Lightning protection as part of wind turbines foundation design

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DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service
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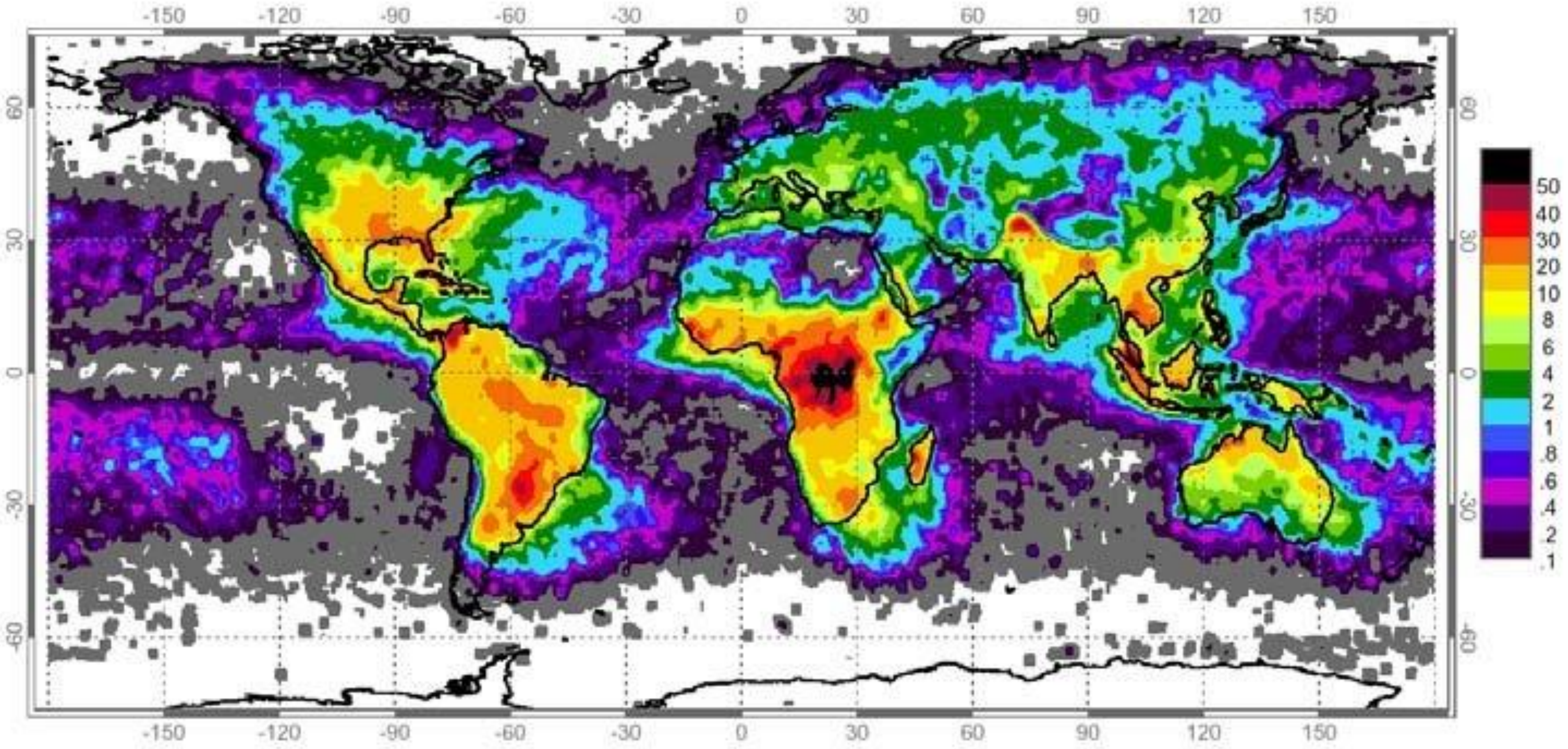
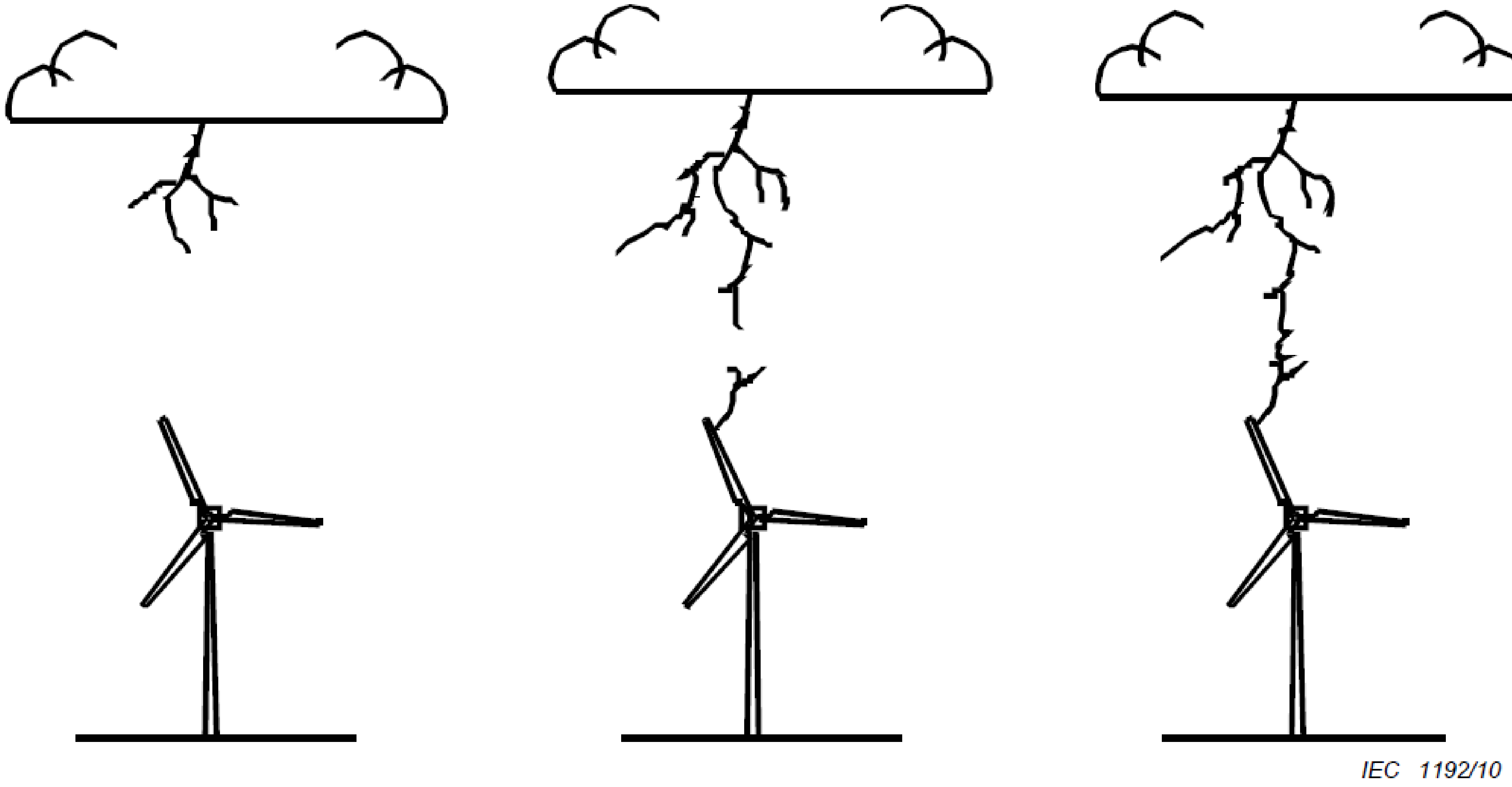
UNIVERSITY OF PATRAS

- ✓ Lightning strike formation and electrical parameters.
- ✓ Standards relating to lightning protection of wind turbines.
- ✓ Damage in wind turbines components due lightning strike.
- ✓ Wind turbine electrical grounding.
- ✓ Safety against touch and step voltages.

Global thunder day map



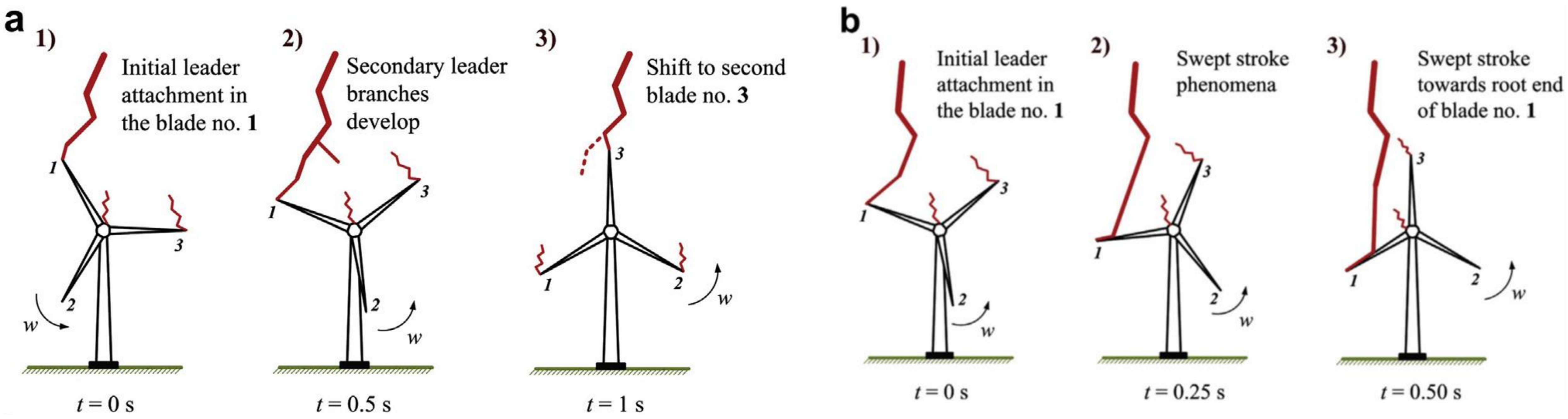
Lightning strike formation and electrical parameters.



Processes involved in the formation of a cloud-to-ground flash

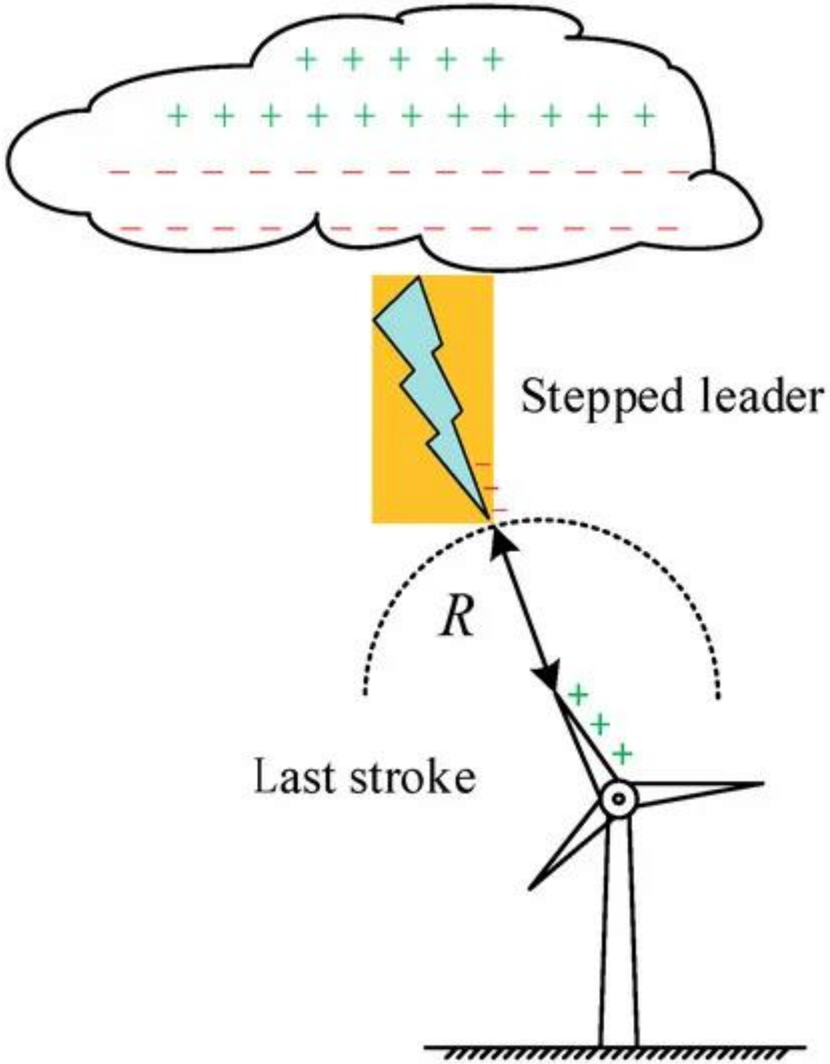
Influence of blade rotation on the lightning stroke characteristic of a wind turbine, DOI: 10.1002/we.2341

Lightning strike formation and electrical parameters.



Impact of wind turbine blade rotation on the lightning strike incidence A theoretical and experimental study using a reduced-size model ELSEVIER Energy 45 (2012) 644e654

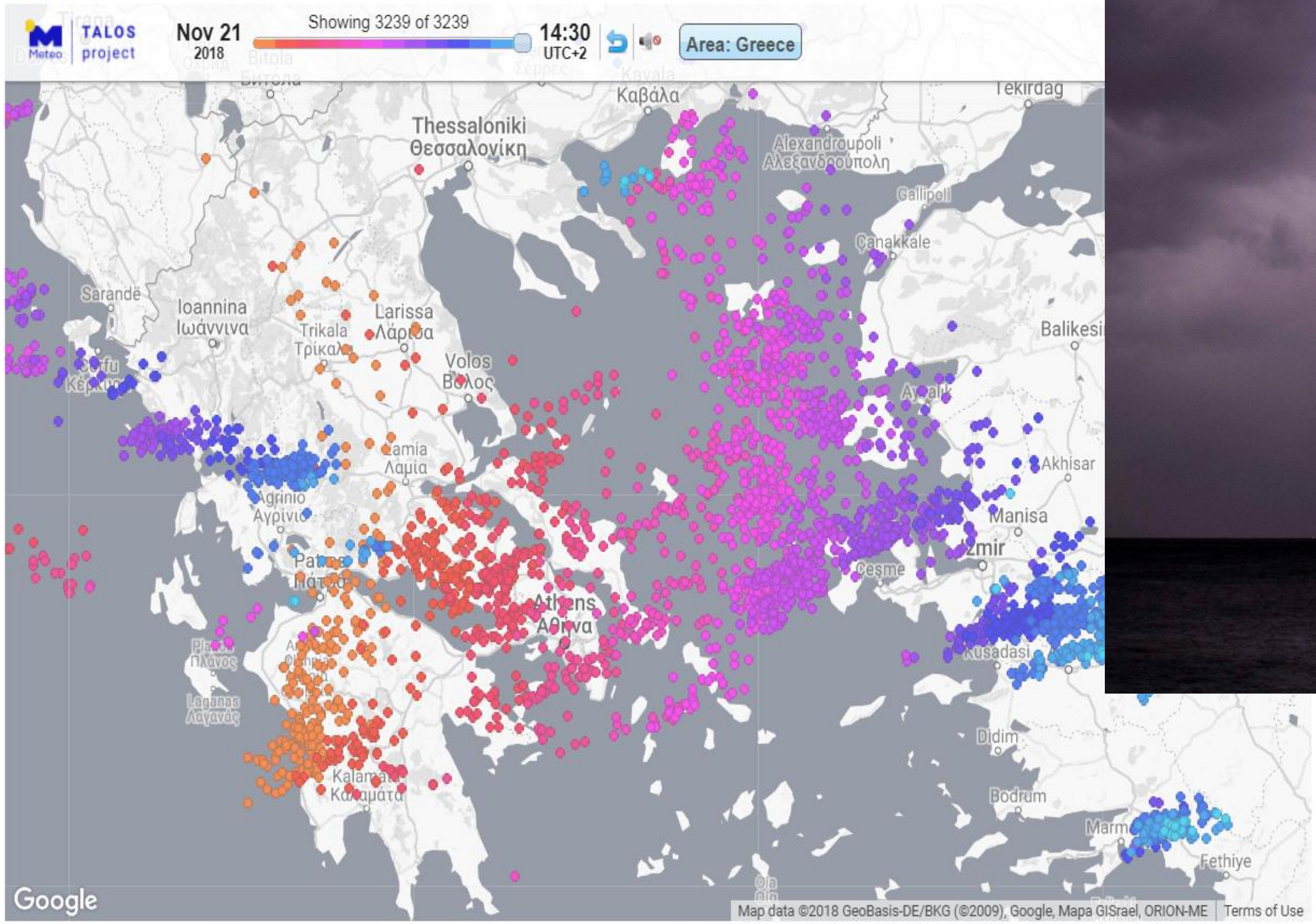
Lightning strike formation and electrical parameters.



