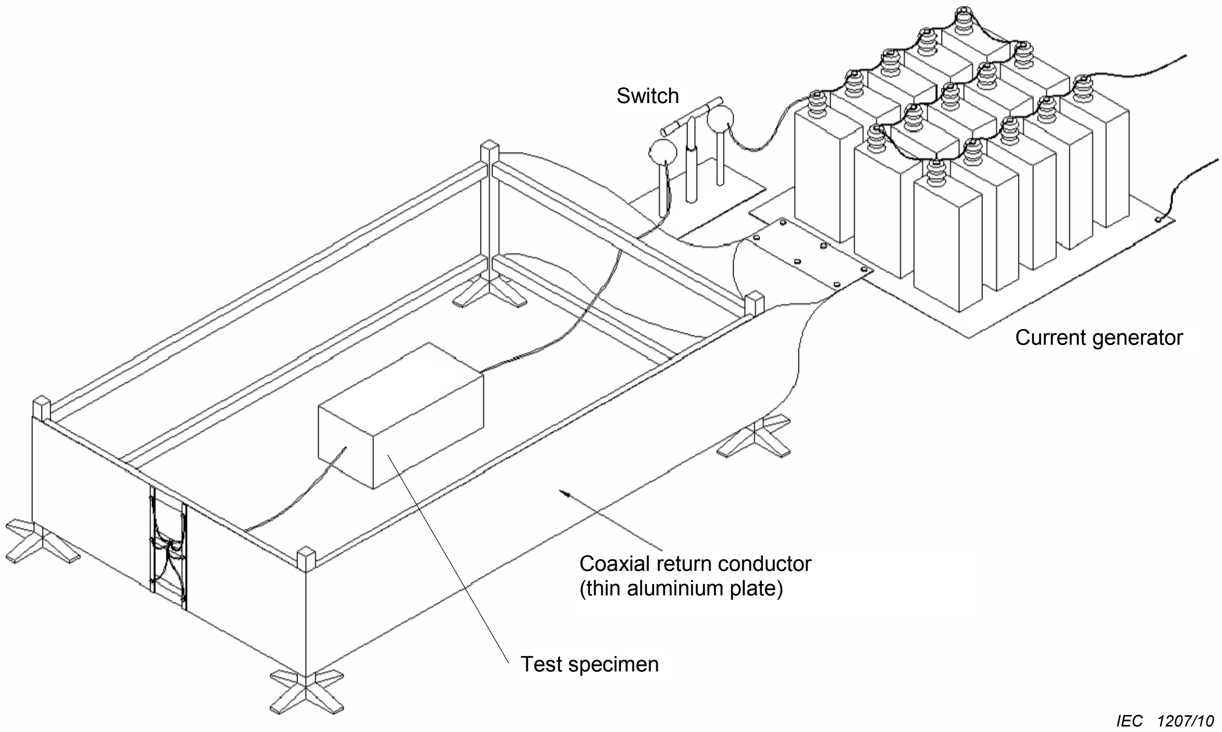


Figure D.12 – Example of an arrangement for conducted current tests

D.3.4.6 Test procedure

The test procedure is as follows.

a) Measure laboratory environmental conditions.

b) Review and implement safety procedures. Some areas of concern are as follows: test areas must be safe and clear of personnel prior to charging of test equipment, and capacitor banks must be shorted out prior to entry of personnel into the test area. Eye and ear protection may be required.

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 correct, adjust the generator parameters.

   4) Repeat steps 2) through 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 which could affect test results.

e) Apply a test to the specimen.

f) Inspect the test specimen and document the results.

g) Repeat steps e) and f) to apply additional tests as called for in the test plan.

NOTE It is often appropriate to apply lower amplitude currents to the test specimen to determine the generator settings necessary to achieve the desired full-scale currents. If this is done, step c) can be omitted.

D.3.4.7 Data interpretation

Test specimens should undergo a thorough post-test evaluation to determine the adequacy of the design with respect to pass/fail criteria.

General pass/ fail criteria are defined in EN 50164-1, which could be adopted.

Annex E
(informative)

Application of lightning protection zones (LPZ) concept at a wind turbine

E.1 Definition of lightning protection zones

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.1 lists the definitions of lightning protection zones according to IEC 62305-1.

Table E.1 – Definition of lightning protection zones according to IEC 62305-1

Outer zones	
LPZ 0	Zone where the threat is due to the unattenuated 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 LPZ 0

The boundary between LPZ 0_A and LPZ 0_B can be determined by means of the rolling sphere model as shown in Figure E.1 (see also IEC 62305-1 and IEC 62305-3). The areas marked in grey are LPZ 0_B where lightning cannot attach, and the rest of the surface of the wind turbine is LPZ 0_A. Locations against which the sphere cannot roll are protected against direct lightning attachment. As can be seen, lightning may attach to most of the surface of the wind turbine – such areas are consequently LPZ 0_A. Computer models can also be used; these models will typically be based on the rolling sphere method. 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. At the foot of the wind turbine there is also an LPZ 0_B where a transformer kiosk, if any, will 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 must be verified according to 8.2.3.

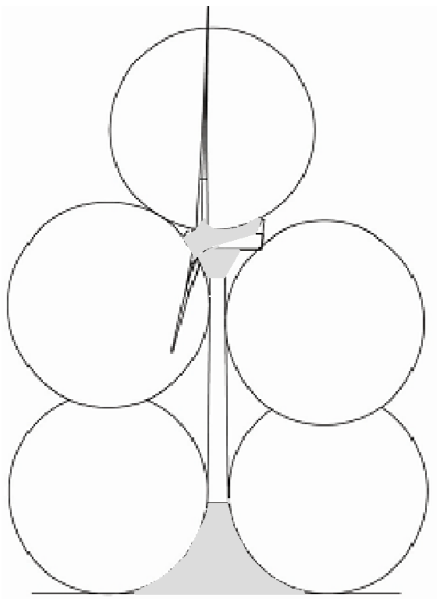


Figure E.1 – Rolling sphere model

E.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.2 and E.3). 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.5 and E.6 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 transformer 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 (Note 1).

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 (Note 1). 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) must be reduced to in that zone. Therefore, no specific values of current, voltage and electromagnetic field in each zone are recommended in 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.

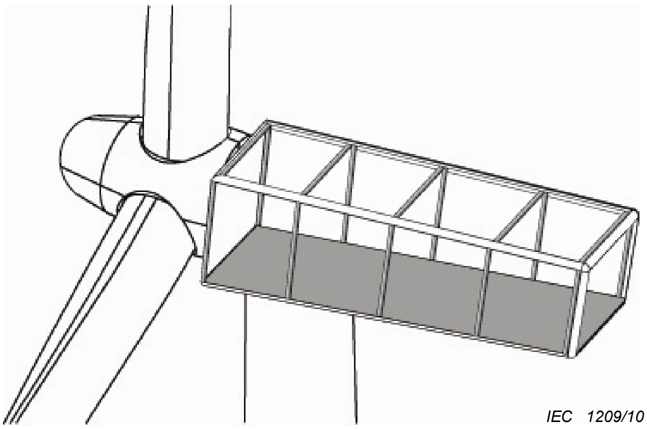


Figure E.2 – Mesh with large mesh dimension for nacelle with GFRP cover

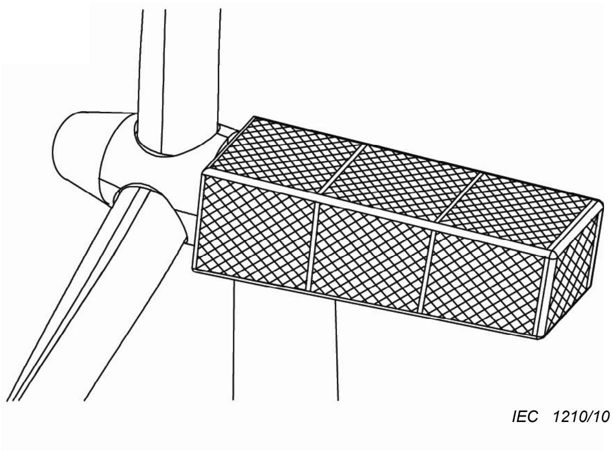


Figure E.3 – Mesh with small mesh dimension for nacelle with GFRP cover

E.4 Zone boundaries

At each zone boundary, it must 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 which must 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.4). 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.

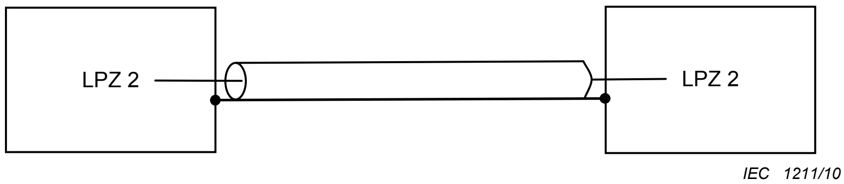


Figure E.4 – Two cabinets both defined as LPZ 2 connected via the shield of a shielded cable

E.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, test and verification must be made and documented.

Protection may be achieved by using coordinated SPDs, by using shielded cables, by using shielding cable routes, or combinations thereof as needed).

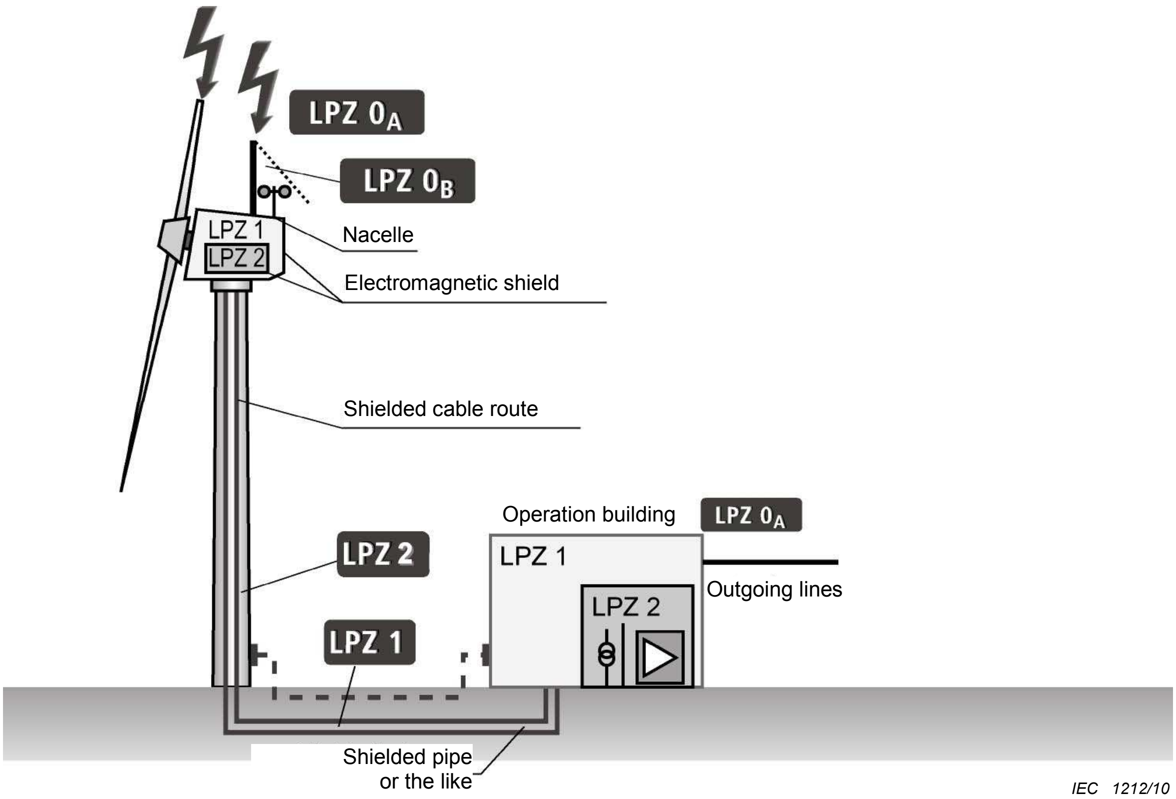


Figure E.5 – Example: Division of wind turbine into different lightning protection zones

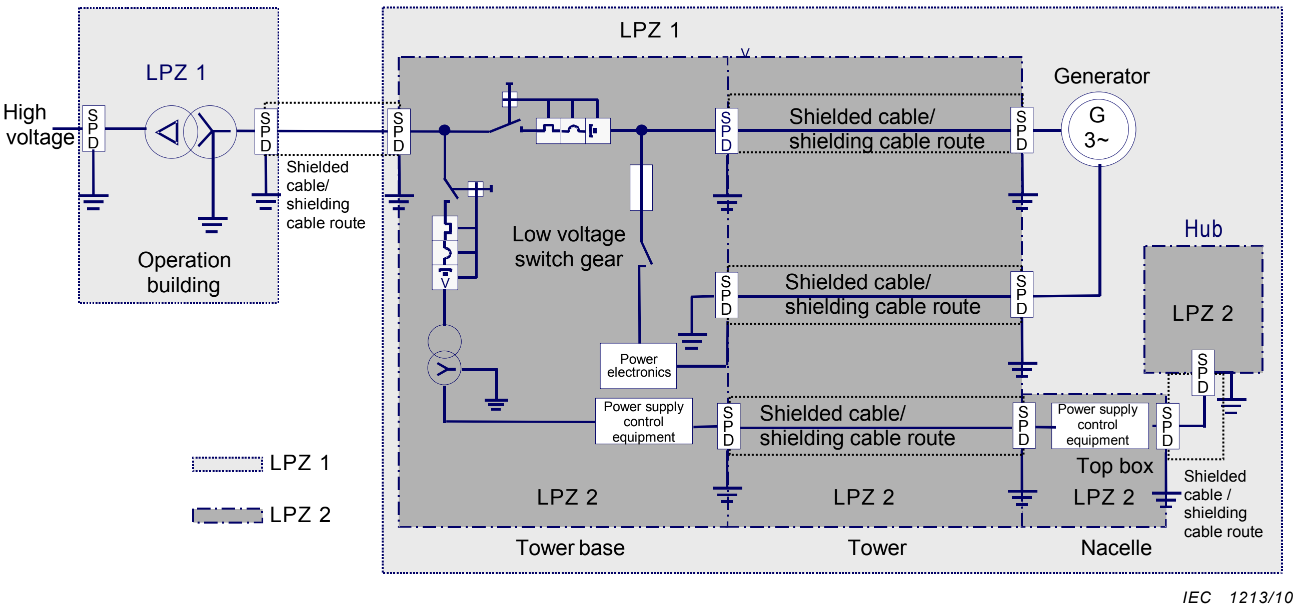


Figure E.6 – Example of how to document LPMS division of electrical system into protection zones with indication of where circuits cross LPZ boundaries and showing the long cables running between tower base and nacelle

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 due 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.