Optimized Design of Wind Turbine Blade Receptors Based on Electrostatic Field Theory, https://doi.org/10.3390/electronics8121418

Lightning strike formation and electrical parameters.

Lightning in Greece – 21.11.2018



Upward Lightning from a wind turbine
Region of Patras – 21.11.2018

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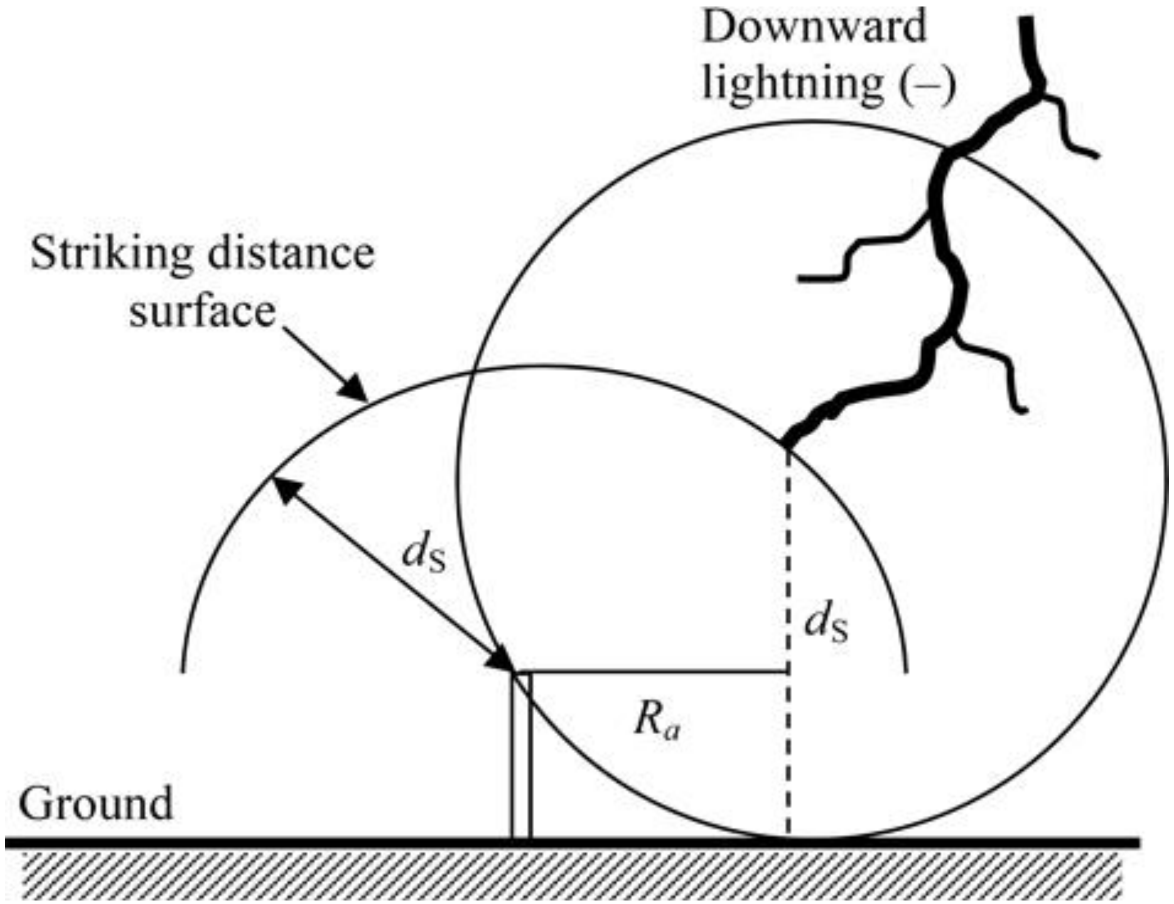
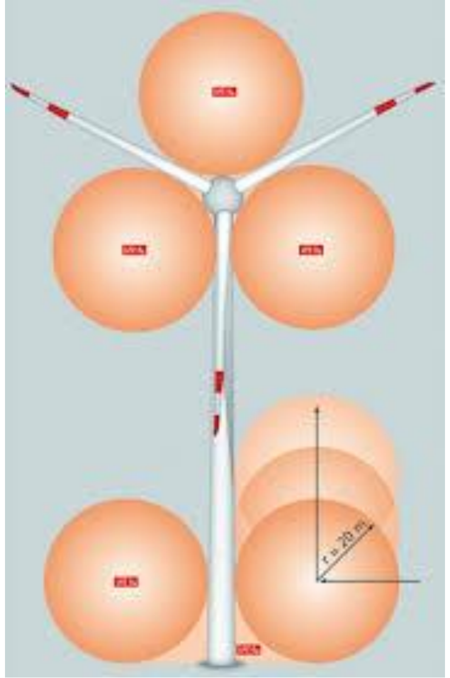
Lightning strike formation and electrical parameters

Upward Lightning strike formation

Lightning strike formation and electrical parameters



Lightning strike formation and electrical parameters



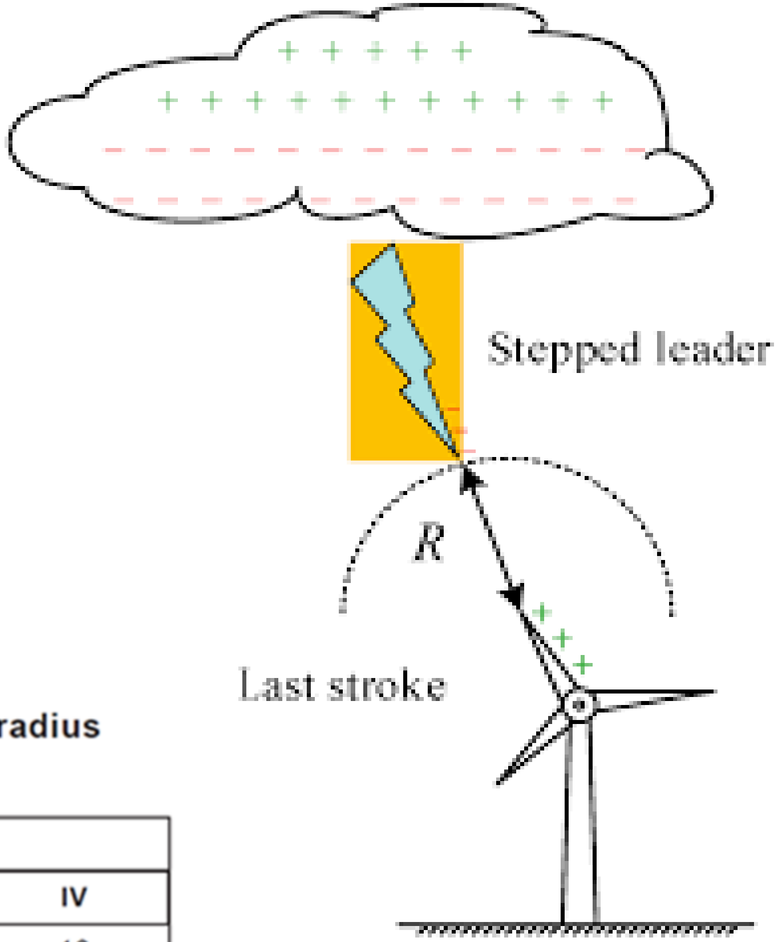
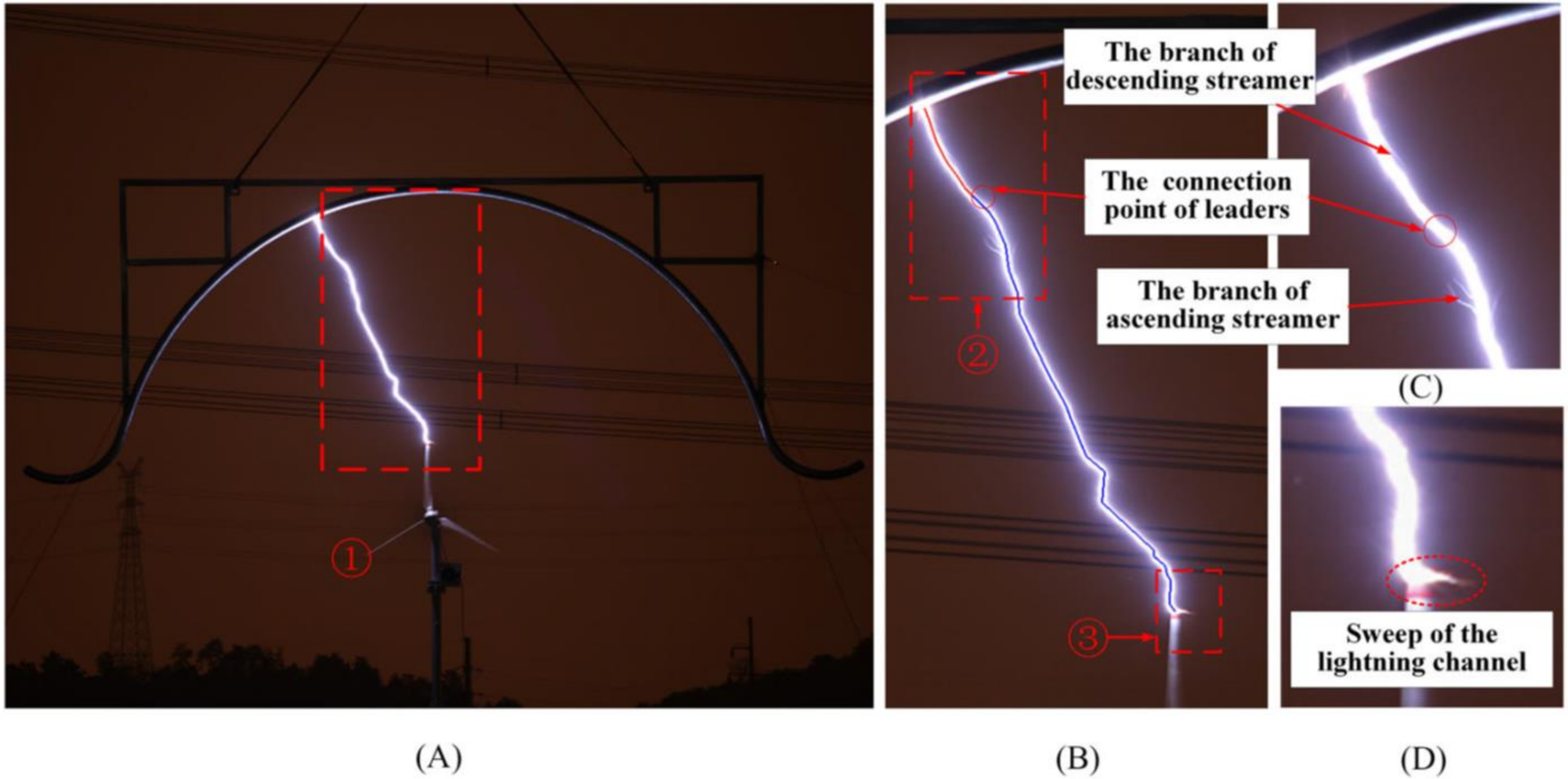


Table 2 – Minimum values of lightning parameters and related rolling sphere radius corresponding to LPL (Table 6 in IEC 62305-1)

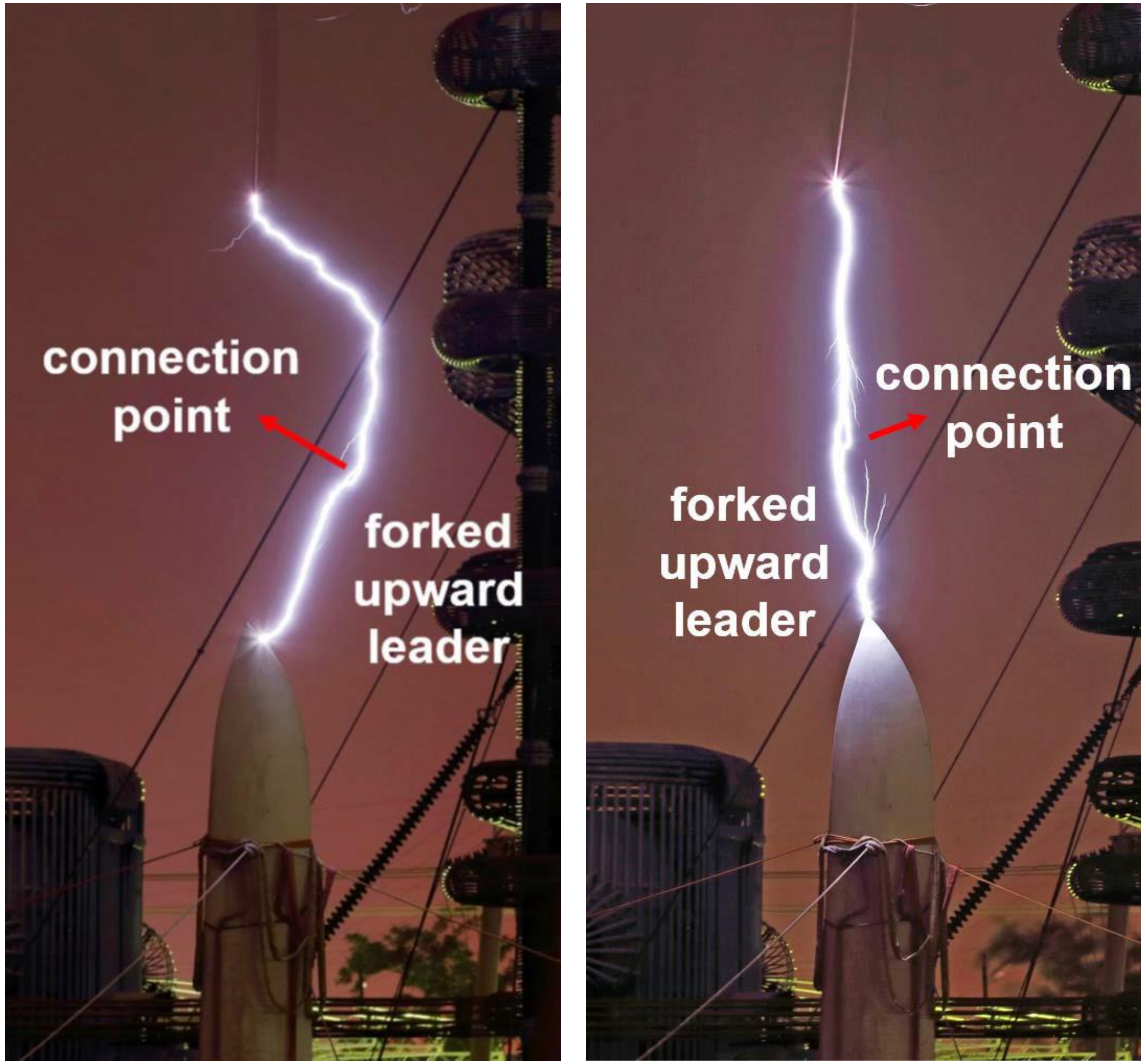
Interception criteria			LPL			
	Symbol	Unit	I	II	III	IV
Minimum peak current	*I*	kA	3	5	10	16
Rolling sphere radius	*r*	m	20	30	45	60