Clause D.2.3 of IEC 62305-4 describes the oscillation protection distance. 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.

Clause D.2.4 of IEC 62305-4 describes the problem of induction protection distance. 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.

Due to overvoltages, which are caused e.g. 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 61643-1 and IEC 61643-21.

F.3 Installation of SPDs

With the 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;
- the so-called point-to-point installation scheme must be according to Figure F.1;

- earthing connections 5a and 5b must be according to Figure F.2.

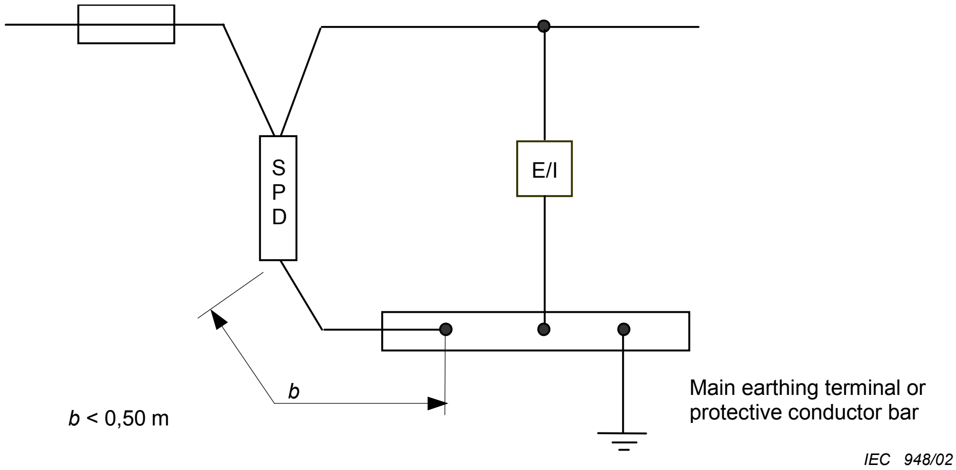


Figure F.1 – Point-to-point installation scheme (Figure 53E in IEC 60364-5-53)

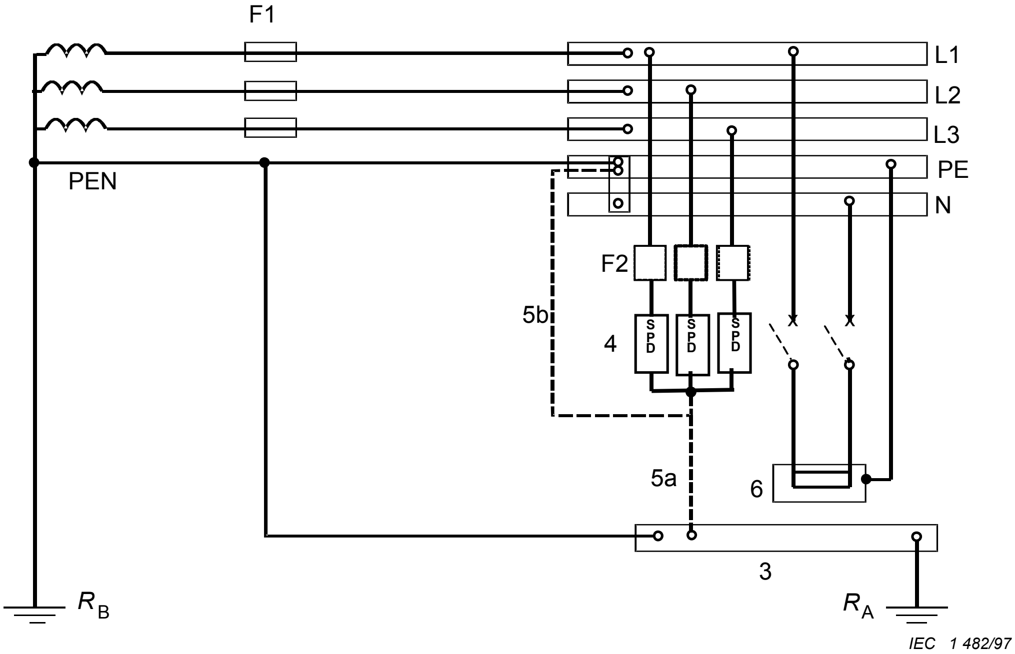


Figure F.2 – Earthing connection installation scheme (Figure A.1 in IEC 60364-5-53)

F.4 Environmental stresses of SPDs

IEC 61643-1 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 must be between 30 % and 90 %;
- IEC 61643-1 does not at this time include requirements for vibration.

If the actual environmental stress of the SPDs installed in wind turbines exceeds the values given in IEC 61643-1, appropriate test methods and stress values of the IEC 60068 series shall be applied. The manufacturer of the wind turbine shall 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 due to exceptional high lightning currents or due to repetitive stress. Furthermore, critical parts of the electrical and control systems of wind turbines such 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 provided e.g. by:

- a system to monitor the SPDs;
- signalling and control mechanism within the SPD to give warning against upcoming SPD failures;
- 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, 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 life time of SPDs in 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 8.5.6.10. This kind of equipment is classified as externally installed equipment, according to IEC 62305-4, Clause B.9.

A typical example of externally installed equipment in wind turbines is wind measuring systems etc.

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 according to both SPD Class I and SPD Class II, the rating of I_n and of I_{imp} should be in agreement with the values in Table F.1 and 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 depend on the number of parallel paths between witch the current is shared and the impedances of the individual paths – IEC 62305-1 Annex E provides guidance on how to do the calculation.

Annex G
(informative)

Additional 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 [H/m] is the inductance of the conductor;

$\mathrm{d}i/\mathrm{d}t$ [A/s] is the maximum rate of change of lightning current.

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.

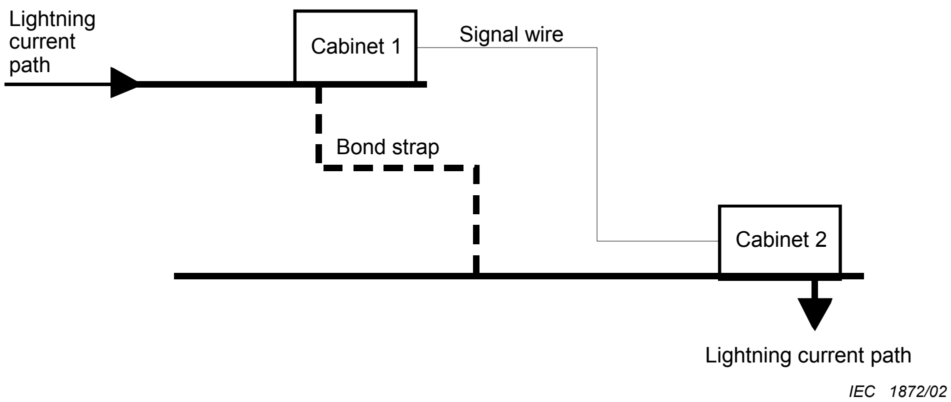


Figure G.1 – Two control cabinets located on different metallic planes inside a nacelle

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.

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 regarding LEMP protection

Detailed information regarding spatial shielding, line routing and line shielding is given in IEC 62305-4, Subclause A.2.1.

In general, the transient voltage and current withstand levels (immunity) of the equipment should be documented by testing according to 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. Furthermore, the insulation withstand levels of the wiring etc. needs to be documented according to the insulation coordination standard IEC 60664-1.

G.3 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 must 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).

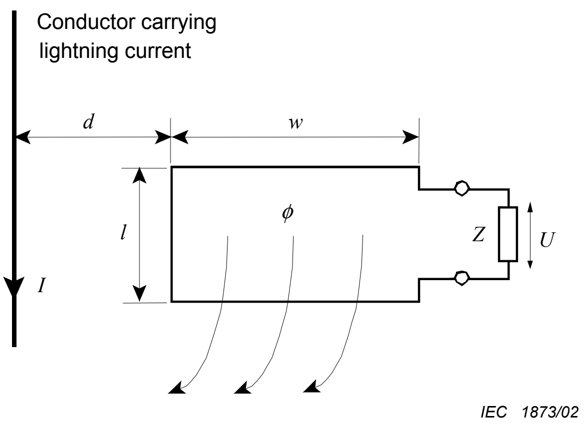


Figure G.2 – Magnetic coupling mechanism

This can be expressed in the following formulae:

$$U = -\frac{\mathrm{d}\phi}{\mathrm{d}t} \tag{G.2}$$

where

ϕ [Wb] is flux linkage;

U [V] is the voltage induced in the loop.

It can be shown that the total flux passing through the loop is:

$$\phi = \frac{\mu_0 l \cdot I}{2\pi}\left[\ln\left(\frac{d+w}{d}\right)\right] \tag{G.3}$$

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 [H/m] is the mutual inductance between the loop and the current-carrying conductor.

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. The shield must be correctly bonded (360° connection to the equipment chassis) in both ends to work as expected.

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 must 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.

If the signal in the shielded cables is too sensitive, it can be necessary to protect the wire with a SPD.

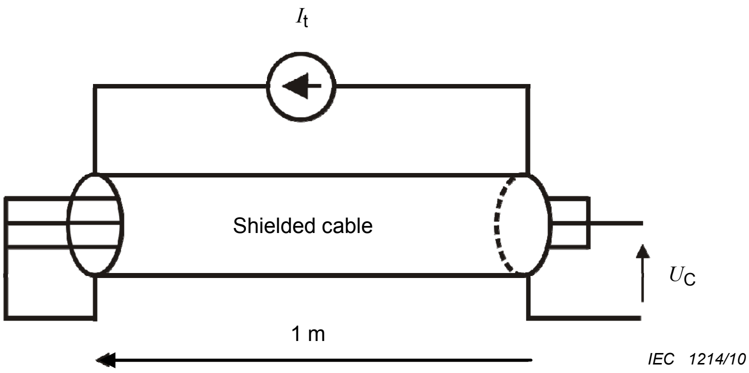


Figure G.3 – Measuring of transfer impedance

Measuring of the transfer impedance can be done according to 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:

$$Z_T = \frac{U_c}{I_t} \qquad (G.6)$$

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 [V] is the voltage between shield and wires;

l [m] is the length of cable;

I_t [A] is the current in the shield;

Z_T [Ω] is the transfer impedance.

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.

In case 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 connection 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 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).

Annex H
(informative)

Testing methods for system level immunity tests

The following testing methods apply for system level immunity tests.

– SPD discharge current test under service conditions:

a) Prior to the system level immunity test:
The equipment to be protected, the immunity of which has to be determined by applying the methods according to IEC 61000-4-5.
The protective effect of the SPDs has to be determined with test procedures according to IEC 61643-1.

b) 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 nominal discharge current parameters of the installed SPDs. Where applicable, additional circuits, such as communication lines, sensors, motors must be connected.

c) Figure H.1 gives an example circuit of a SPD discharge current test under service conditions including SPDs class II and a pitch control system of a wind turbine.

– Induction test due to lightning currents:

a) Impulse currents shall 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.

b) The system under test must be installed as realistically as possible.
This simulated installation must include individual equipment, all installed SPDs and the real length and type of the interconnection lines.

c) The resulting induced impulse currents within the cabling of the complete system shall be monitored.

d) The characteristic and applicable values of the primary lightning currents shall be derived from IEC 62305-1, Table C.3.

e) Figure H.2 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.

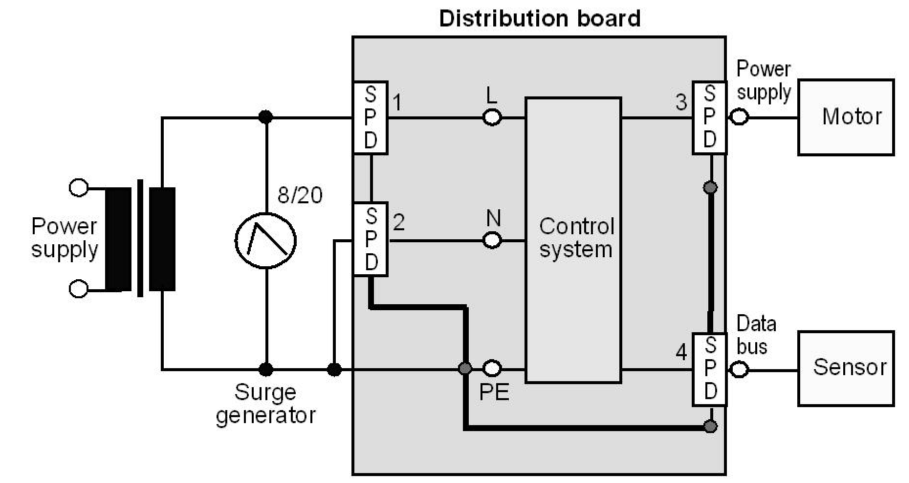
– Recommended test classification of system level immunity test (following IEC 61000-4-5):

a) Normal performance within limits specified by the manufacturers.

b) 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.

c) Temporary loss of function or degradation of performance, the correction of which requires operator intervention.

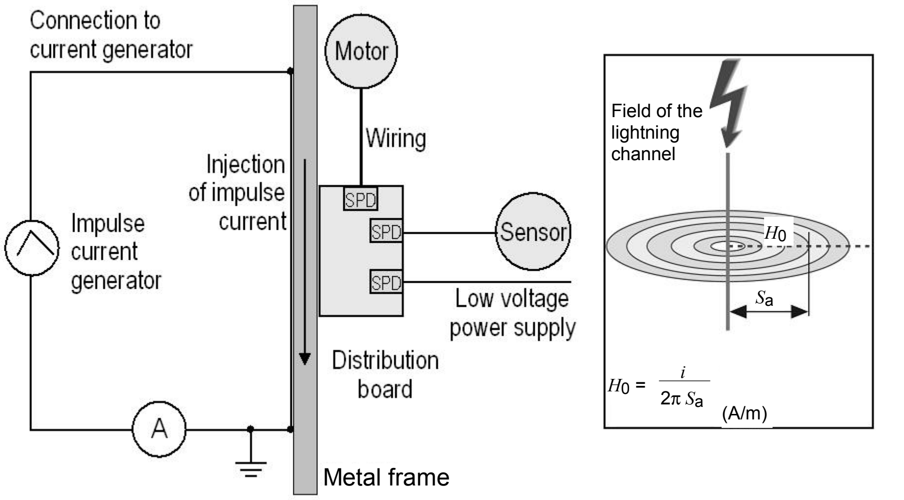
d) Loss of function or degradation of performance which is not recoverable owing to damage to hardware or software or loss of data.