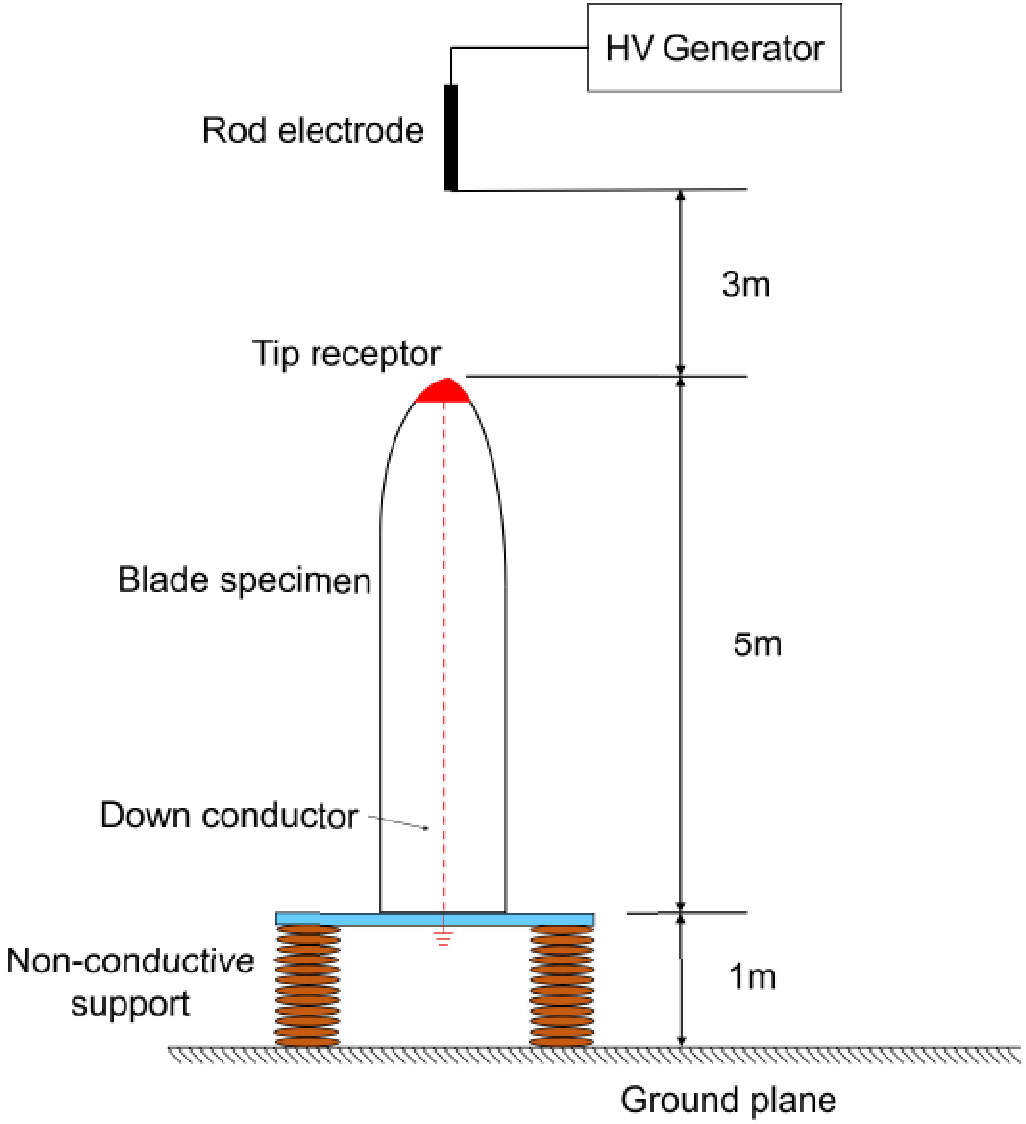
Lightning strike formation and electrical parameters.



A typical flashover photographs: A, flash photograph of the rotating wind turbine with a gap of 4 m;
B, connection process of the upward and downward leaders (zoom in area ①);
C, connecting area between the upward and downward leaders (zoom in area ②); and D, characteristics of the tip arc during lightning strike (zoom in area ③)
[*Colour figure can be viewed at wileyonlinelibrary.com*]

Lightning strike formation and electrical parameters.





Lightning strike formation and electrical parameters.

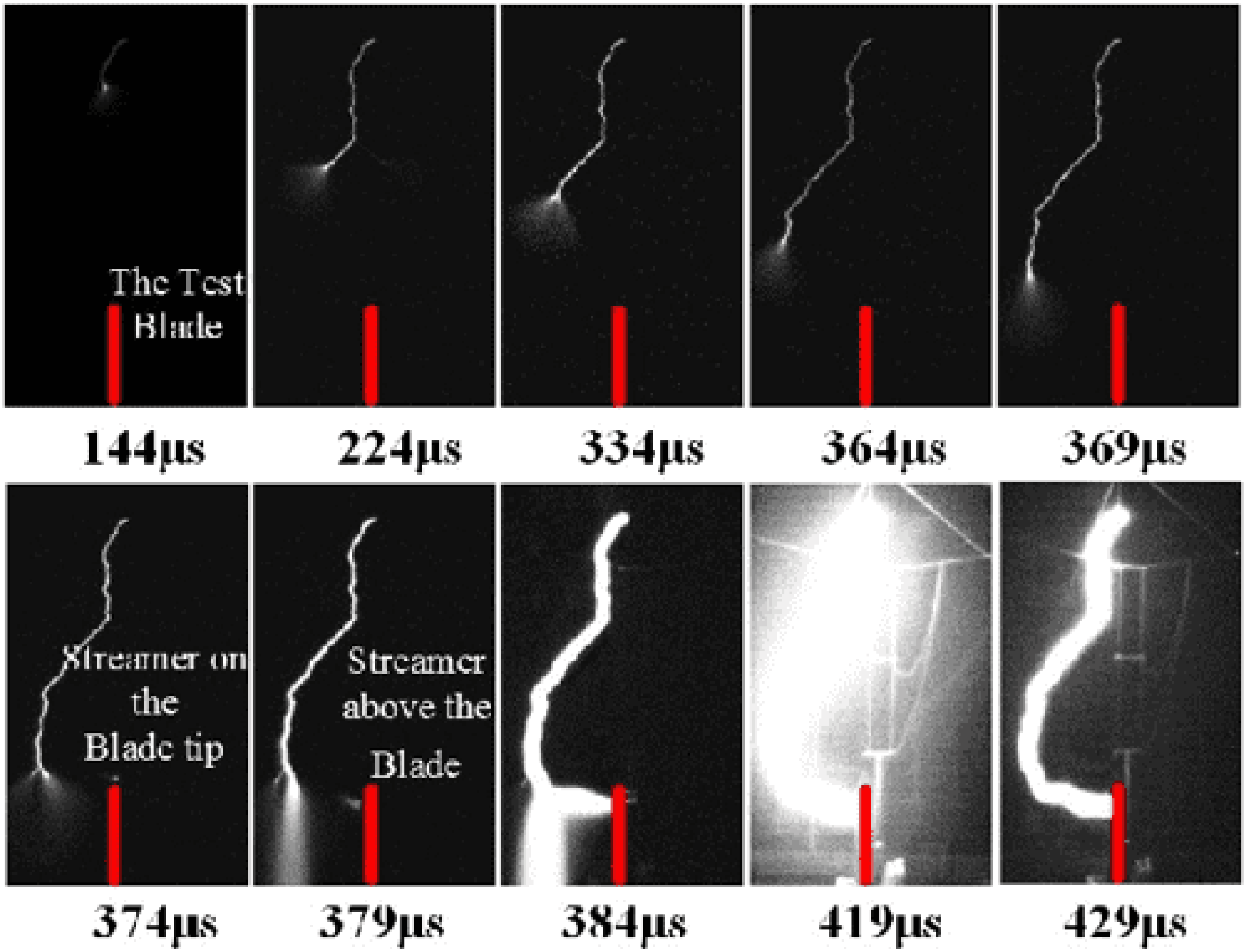
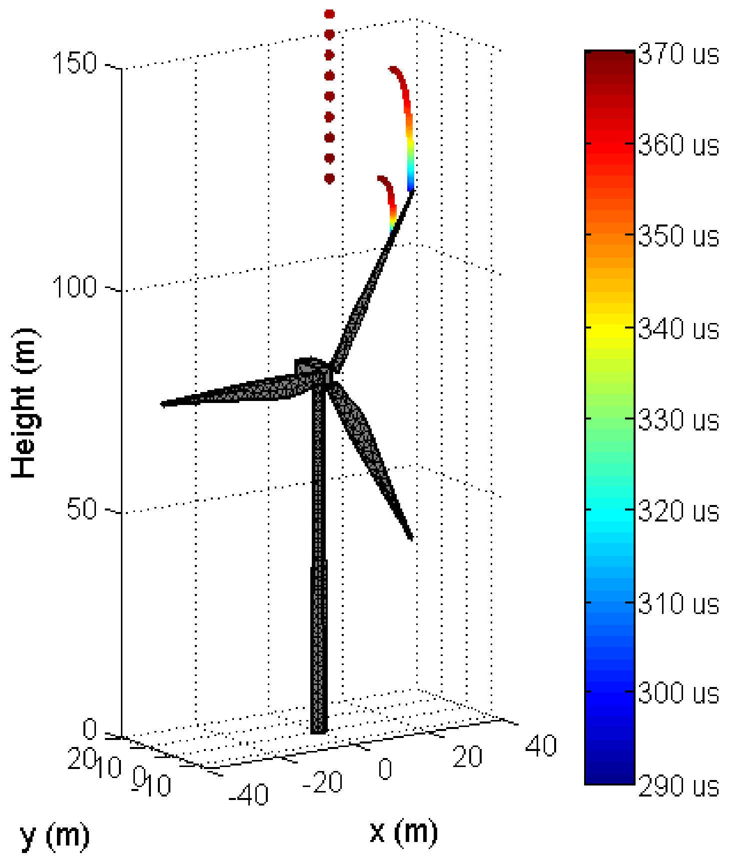


Fig. 1 Process of blades penetration by using long sparks

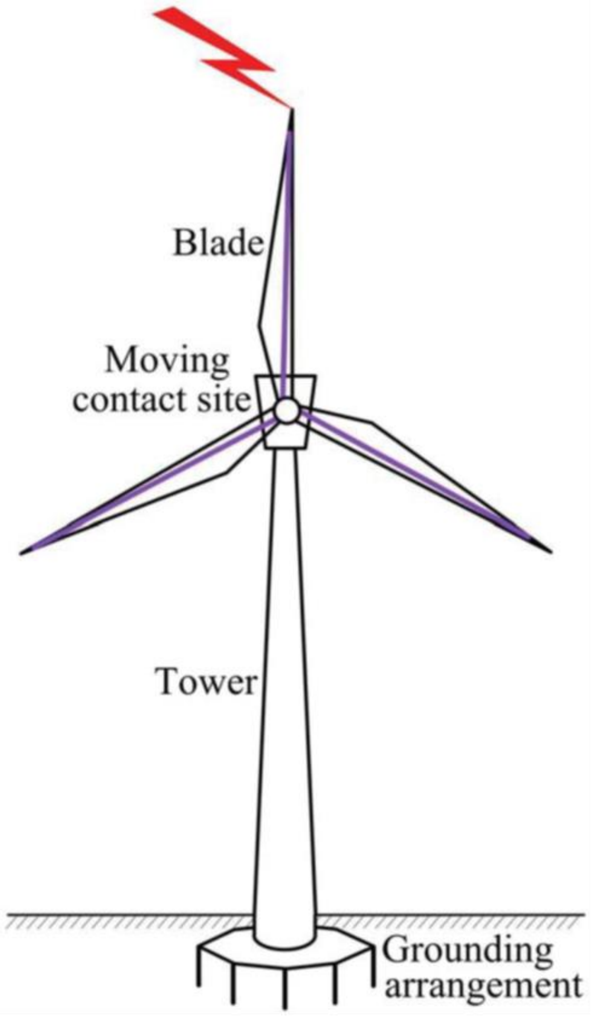
Research on the Performance of the Lightning Protection System with Overlying Conductors on the Tip of the Wind Turbine Blades, Tianyu He, K. Bian, +3 authors Zhehao Pei
Published 2019, Environmental Science
2019 11th Asia-Pacific International Conference on Lightning (APL)

Lightning strike formation and electrical parameters.



3D plot of the dart leader and the upward connecting leaders during lightning attachment. The colour legend indicates time starting at the initiation of dart leader from the thundercloud base.

On the Attachment of Lightning Flashes to Wind Turbines Mengni Long, Doctoral Thesis School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden 2016



Statistic analysis of lightning transients on wind turbines, J. Renewable Sustainable Energy 12, 063302 (2020); https://doi.org/10.1063/5.0031506

Standards relating to lightning protection of wind turbines.

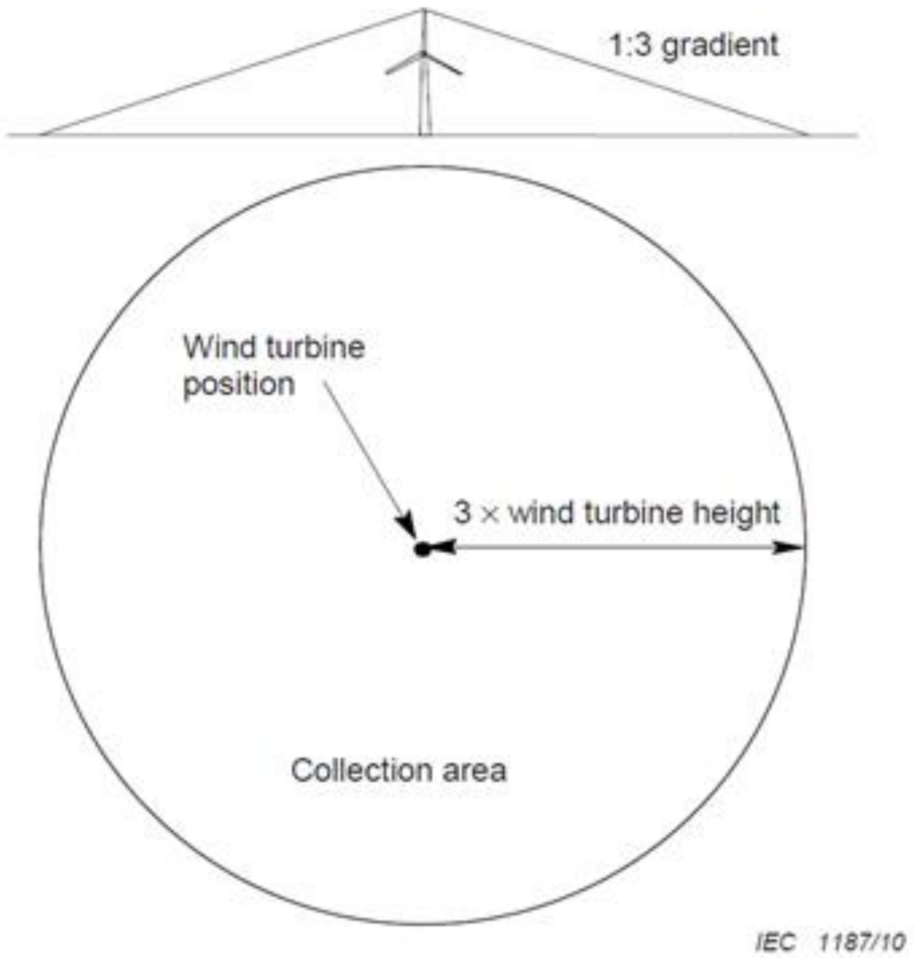
Lightning exposure assessment

T_d is the number of thunder storm days per year obtained from isokeraunic maps [year^{-1}]

$N_g \approx 0.1 \cdot T_d$ is the annual average ground flash density [km^{-2}·year^{-1}]

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

C_d is the environmental factor



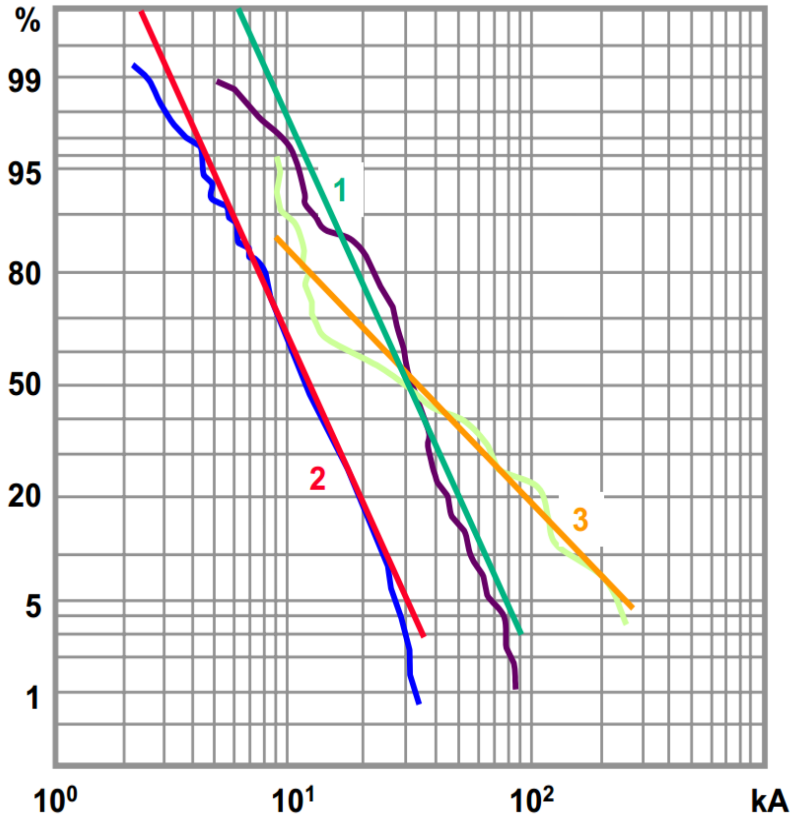
lightning flashes to the wind turbine

$$\boldsymbol{N_d = N_g \cdot A_d \cdot C_d}$$

IEC 61400-24, Wind turbines - Part 24: Lightning protection

Standards relating to lightning protection of wind turbines.

Lightning current

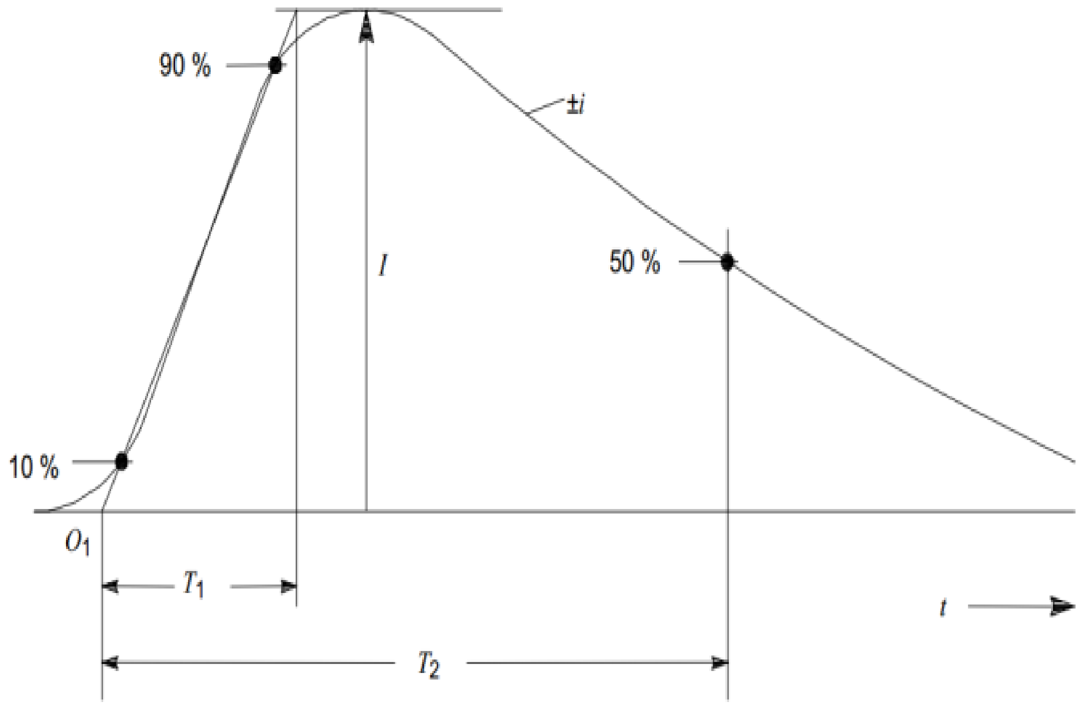


(1) Negative first strokes

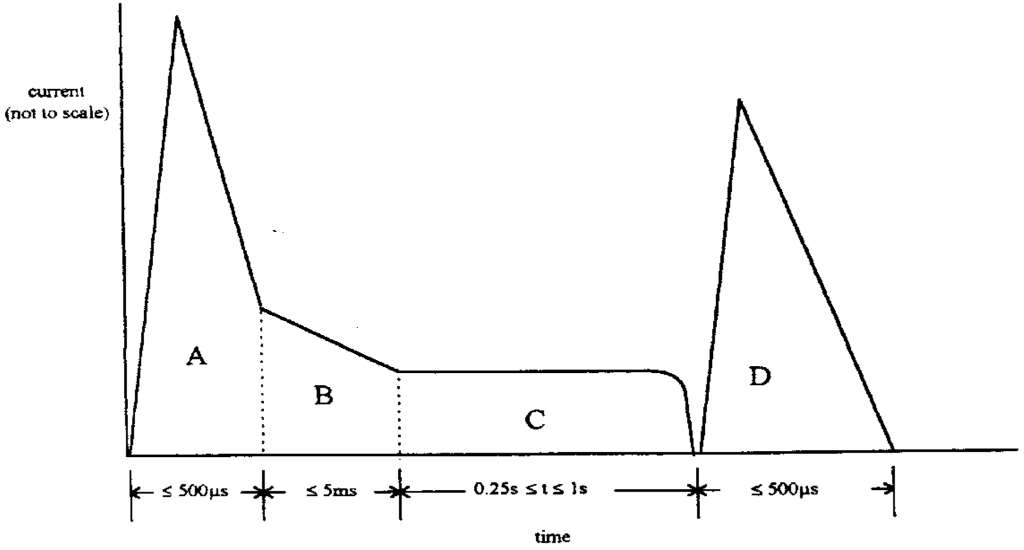
(2) Negative subsequent strokes

(3) Positive strokes

K.Berger, R.B. Anderson, H. Kröninger:
„Parameters of Lightning Flashes“, Electra, No. 41, 1975



Standards relating to lightning protection of wind turbines.



COMPONENT A (First Return Stroke)

Peak Amplitude	:	200kA (± 10%)
Action Integral	:	$2 \times 10^6 A^2s$ (± 20%) (in 500μs)
Time Duration	:	≤ 500μs

COMPONENT B (Intermediate Current)

Max. Charge Transfer	:	10 Coulombs (± 10%)
Average Amplitude	:	2kA (± 20%)
Time Duration	:	≤ 5ms

COMPONENT C (Continuing Current)

Amplitude	:	200 - 800A
Charge Transfer	:	200 Coulombs (± 20%)
Time Duration	:	0.25 to 1 s

COMPONENT D (Subsequent Return Stroke)

Peak Amplitude	:	100kA (± 10%)
Action Integral	:	$0.25 \times 10^6 A^2s$ (± 20%) (in 500μs)
Time Duration	:	≤ 500μs

Standardized Aircraft Lightning Environment

Standards relating to lightning protection of wind turbines.

Lightning current for simulation purpose

$$i = \frac{I}{k} \cdot \frac{\left(\frac{t}{\tau_1}\right)^{10}}{1 + \left(\frac{t}{\tau_1}\right)^{10}} \cdot exp\left(\frac{t}{\tau_2}\right)$$

Parameters	First short stroke			Subsequent short stroke		
	LPL			LPL		
	I	II	III-IV	I	II	III-IV
I (kA)	200	150	100	50	37,5	25
k	0,93	0,93	0,93	0,993	0,993	0,993
τ_1 (μs)	19	19	19	0,454	0,454	0,454
τ_2 (μs)	485	485	485	143	143	143

Standards relating to lightning protection of wind turbines.

62305-1/FDIS © IEC – 24 –

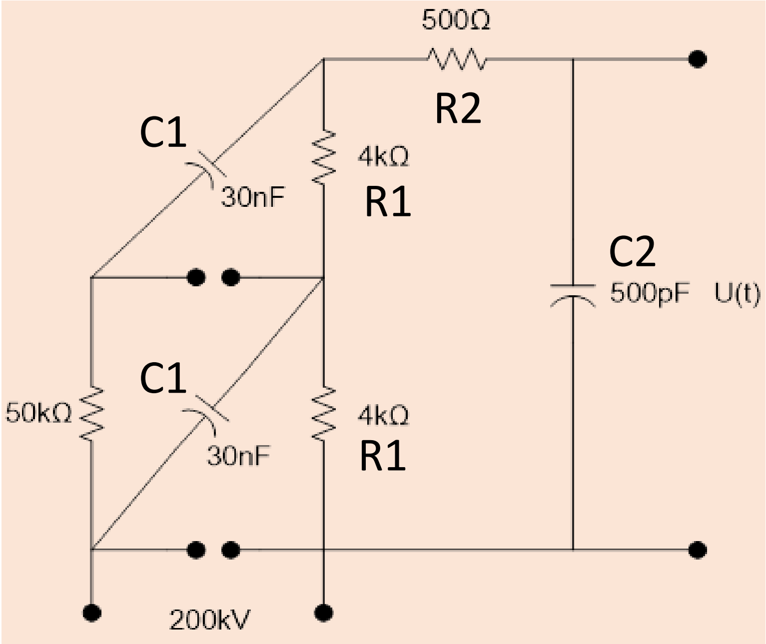
Table 5 – Maximum values of lightning parameters according to LPL

First short 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			
Subsequent short stroke			**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	

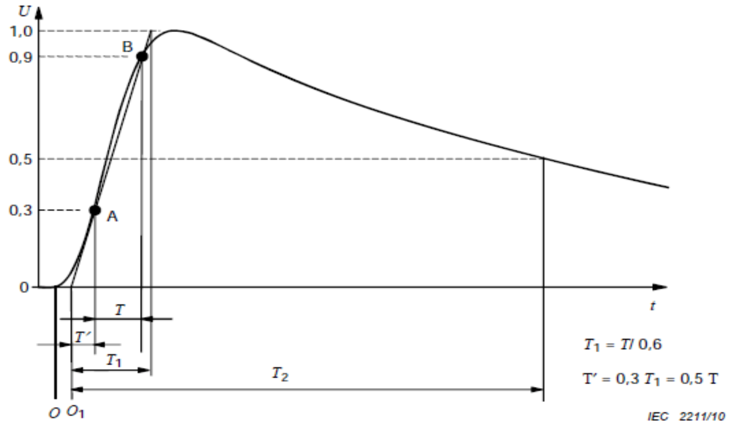
Lightning parameters

Standards relating to lightning protection of wind turbines

Upatras High voltage impulse generator



$t_1 \cong 2 \div 3 R_2 \cdot C_2$ $\qquad$ $t_2 \cong 0.7 R_1 C_1$



Standards relating to lightning protection of wind turbines.