SPD1 + SPD2 + SPD3: Surge protective device for power circuits
SPD4: Surge protective device for telecommunications and signalling networks

IEC 1215/10

Figure H.1 – Example circuit of a SPD discharge current test under service conditions



IEC 1216/10

Figure H.2 – Example circuit of an induction test due to lightning currents

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 which incorporates large amounts of steel in large dimensions. The steel in the foundation structure shall 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 shall select suitable types of earth electrodes. The LPS designer and the LPS installer shall 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 must 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, Subclauses 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 shall be used for wind turbines.

NOTE 2 For further information on type B arrangements, see IEC 62305-3, Subclauses 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 which 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.

Metals used for earth electrodes shall conform to the materials listed in IEC 62305-3, Table 7, and the behaviour of the metal with respect to corrosion in the soil must always be taken into account. Some guidance is given in IEC 62305-3, Subclause 5.6. 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 must 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 must 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 shall 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, Table 7 must 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 must be sufficiently separated from existing cables, metal pipes, etc. in the earth, and due allowance must 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 shall 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 surface and thus lower step voltages reducing the danger to living beings on the earth 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 shall be provided. More ring earth electrodes shall be installed at reasonable distances from the first and subsequent ring conductors. These ring earth electrodes shall 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 shall 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 shall, 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 shall 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 shall 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 shall 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.

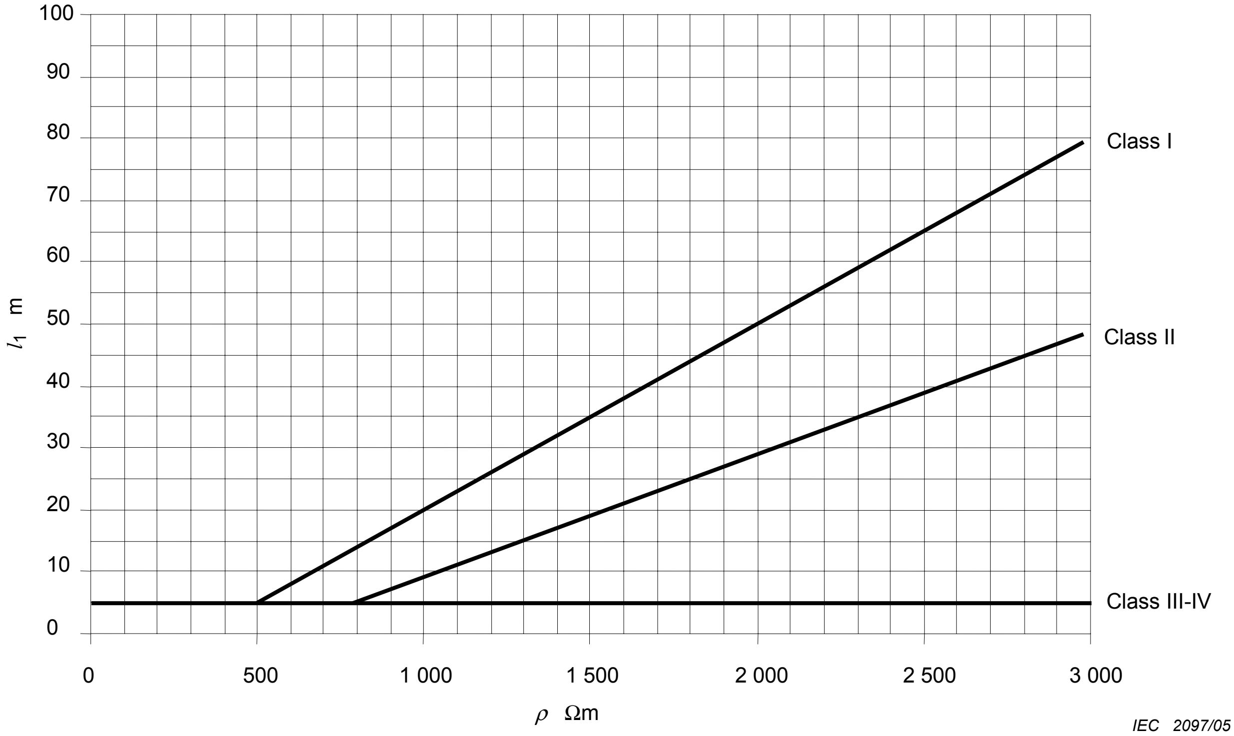


Figure I.1 – Minimum length (l_1) of each earth electrode according to the class of LPS (Figure 2 in IEC 62305-3)

Due 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) shall 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 shall 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 shall be not less than two.

The additional electrodes should be connected as equidistantly as possible.

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 case 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 shall 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 due 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 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.

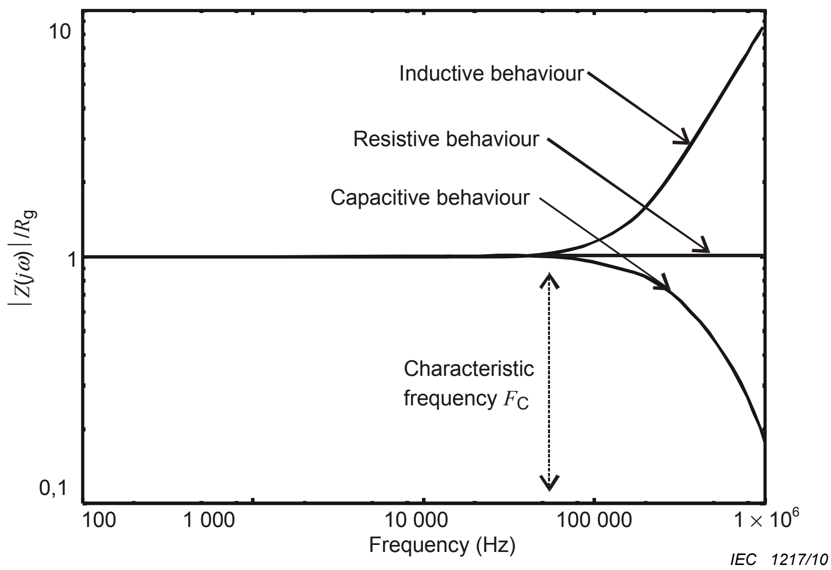


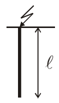
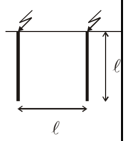
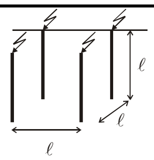
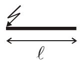
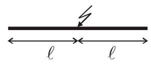
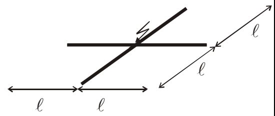
Figure I.2 – Frequency dependence on the impedance to earth (adapted from Cigré WG C.4.4.02 July 2005 [49]**)**