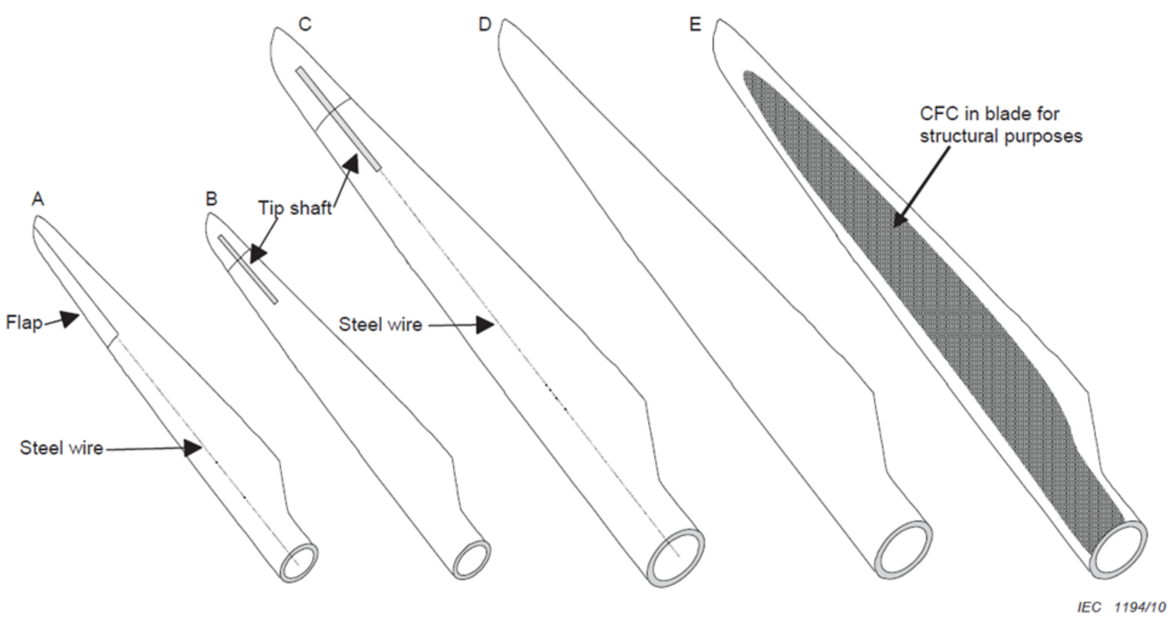


Figure C.1 – Types of wind turbine blades

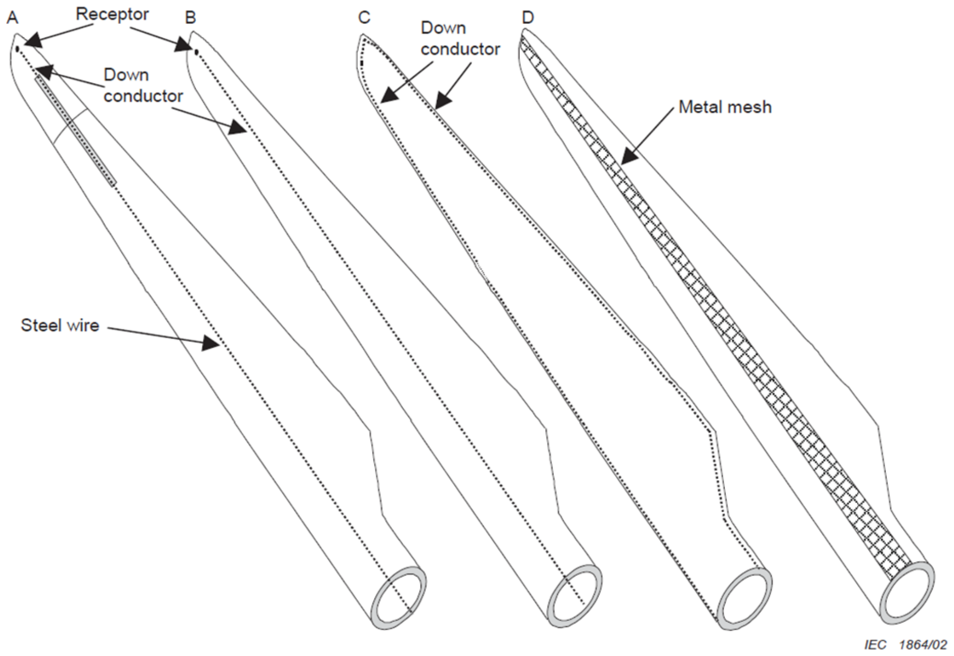
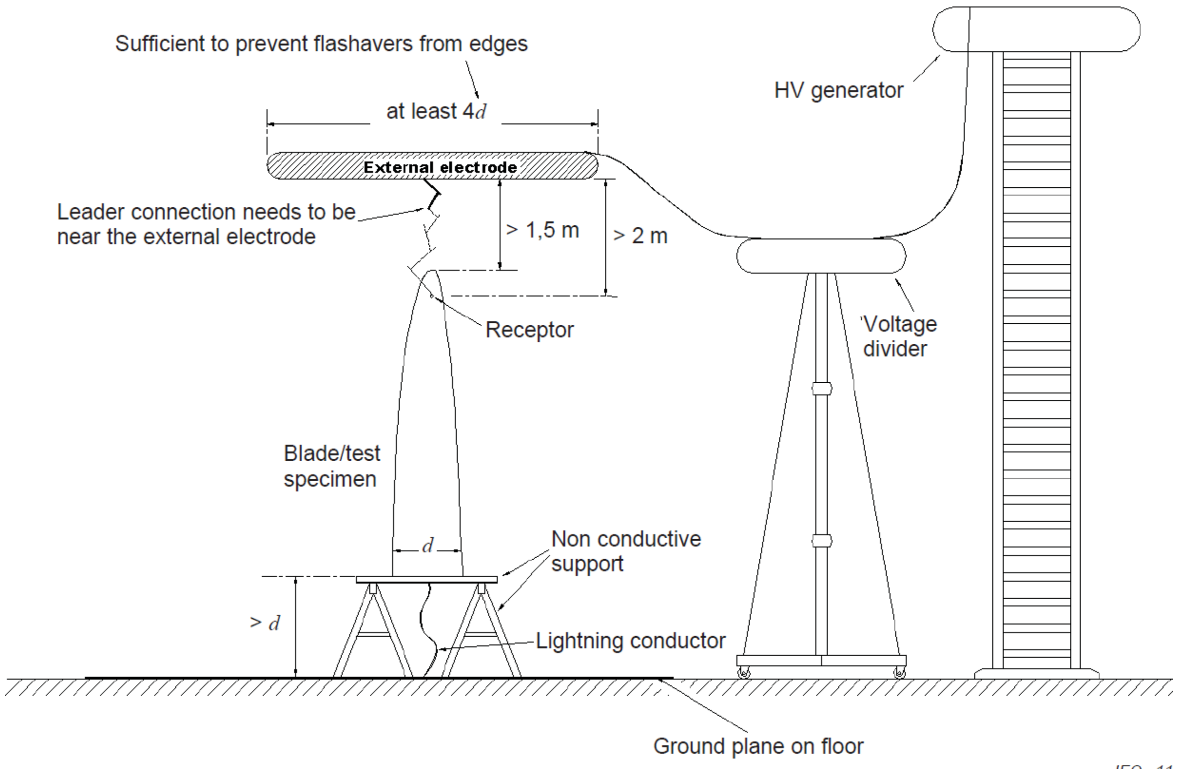
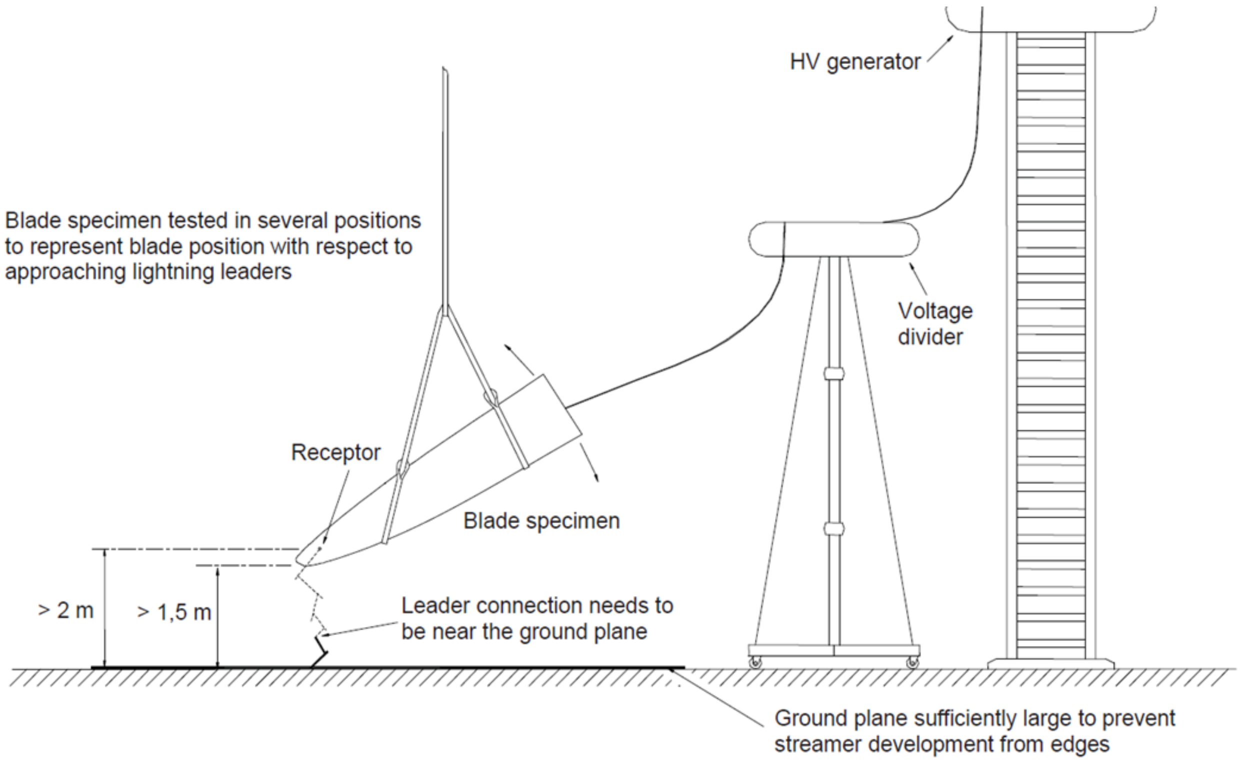


Figure C.2 – Lightning protection concepts for large modern wind turbine blades

IEC 61400-24, Wind turbines - Part 24: Lightning protection

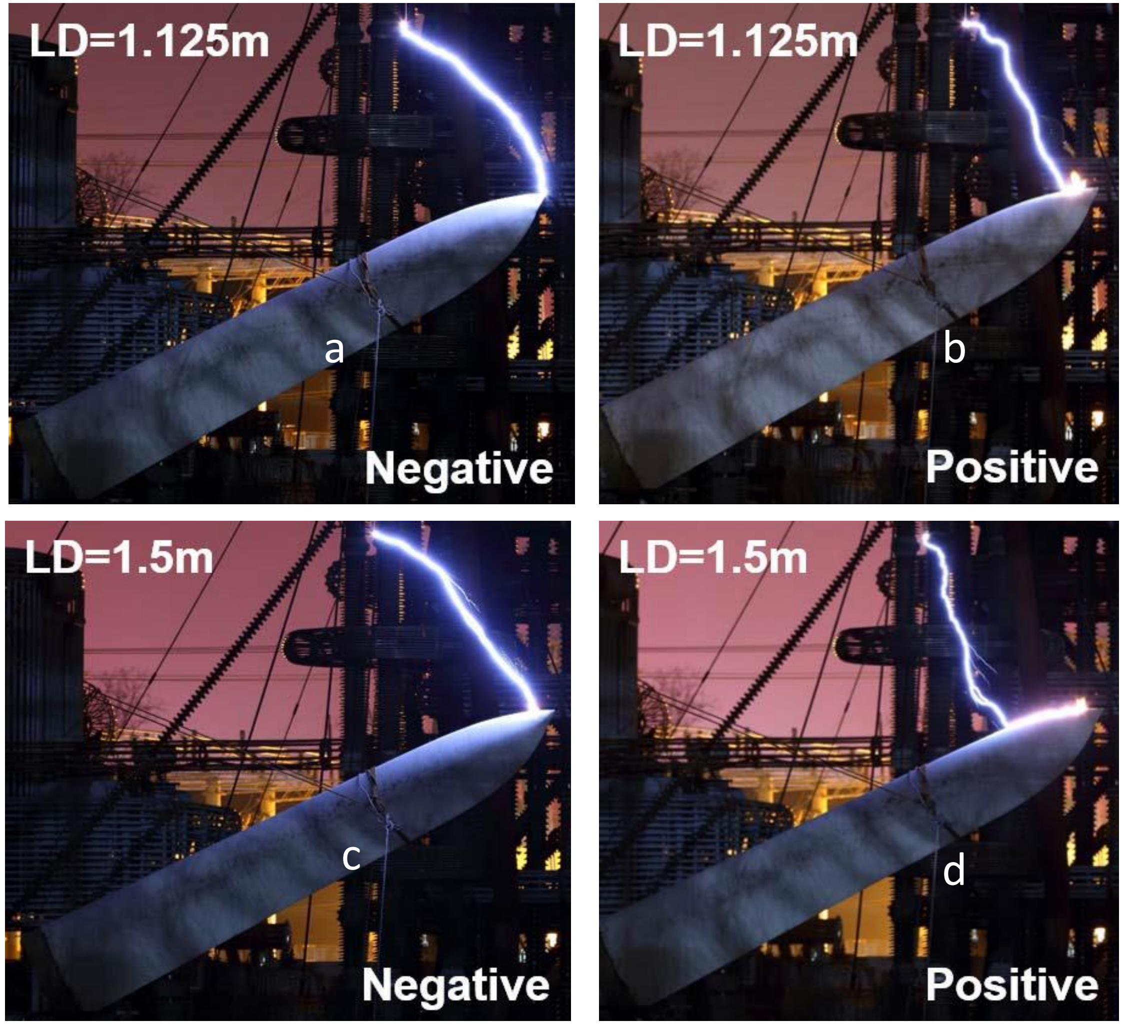
Standards relating to lightning protection of wind turbines.





IEC 61400-24, Wind turbines - Part 24: Lightning protection

Standards relating to lightning protection of wind turbines.



(a) For LD = 1.125 m, the negative discharge hits on the tip of the receptor.
(b) For LD = 1.125 m, the positive discharge hits on the blade surface and cause creeping discharge.
(c) For LD = 1.5 m, the negative discharge hits on the side of the receptor.
(d) For LD = 1.5 m, the positive discharge hits on the blade surface and causes longer creeping discharge.

Experimental Study on Lightning Attachment Manner to Wind Turbine Blades With Lightning Protection System, Zixin Guo , Qingmin Li, Yufei Ma, Hanwen Ren, Zhiyang Fang, Chun Chen, and Wah Hoon Siew, IEEE TRANSACTIONS ON PLASMA SCIENCE, 2018

Standards relating to lightning protection of wind turbines

61400-24 © IEC:2010(E) – 123 –

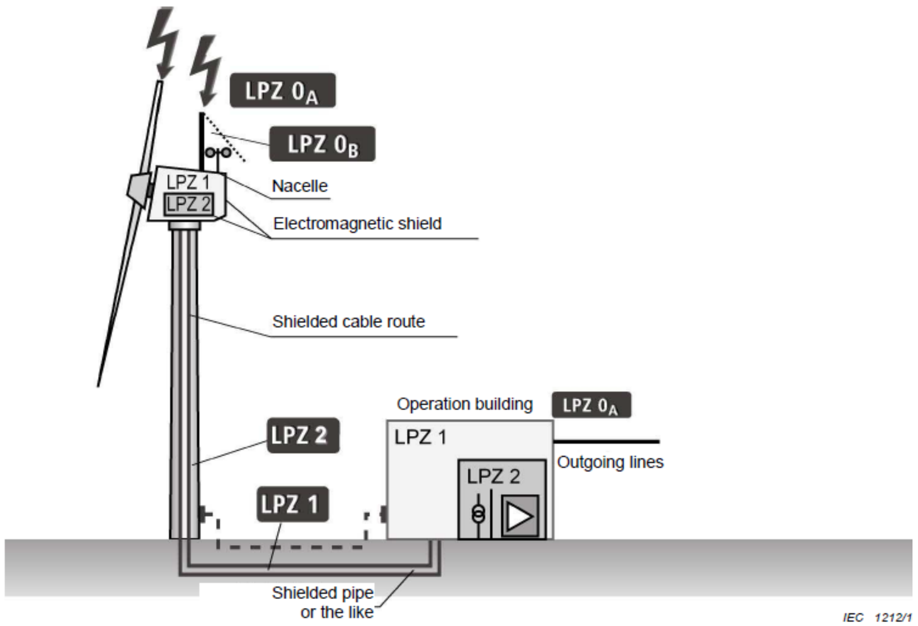


Figure E.5 – Example: Division of wind turbine into different lightning protection zones

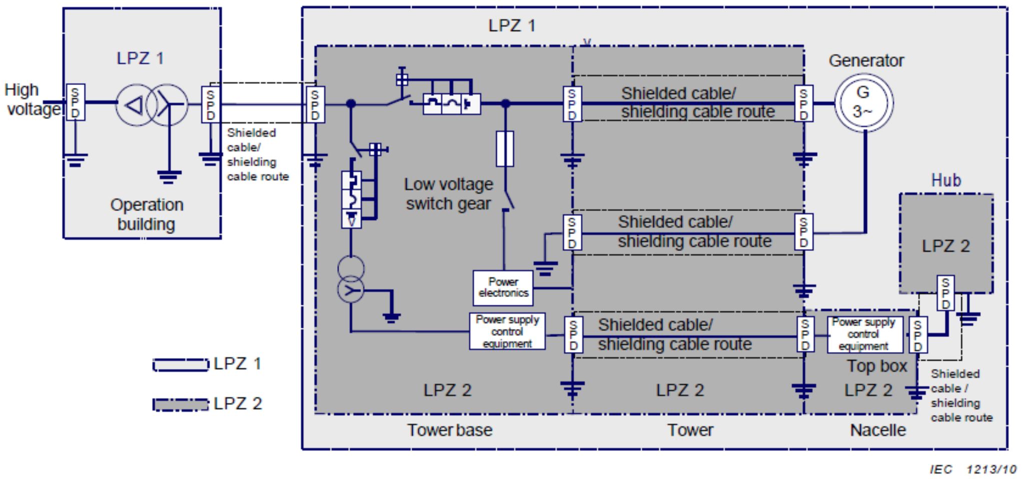


Figure E.6 – Example of how to document LPMS division of electrical system into protection zones with indication of where circuits cross LPZ boundaries and showing the long cables running between tower base and nacelle

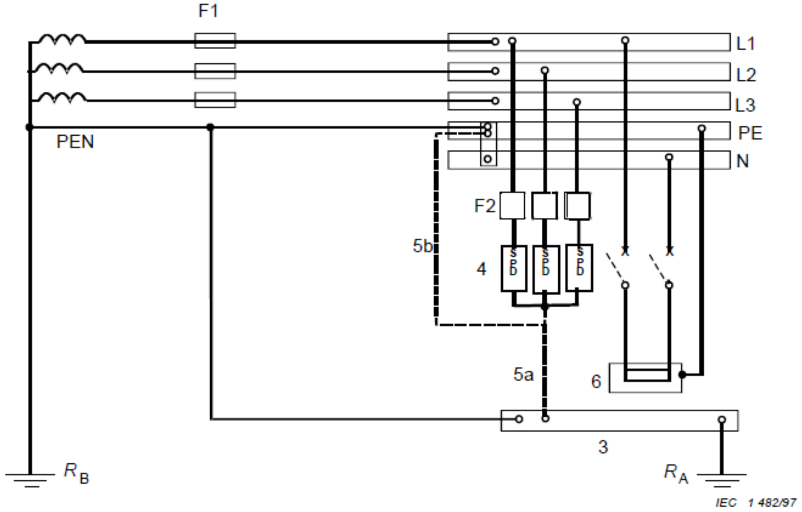


Figure F.2 – Earthing connection installation scheme (Figure A.1 in IEC 60364-5-53)

IEC 61400-24, Wind turbines - Part 24: Lightning protection

Standards relating to lightning protection of wind turbines

Results due to lightning strike

Electrical results	$\mathbf{i\ (A)}$	$\mathbf{U = R \cdot i\ (V)}$
Electrical results	$\frac{di}{dt}\ (\mathbf{A} \cdot s^{-1})$	$\mathbf{U = L} \cdot \frac{di}{dt}\ \mathbf{(V)}$
Thermal results	$\mathbf{SE} = \int i^2 dt\ (A^2\mathbf{s})$	$\mathbf{E} = \int \mathbf{R} \cdot i^2 dt\ (\Omega \cdot A^2\ \mathbf{s})$
Thermal results	$\mathbf{Q\ (A \cdot s)}$	$\mathbf{W = U \cdot Q\ (V \cdot A \cdot s)}$
Mechanical results	$I^2 (A^2)$	$\mathbf{F} = \frac{\mu_0}{2\pi} \frac{I^2}{\alpha} \cdot \mathbf{l}$

Damage in wind turbines components due lightning strike

Results due to lightning strike

Lightning hits on blade receptor

Damage in wind turbines components due lightning strike.

Burn and delamination on the shell at about 3m from the blade tip due to lightning direct strike.

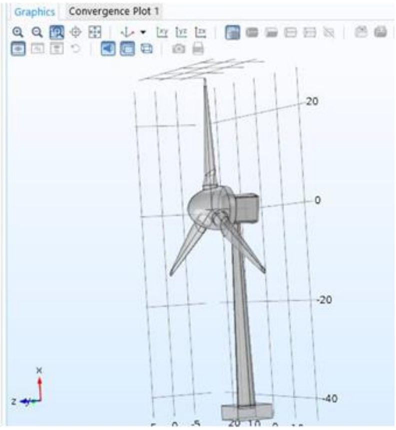
Delamination on the shell at about 2m from the blade tip due to lightning direct strike.

The analysis revealed that most lightning strikes to wind turbine blades are concentrated at the outermost 4 m of the blade, in particular at the last 0.5 m of the tip, regardless the blade geometry and material. The damage presented similar patterns in all the blades and could be classified in four types, including delamination, debonding, shell detachment and tip detachment

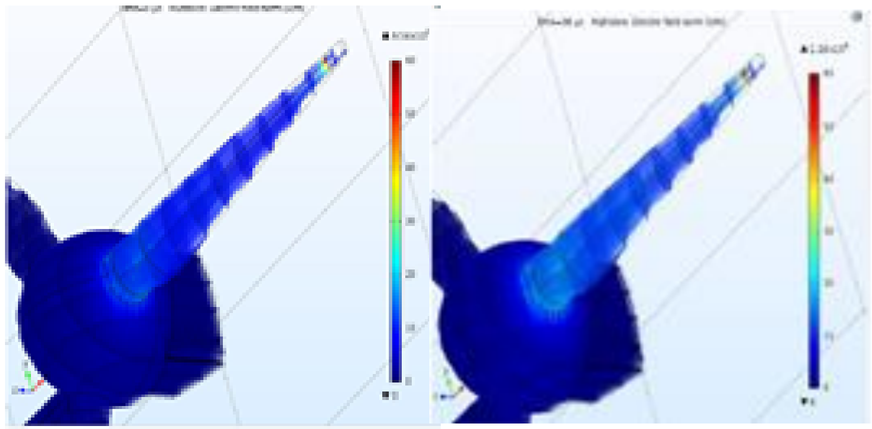
A. Candela Garolera, S. F. Madsen, M. Nissim, J. D. Myers and J. Holboell, "Lightning Damage to Wind Turbine Blades From Wind Farms in the U.S.," in IEEE Transactions on Power Delivery, vol. 31, no. 3, pp. 1043-1049, June 2016, doi: 10.1109/TPWRD.2014.2370682

Damage in wind turbines components due lightning strike

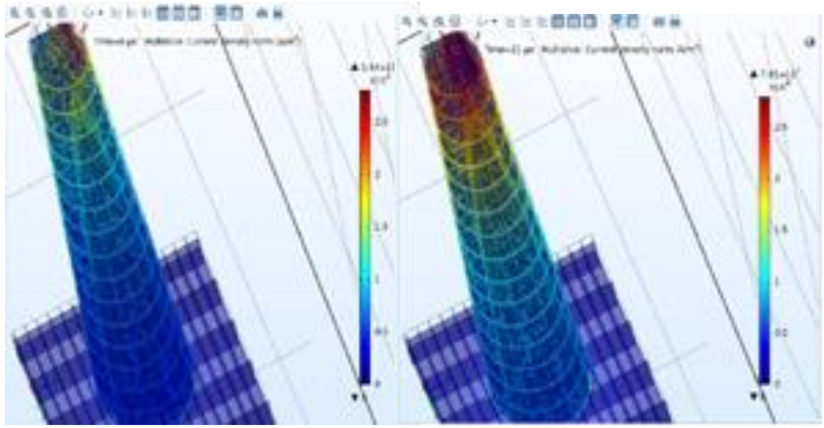
Simulation Results for a 100kA lightning strike



Wind turbine model



Electrical field in WT tip (9μs, 96μs).



Current density in 3D (9μs, 21μs).

The proper sizing of the down-conductors, the equipotential bonding of the all the parts and the choice of the surge protection devices can ensure a reliable protection of the wind turbine. Material discontinuities and abrupt pipeline changes must be avoided as they lead to the creation of an electric and magnetic field which depending the conditions may lead to a component failure. The high electric field at the wind turbine tower base creates risk for high step and touch voltages which is critical for the safety of life beings

CURRENT DENSITY

Point	Ip=100kA (10/350μs)	
	Position	A/cm^3
A	Tower base – surrounding soil	55
B	Down conductor-Tower	30
C	Blade and main down conductor	22
D	Blade tip	0,140

Investigation of lightning strike effects on wind turbine critical components
S. A. Pastromas, K. Sandros, K. N. Koutras, E. C. Pyrgioti ICHVE 2018

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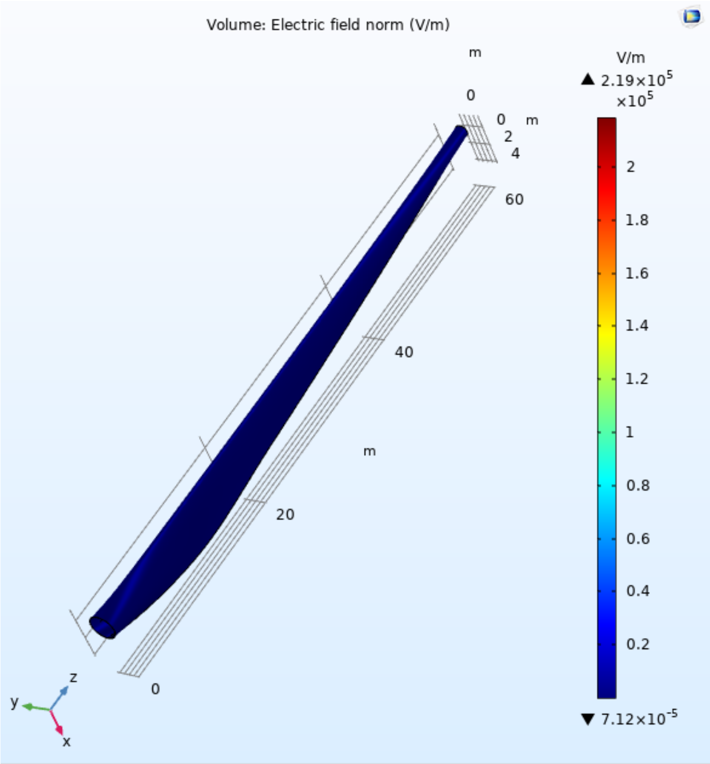
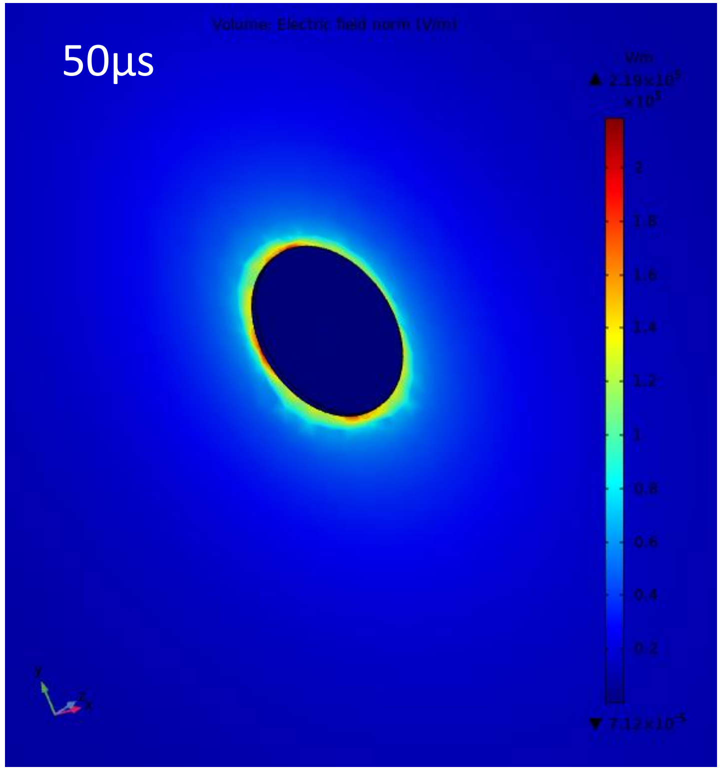
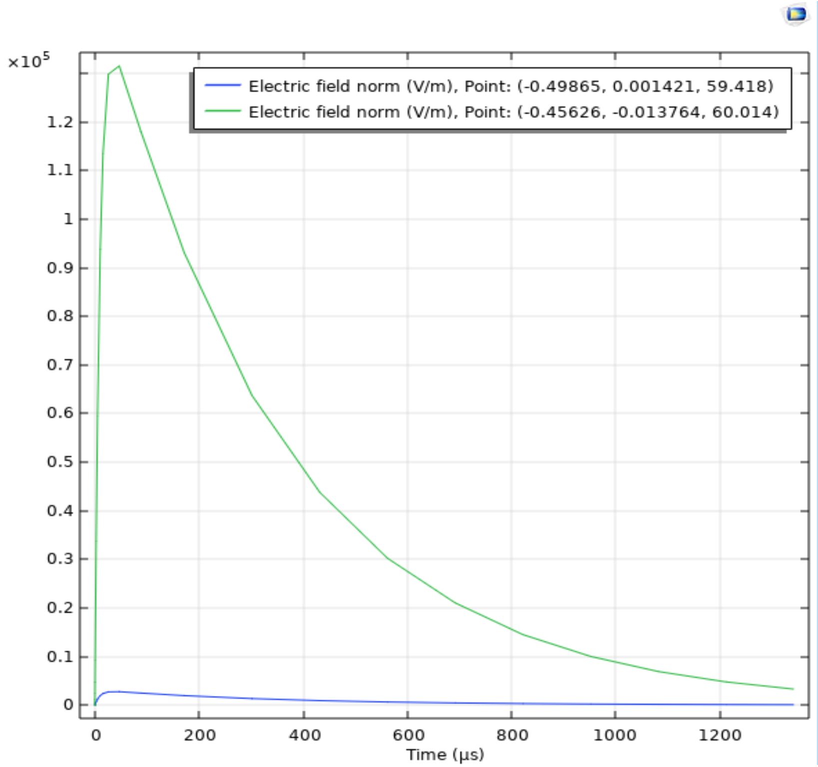
Damage in wind turbines components due lightning strike

Simulation results for a 200kA lightning strike, ground wire(GW) $50 mm^2$, Electric field 2.19 kV/cm



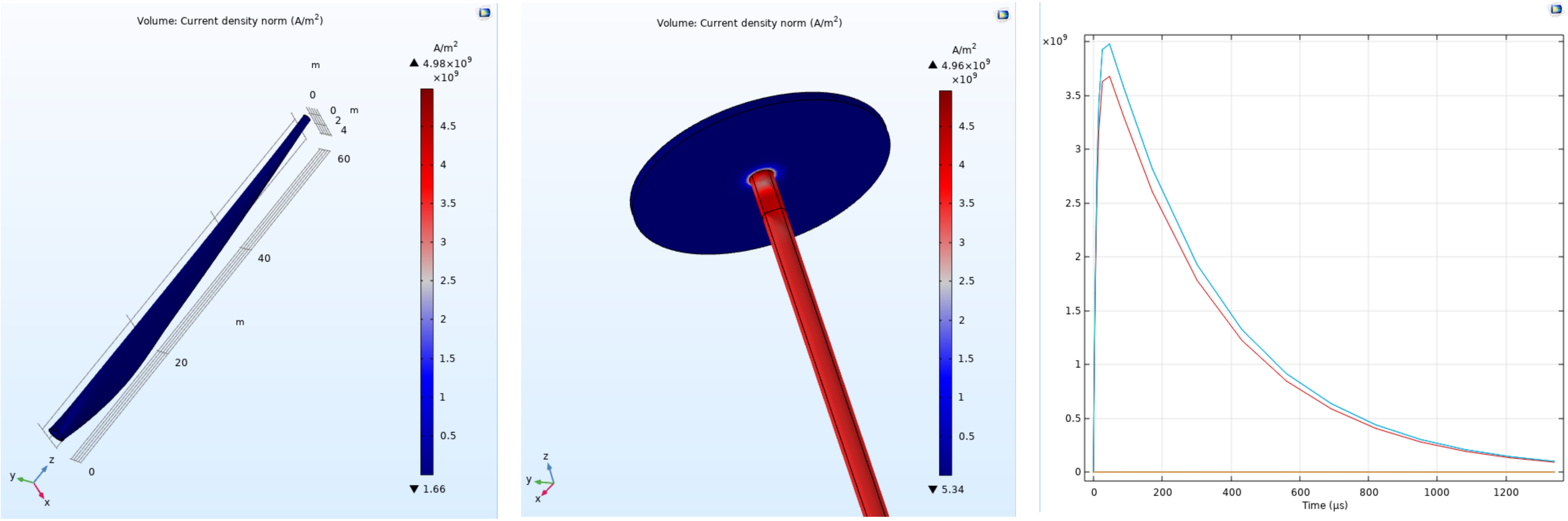




Blades' response to lightning strike, Apostolopoulou Kleopatra, Thesis, Upatras 2021

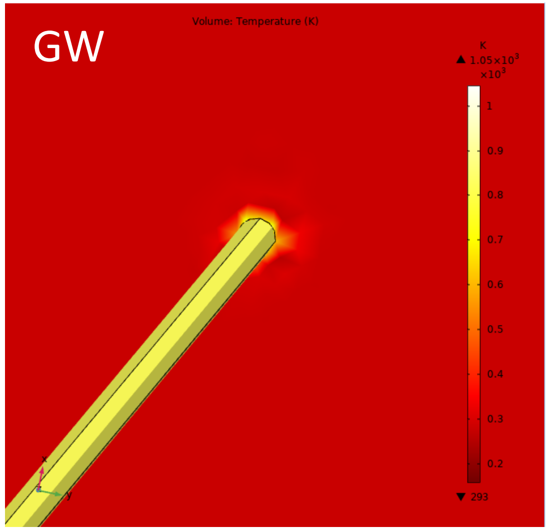
Damage in wind turbines components due lightning strike

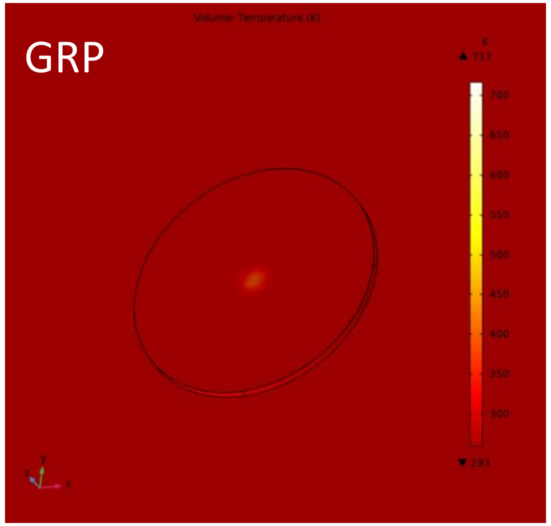
Simulation results for a 200kA lightning strike, GW 50mm^2 , GW current density 4.96×10^6 kA/m^2