Figure I.2 shows typical dependence on the impedance to earth, the ratio of the impedance modulus ($Z(\mathrm{j}\omega)$) 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 system with few long electrodes is mostly inductive behaviour. The use of multiple earthing arrangements 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 %) (adapted from Cigré WG C.4.4.02 July 2005)

Ground rod arrangement						
Percentage	100	95	85	85	80	70

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 case such tools are not available, the formulae for simple earthing electrode configurations and combinations listed in the following Tables I.2 to 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	3,1415

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} $$R=\frac{\rho}{2\pi L}\left(\ln\frac{4L}{\sqrt{aa_{12}}}-1\right) \quad \text{I.7}$$ 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	$R_1 = \frac{\rho}{\pi^2 D} \ln \frac{4D}{\sqrt{2ad}}$	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	$R_2 = \frac{\rho}{2n\pi L}\left(\ln \frac{4L}{a} - 1 + \frac{L}{D} \sum_{m=1}^{n-1} \frac{1}{\sin\left(\frac{\pi m}{n}\right)} \right)$	I.13
Mutual earthing resistance between the ring electrode and the n of ground rods arranged on a circle of diameter D	$R_3 = \frac{\rho}{\pi^2 D} \ln \frac{4D}{\sqrt{2 \frac{L}{e} d}}$	I.14
Combined resistance	$R = \frac{R_1 R_2 - R_3^2}{R_1 + R_2 - 2R_3}$	I.15

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

Annex J
(informative)

Example of defined measuring points

An example of the definition of measuring points is given in Figure J.1.

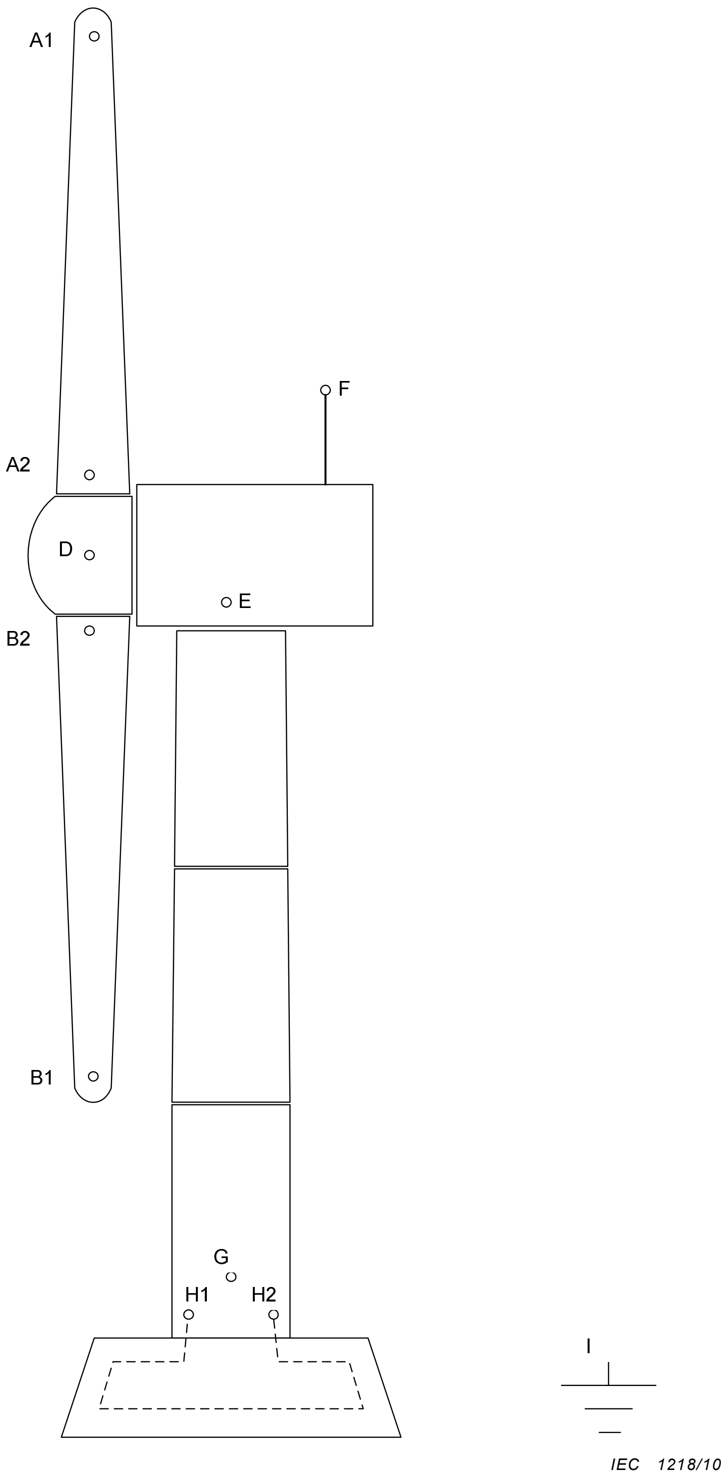


Figure J.1 – Example of measuring points

Following this example, the following measurements can be performed (see Table J.1):

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 A	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	

Annex K
(informative)

Typical lightning damage 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:

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. Suspected lightning attachment point(s):

❍ Blades ❍ Nacelle ❍ Meteorological equipment ....
❍ Tower ❍ Nacelle lightning conductor ❍ Other: ....
❍ Other comments:

8. 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:

9. Consequences of lightning damage:

❍ Lost production time: .... hours ❍ Repair costs (state currency): ....
❍ Cost of lost electrical production (state currency): ....
❍ Other comments:

10. Turbine lightning protection system details (except blades):

❍ None ❍ Ring earth electrode ❍ Foundation earth electrode

❍ Air termination system (type/location):

❍ Down conductors (type/location):

Overvoltage/surge protection:

❍ None ❍ Incoming power connection

❍ Generator ❍ External data lines

❍ Internal control lines ❍ Telephone lines

❍ Other comments:

11. 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

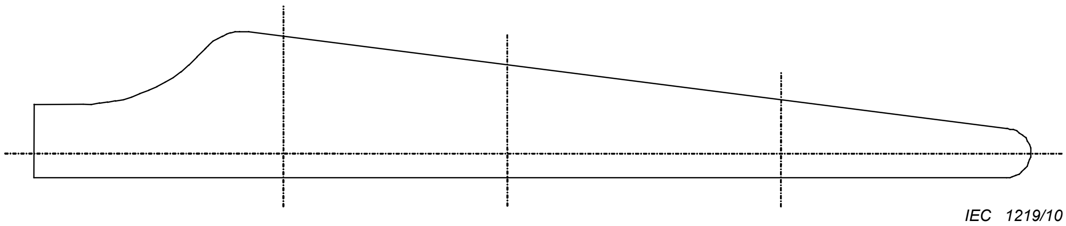
❍ Crack in blade face (length): .... ❍ Crack in blade edge (length): ....

❍ Other: ....