Blades' response to lightning strike, Apostolopoulou Kleopatra, Thesis, Upatras 2021

Damage in wind turbines components due lightning strike



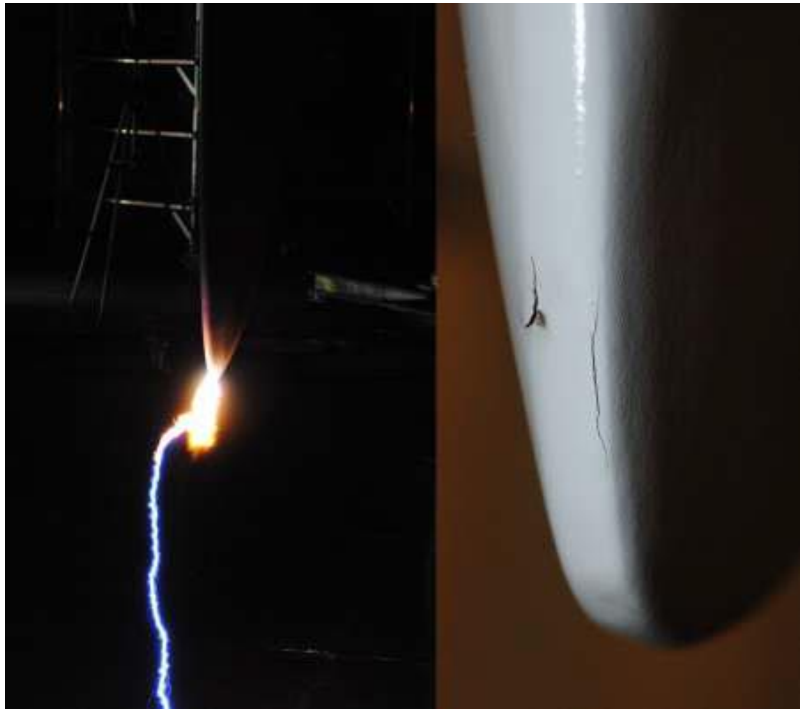


Max. Temperature → Ground Wire-787°C, Blade Surface 420°C

Lightning I_{peak}	200 kA	150 kA	50 kA
	GW-50mm²		
Current density	4.96×10^9 A/ m²	3.74×10^9 A/ m²	1.25×10^9 A/ m²
Electric field	2.19×10^5 V/m	1.65×10^5 V/m	5.49×10^4 V/m
Max. Temp. GW	787 °C	444 °C	67 °C
Max. Temp. GRP	420 °C	247 °C	47 °C
	GW-100mm²		
Current density	269 kA/cm²	2.02×10^9 A/ cm²	6.74×10^8 A/ m²
Electric field	10 kV/cm	7.3 kV/cm	2.42×10^4 V/m
Max. Temp. GW	206 °C	122 °C	32 °C
Max. Temp. GRP	107 °C	70 °C	26 °C
	GW-200mm²		
Current density	1.35×10^9 A/ m²	1.01×10^9 A/ m²	3.36×10^8 A/ m²
Electric field	6.09×10^4 V/m	4.57×10^4 V/m	1.52×10^4 V/m
Max. Temp. GW	69 °C	48 °C	23 °C
Max. Temp. GRP	38 °C	30 °C	21 °C

Blades' response to lightning strike, Apostolopoulou Kleopatra, Thesis, Upatras 2021

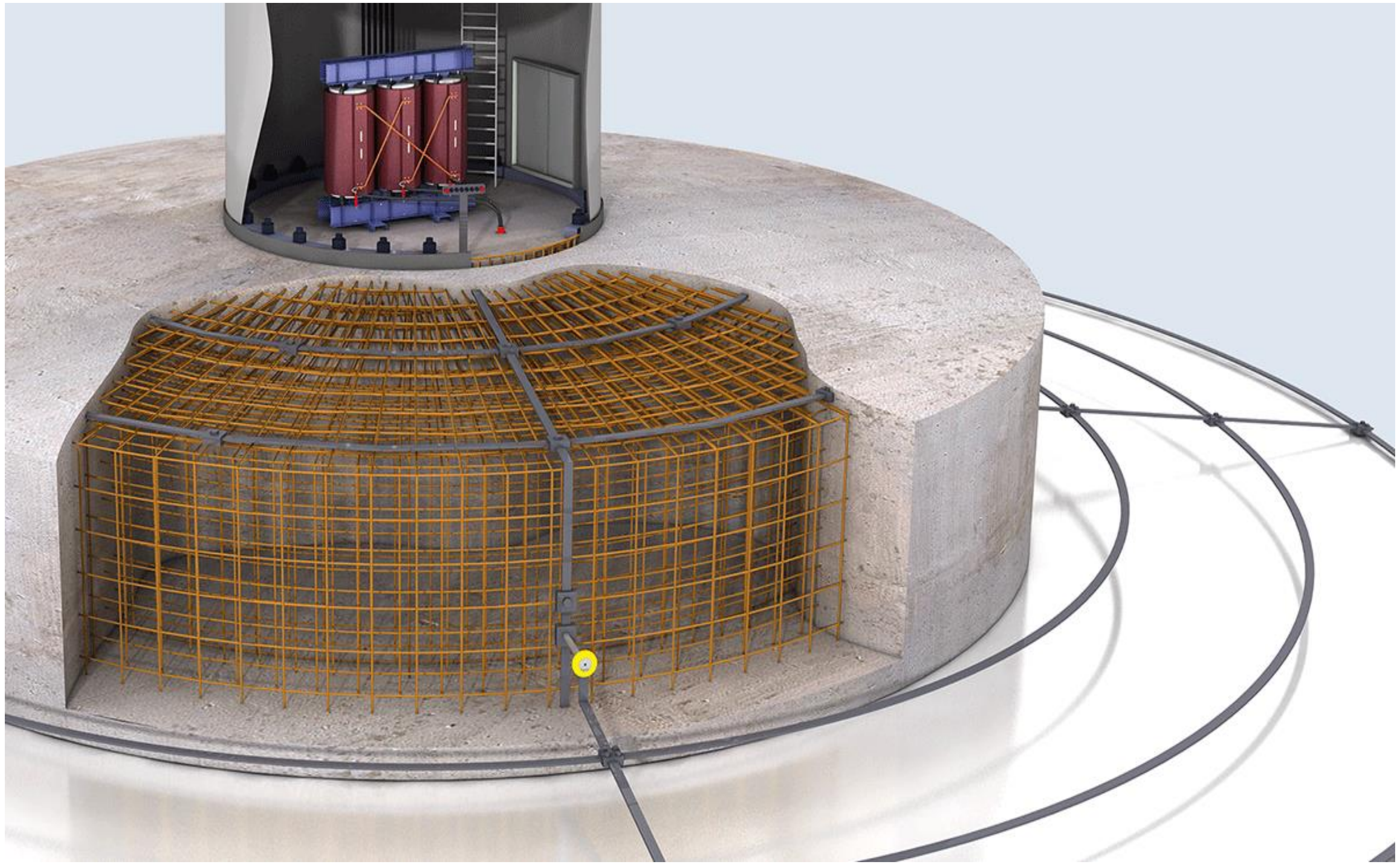
Damage in wind turbines components due lightning strike.

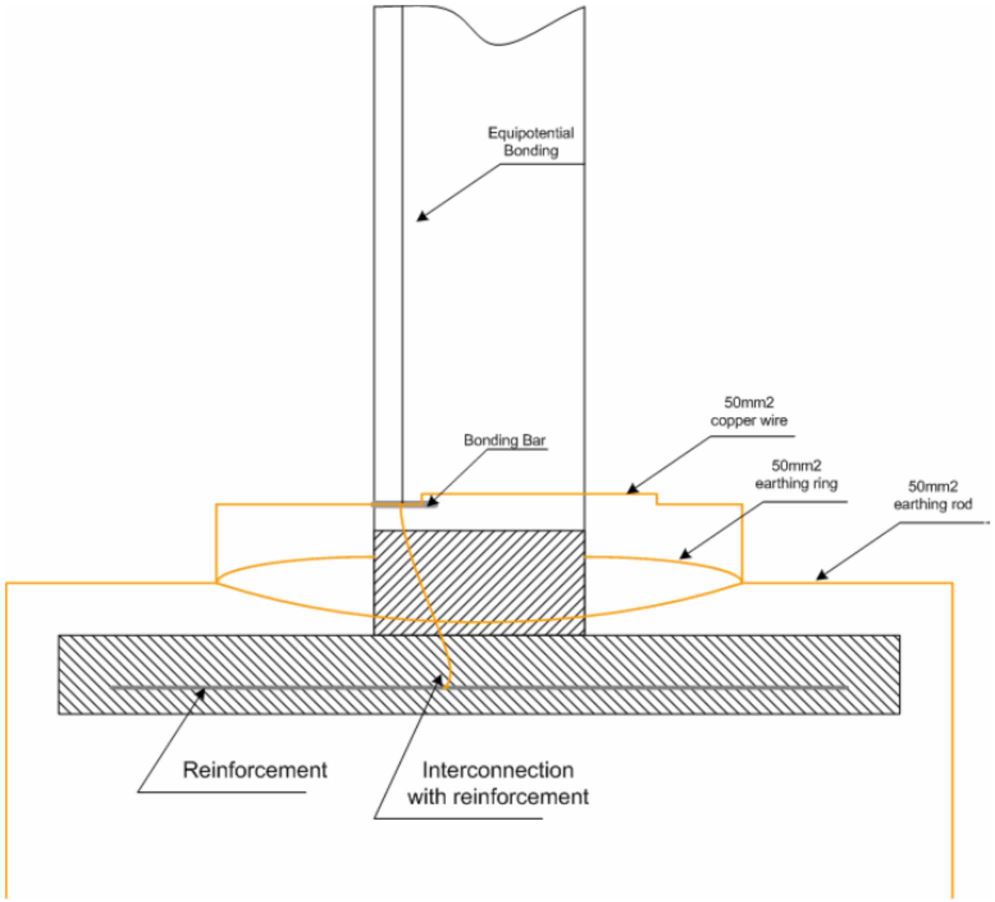


Tip Breakdown of Carbon Loaded Blade and Resultant Damage

Vidyadhar Peesapati,LIGHTNING PROTECTION OF WIND TURBINES, Phd Thesis, Manchester, 2010

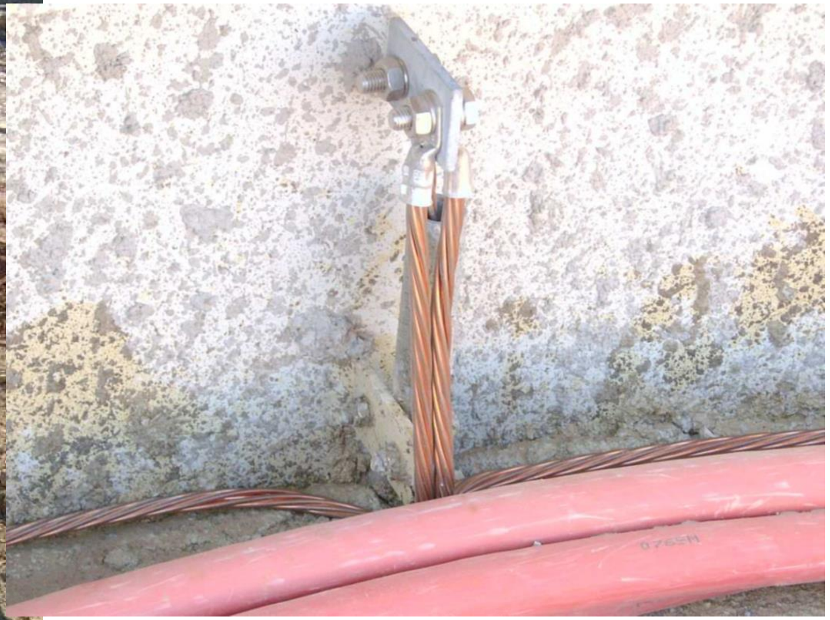
Wind turbine electrical grounding



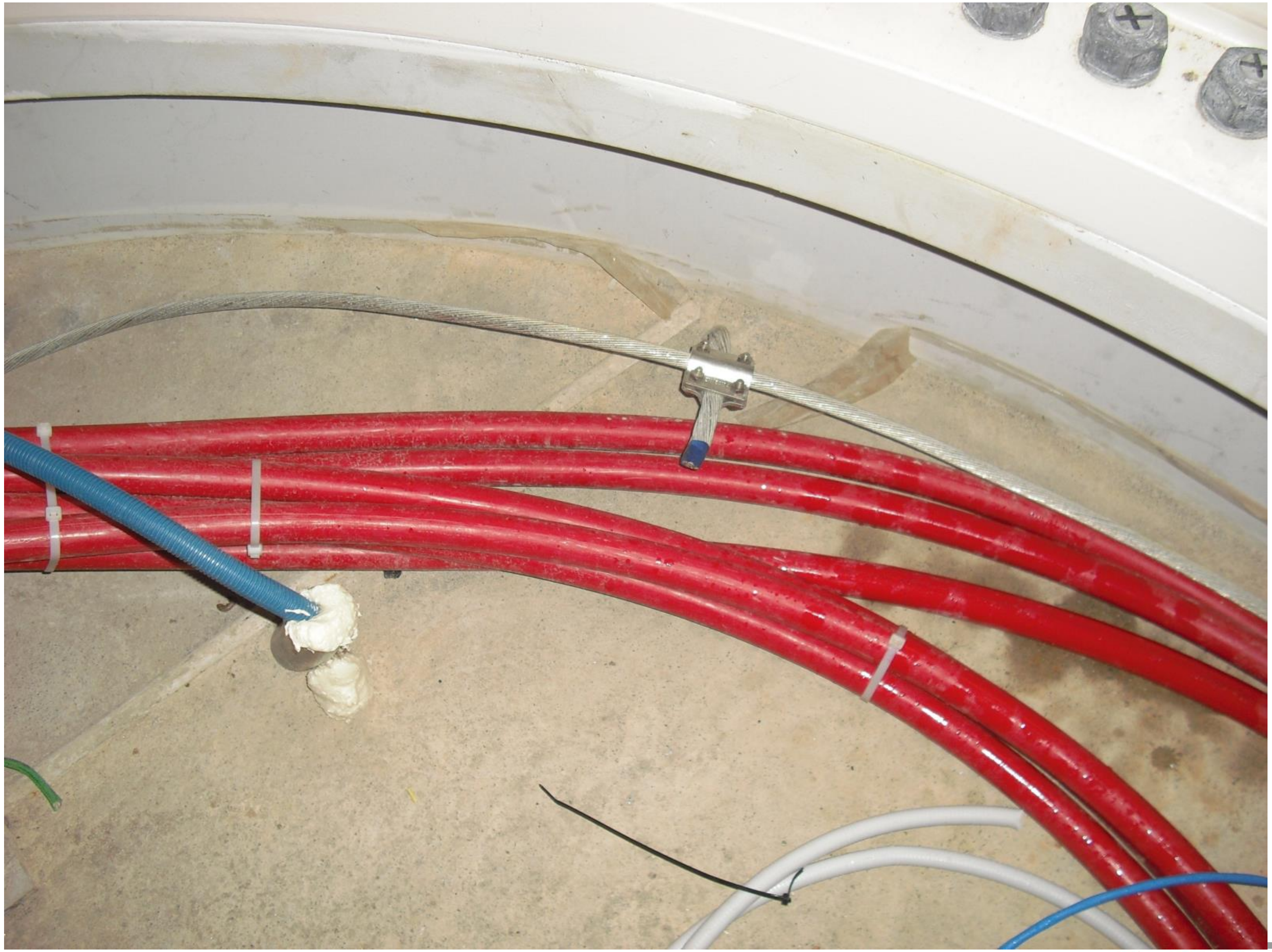


https://www.dehn-international.com/en/protective-measures-foundations

Wind turbine electrical grounding.



Wind turbine electrical grounding



Wind turbine electrical grounding.