❍ Other comments:

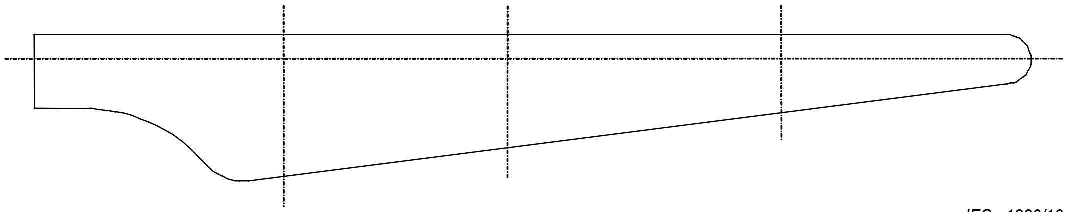
Please mark the locations where damage has been observed on the blade (see Figure K.1):

❍ Windward side:



IEC 1219/10

❍ Leeward side:



IEC 1220/10

Figure K.1 – Blade outlines for marking locations of damage

Annex L
(informative)

Monitoring systems

It is recommended that wind turbines are 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 play a part in operation and maintenance regimes;
- provide valuable data on the expected number of lightning strikes to tall wind turbines and to assess their magnitude/characteristics, aiding in future 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. These use multiple antennae to locate lightning flashes based on direction finding or time of arrival techniques. Data from these systems is generally available in real time. The data output will not normally allow exact lightning flash to be pinpointed as the accuracy of such systems can be limited to from a few hundred metres to a few kilometres (the accuracy depends on the relative location of the lightning flash to the antennae and its magnitude). Such a system is therefore only of real use in confirming whether damage to a wind turbine was caused by lightning.

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 magnetic field criteria. The antennae prevent 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 strike to a wind turbine. It is, however, a good option for an operator who wishes to be proactive in monitoring wind turbines after a lightning storm.

Other developers have produced sensors that allow current transducers to be fitted directly into blades or on other lightning down conductors. Through the use of a transducer such as a rogowski coil or a fibre optic based technique, these sensors can both provide an alarm functionality and collect valuable peak current/waveform data for use in future risk assessment studies.

c) Local passive lightning detection systems

Peak current sensor (PCS) cards have a magnetic strip with a pre-defined field pattern. They are clamped to a down-conductor, and the pre-defined pattern is partially erased by the magnetic field of the current flowing through the wire. The higher the lightning current, the higher the magnetic field around the down conductor and the more of the pre-defined field pattern that is erased/distorted. This form of system typically claims to have a detection range of 3 kA to 120 kA with results deviating not more than ±2 kA. The cards only record peak currents and have the capability of storing only one such reading. Thus, in the event of multiple lightning strokes, only the highest peak current among all the strokes is stored. There is no time reference and they cannot be interfaced into a SCADA system or similar.

Annex M
(informative)

Guidelines for small wind turbines – Microgeneration

This standard is developed for use with industrial-scale wind turbines. These can be typified by certain features: power generation capacity greater than 100 kW, mounted on towers taller than 30 m, with a nacelle housing the generator, control and converter systems and blades longer than 10 m.

Below this size, there is a class of wind turbine 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 environments for these two distinct types of wind generators are very different and therefore the requirements and guidelines for lightning protection will also be quite different.

The issue of lightning protection must still be considered for small-scale 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-scale systems 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 damage to people or 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 standard does not cover lightning protection of small-scale 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.

Bibliography

[1] RAKOV V.A., UMAN, M.A. *Lightning Physics and Effects*. Cambridge University Press, 2003, ISBN 0 521 58327

[2] BERGER, K., ANDERSON R.B., and KRONINGER, H. *Parameters of lightning flashes*. Electra, Vol. 80, pp. 23-37, 1975

[3] ANDERSON, RB., and ERIKSSON AJ. *Lightning parameters for engineering applications*. Electra Vol. 69, pp. 65-103, 1980

[4] WADA, A., YOKOYAMA, S., NUMATA, T., ISHIBASHI, Y., HIROSE, T. *Lightning Damages of Wind Turbine Blades in Winter in Japan – Lightning Observation on the Nikaho-Kogen Wind Farm*, Proceedings of the 27th International Conference on Lightning Protection, Avignon , France, pp. 947-952, 2004.

[5] JANISCHEWSKYJ, W., HUSSEIN, AM., SHOSTAK, V., RUSAN, I., Li, JX., and CHANG, JS. *Statistics of lightning strikes to the Toronto Canadian National Tower* (1978-1995). IEEE Power Engineering Summer Meeting, Denver, Colorado, 1996

[6] HOPF, C., and WIESINGER, J. *Lightning protection of wind power plants.* Elektrizitaets-wirtschaft, Vol. 94, no. 15, July 1995, pp. 921-5

[7] FUCHS, F., LANDERS, EU., SCHMID, R., and WIESINGER, J. *Lightning Current and Magnetic Field Parameters Caused by Lightning Strikes to Tall Structures Relating to Interference of Electronic Systems.* IEEE Transactions on Electromagnetic Compatibility, Vol. 40, Nov. 1998

[8] ERIKSSON, AJ. and MEAL, DV. *The Incidence of Direct Lightning Strikes to Structures and Overhead Lines*. IEE-Conference on Lightning and Power Systems. IEE-Conference Publications 236, pp. 67-71, 1984

[9] TSUCHIYA, K., YAMADA, S., and MATSUZAKA, T. *A Study of Lightning Damage to WECs with Artificial Lightning Strokes. Wind Energy: Technology and Implementation*, pp. 737-741. Amsterdam EWEC '91. Elsevier Science Publ., 1991

[10] FISHER, F.A., PLUMER, J.A. and Perala, R.A. *Lightning Protection of Aircraft*. Second edition. Lightning Technologies Inc., Pittsfield, MA, USA, 2004

[11] GEWEHR, HW. *Lightning Protection for Composite Rotor Blades*. American Wind Energy Association. Nat. Conf. Pittsburgh PA, USA, June 8-11, 1980

[12] DALÉN, G. *Lightning Protection of Large Rotor Blades, Design and Experience*. IEA R&D Wind, ANNEX XI, 26th Meeting of Experts. Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems. Cologne Monzese, Milan, Italy, March 8-9, 1994

[13] DODD, C W., MCCALLA, T. Jr., and SMITH, JG. *How to Protect a Wind Turbine from Lightning*. Windbooks. P.O.Box 4008, St. Johnsbury, VT, USA. ISBN:0-88016-072-1

[14] DODD, CW., MCCALLA, TM. Jr. and SMITH, JG. *Design Considerations for Lightning Protection of Wind Turbines*, Sixth Biennial Wind Energy Conference and Workshop. pp. 687-695. American Solar Energy Society, 1983

[15] SCHMID, R. *Investigations on GRP-Rotor Blade Samples of Wind power Plants Regarding Lightning Protection*. 24th Int. Conf. on Lightning Protection, pp. 955-959, Birmingham UK, 14th-18th September 1998

[16] NIELSEN, JO., and PEDERSEN, AA. Status Report for the Pilot Project: Lightning protection for Wind Turbines – Especially Non-conducting Wind Turbine Blades. Technical University of Denmark, December 1994. (in Danish)

[17] DRUMM, F. Investigation into Segmented Diverter Strips. 23rd ICLP, Int. Conf. on Lightning Protection. pp. 796-800, Florence, Italy, Sep. 23-27, 1996

[18] DRUMM, F., and BÄUML, G. Isolation Coordination of Segmented Diverter Strips and Their Current Capability. 24th Int. Conf. on Lightning Protection, pp. 918-923, Birmingham UK, 14th-18th September 1998

[19] SORENSEN, T., BRASK, MH., OLSEN, K., OLSEN, ML., and GRABAU, P. 24th Int. Conf. on Lightning Protection, pp. 938-943, Birmingham UK, 14th-18th September 1998

[20] FAA *Fundamental Considerations of Lightning Protection, Grounding, Bonding, and Shielding*, Federal Aviation Administration, 6950.20, 1978

[21] GONDOT, P., LEPETIT, B., BISIAEV, A., and SOLOLEVSAKIA, H. *Lightning Protection of Aeronautical Structural Materials*. 23rd ICLP, Int. Conf. on Lightning Protection. pp. 563-568, Florence, Italy, Sep. 23-27, 1996

[22] MULJADI, E., and BUTTERFIELD, CP. *Lightning and the Impact on Wind Turbine Generation*. IEA R&D Wind, ANNEX XI, 26th Meeting of Experts. Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems. Cologne Monzese, Milan, Italy, March 8-9, 1994

[23] WACHSMUTH, R. *Rotorblatt in Faserverbundbauweise für Windkraftanlage* AEOLUS II, Phase I/II, Statusbericht für das Jahr 1990 zum Forschungsvorhaben 0328819 A/B des Bundesministeriums für Forschung und Technologie. Statusreport 1990 Windenergie, pp. 279-297, Bundesministerium für Forschung und Technologie, 1990, ISBN 3-8042-0517-8

[24] COTTON, I., JENKINS, N., HATZIARGYRIOU, N., LORENTZOU, M., HAIGH, S., and HANCOCK, M. *Lightning Protection of Wind Turbines – A designer's Guide to Best Practice*. UMIST – Preview edition – January 1999

[25] BALDWIN, RE. *Experience gained in the lightning protection of aircraft and petrochemical installations applicable to wind turbine generators*. IEA R&D Wind, ANNEX XI, 26th Meeting of Experts. Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems. Cologne Monzese, Milan, Italy, March 8-9, 1994

[26] HANSEN, L.B., KORSGAARD, J. and MORTENSEN, I., *Improved lightning protection system enhances the reliability of multi-MW blades.* Copenhagen Offshore Wind 2005

[27] MADSEN, S.F., *Interaction between electrical discharges and materials for wind turbine blades particularly related to lightning protection.* Ørsted-DTU, The Technical University of Denmark, Ph.D. Thesis, March 2006

[28] LARSEN, F.M and SORENSEN, T., *New lightning qualification test procedure for large wind turbine blades.* Proceedings of International Conference on Lightning and Static Electricity, Blackpool, UK, 2003

[29] LENNING, F.E., *Analysis of lightning current flow in anisotropic CFRP using finite difference methods*, Proceedings of International Conference on Lightning and Static Electricity, Blackpool, UK, 2003

[30] MADSEN, S.F., HOLBOLL, J., HENRIKSEN, M., BERTELSEN, K., ERICHSEN, H.V., *New test method for evaluating the lightning protection system on wind turbine blades*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[31] HEATER, J., RUEI, R., A *Comparison of Electrode Configurations for Simulation of Damage Caused by a Lightning Strike,* Proceedings of International Conference on Lightning and Static Electricity, Blackpool, UK, September 2003

[32] BECERRA, M., V. COORAY, *A simplified Physical Model to Determine the Lightning Upward Connecting Leader Inception*, IEEE Transactions on Power Delivery, Vol. 21, No. 2, April 2006

[33] BERTHELSEN, K., ERICHSEN, H.V., SKOV JENSEN, M.R.V., MADSEN, S.F., *Application of numerical models to determine lightning attachment points on wind turbines*, Proceedings of International Conference on Lightning and Static Electricity, Paris, France, August 2007

[34] BERTHELSEN, K., ERICHSEN, H.V., MADSEN, S.F., *New high current test principle for wind turbine blades simulating the life time impact from lightning discharges*, Proceedings of International Conference on Lightning and Static Electricity, Paris, France, August 2007

[35] HOLBOELL, J., MADSEN, S.F., HENRIKSEN, M., BERTELSEN, K., *Discharge phenomena in the tip area of wind turbine blades and their dependency on material and environmental parameters*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[36] SHITAISHI, Y., OTSUKA, T., MATSUURA, H., *The Observation of Direct Lightning Stroke Current to the Wind Turbine Generator System.* Proceedings of the 27th International Conference on Lightning Protection, Avignon, France, pp. 947-952, 2004.

[37] VASE, N.J., NAKA, T., YOKOYAMA, S., WADA, A., ASAKAWA, A., ARINAGA, S., *Experimental study on lightning attachment manner considering various types of lightning protection measures on wind turbine blades*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[38] ARINAGA, S., TSUTSUMI, K., MURATA, N., MATSUSHITA, T., SHIBATA, M., INOUE, K., KORAMATSU, y., UEDA, Y., SUGURO, Y., YOKOYAMA, S., *Experimental study on lightning protection methods for wind turbine blades*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[39] HANAI, M., KOUAMA, H., KUBO, N., HASHIMOTO, Y., SUZUKI, I., UEDA, Y., SAKAMOTO, H., *Reproduction and Test Method of FRP Blade Failure for Wind Turbine Generators Caused by Lightning*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[40] SAKAMOTO, H., KUBO, N., HASHIMOTO, Y., SUZUKI, I., UEDA, Y., HANAI, M., *Lightning Failure Protection of FRP blade for Wind Power Generators*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[41] SAKURANO, H., HASHIMOTO, M., NAKAMURA, K., *Observation of Winter Lightning Striking a Wind Power Generation Tower and a Lightning Tower*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[42] LEWKE, B., KRUG, F., KINDERSBERGER, J., *Risk of Lightning Strike to Wind Turbines for Maintenance Personnel Inside the Hub*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[43] BIRKL, J., FREY, C., ZAHLMANN, P., *How to verify lightning protection efficiency for wind turbines? Testing procedures for lightning protection components*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[44] MINOWA, M., MINAMI, M., YODA, M., *Research into Lightning Damages and Protection Systems for Wind Power Plants in Japan*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[45] YASAMUDA, Y., YOSHIOKA, T., UEDA, T., *FDTD Analysis on Wind Turbine Earthing*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[46] YASUDA, Y., UNO, N., KOBAYASHI, H., FUNABASHI, T., *Surge Analysis on Wind Farm at Winter Lightning Stroke*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[47] SUMI, S.I., AICHI, H., HORII, K., YODA, M., MINAMI, M., MINOWA, M., *Breakdown Tests of Wind Turbine Blade for Improved Lightning Protection*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[48] SHIRASHI, Y., OTSUKA, T., *The Observation and a Study of Direct Lightning Stroke Current through the Wind Turbine Generator System*, Proceedings of the 28th International Conference on Lightning Protection, Kanazawa, Japan, 18-22 September 2006.

[49] Cigré WG C.4.4.02, *Protection of MV and LV networks against lightning, Part 1: Common topics*, July 2005

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
www.iec.ch