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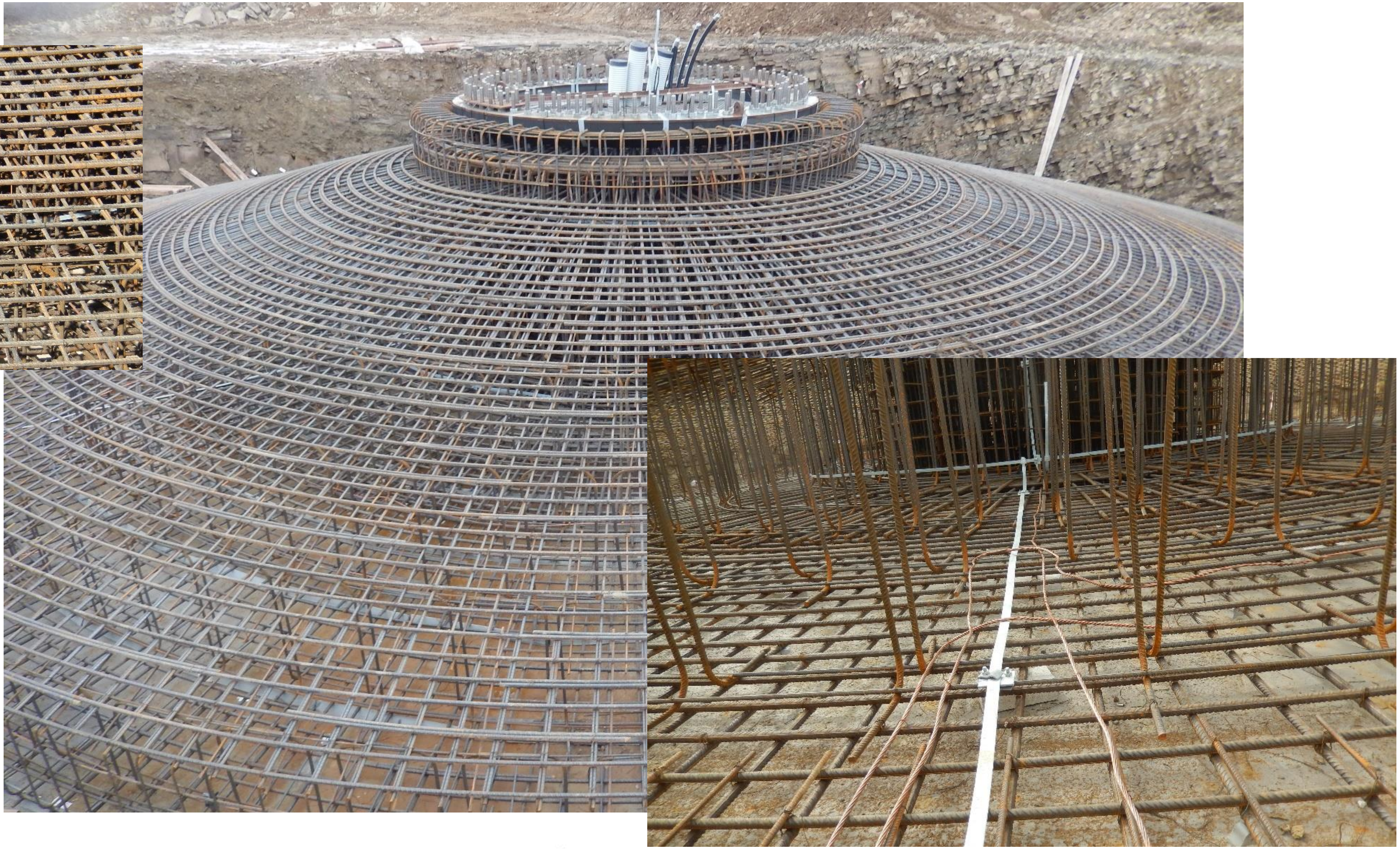
Wind turbine electrical grounding.



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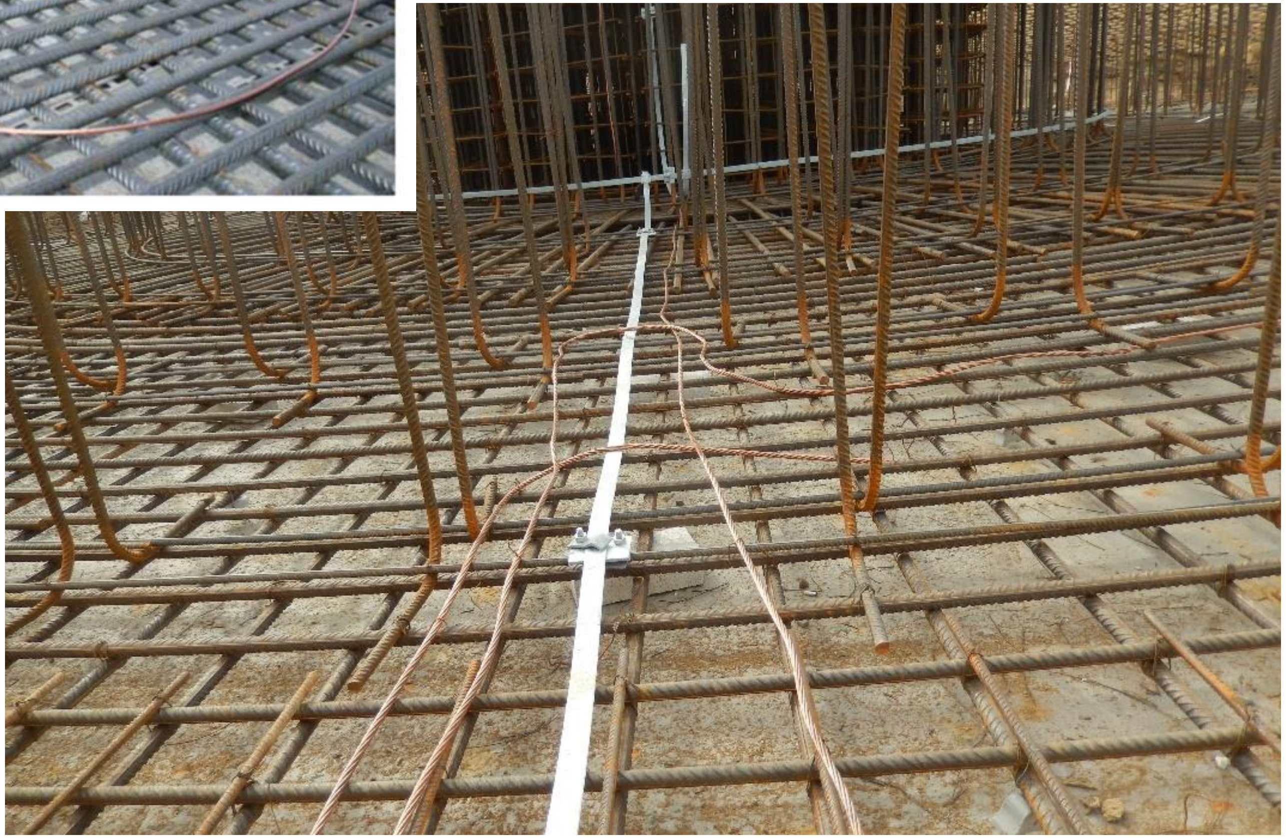
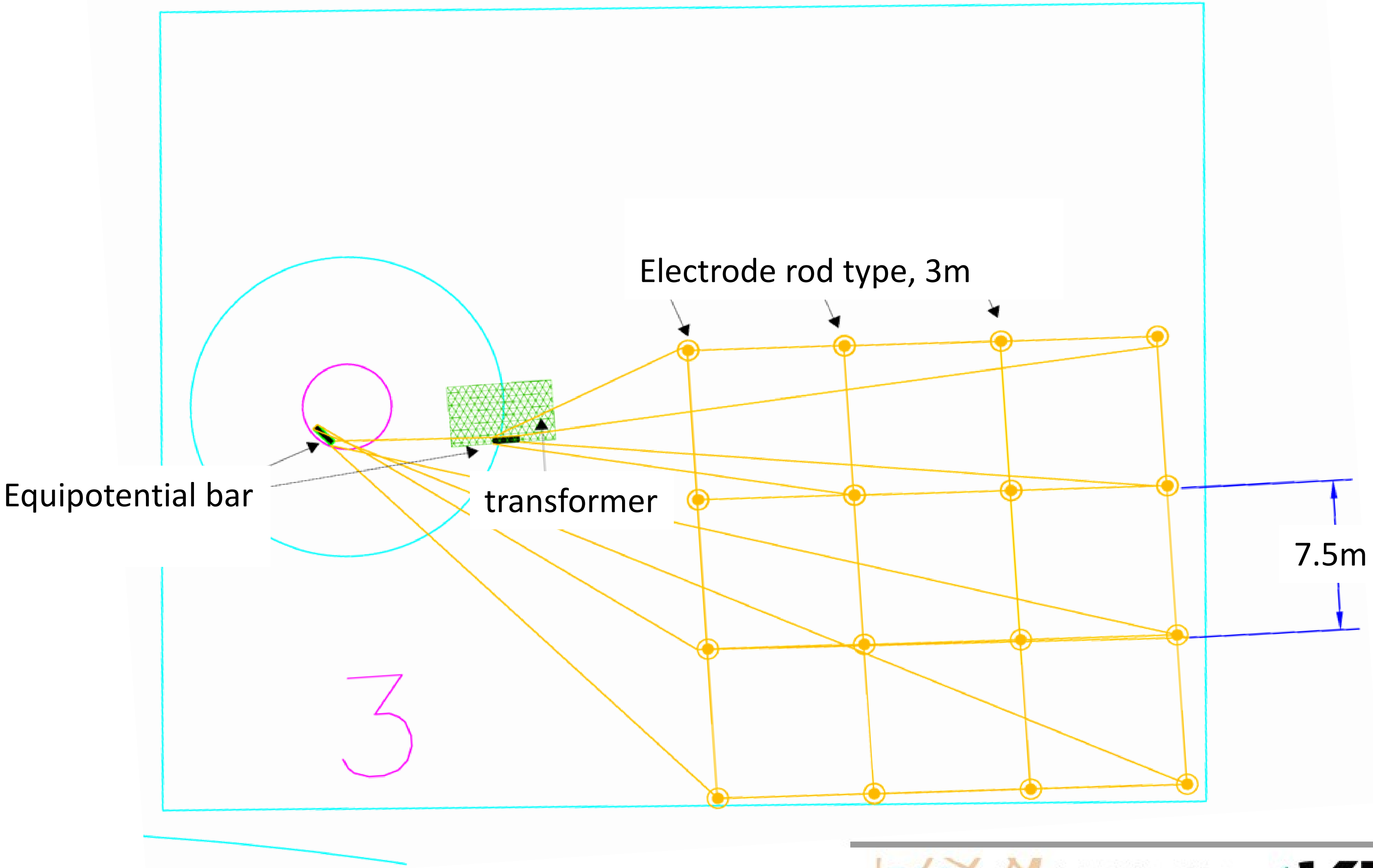
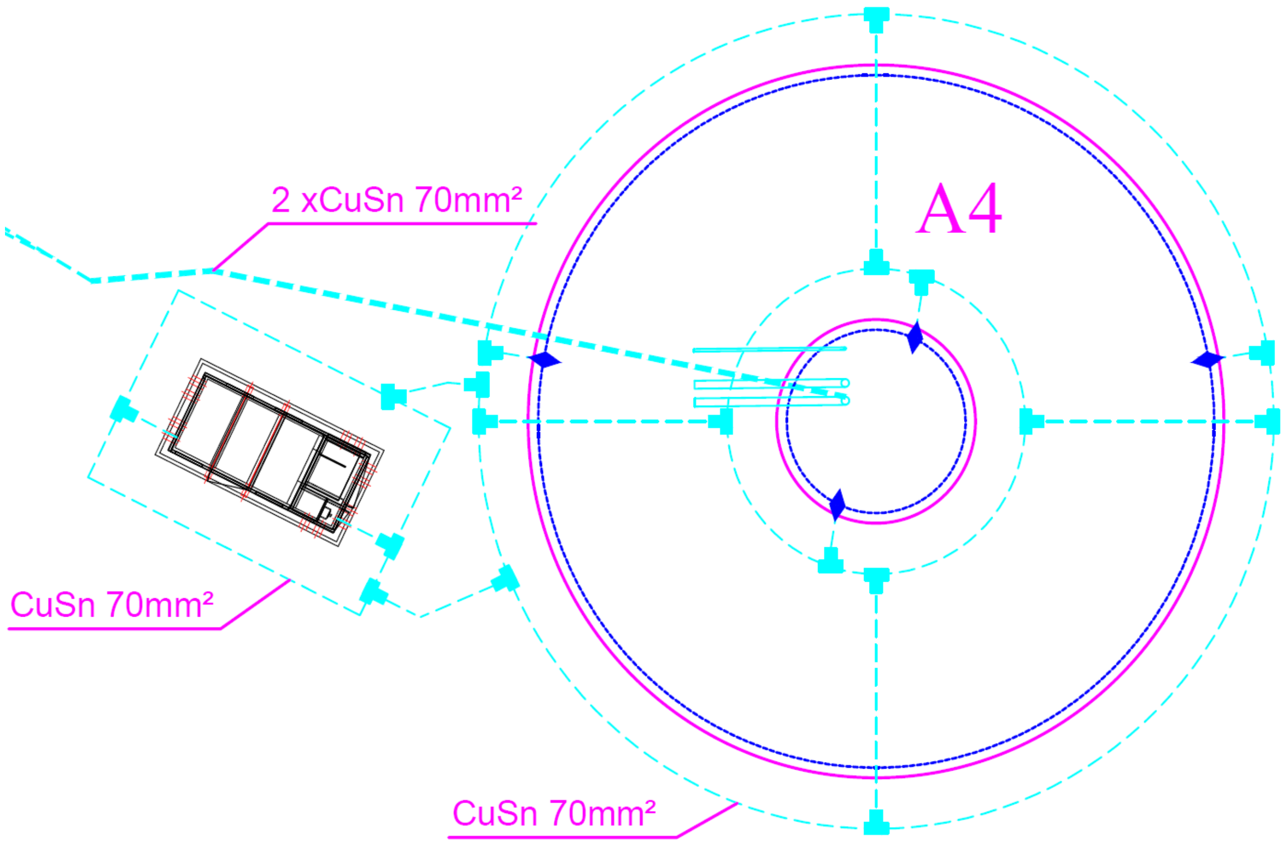


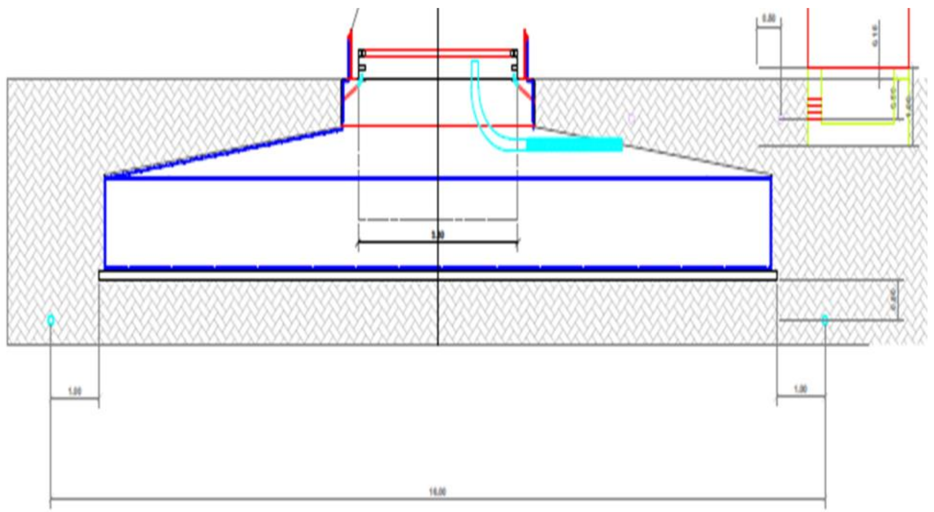
Wind turbine electrical grounding.

Wind turbine electrical grounding.

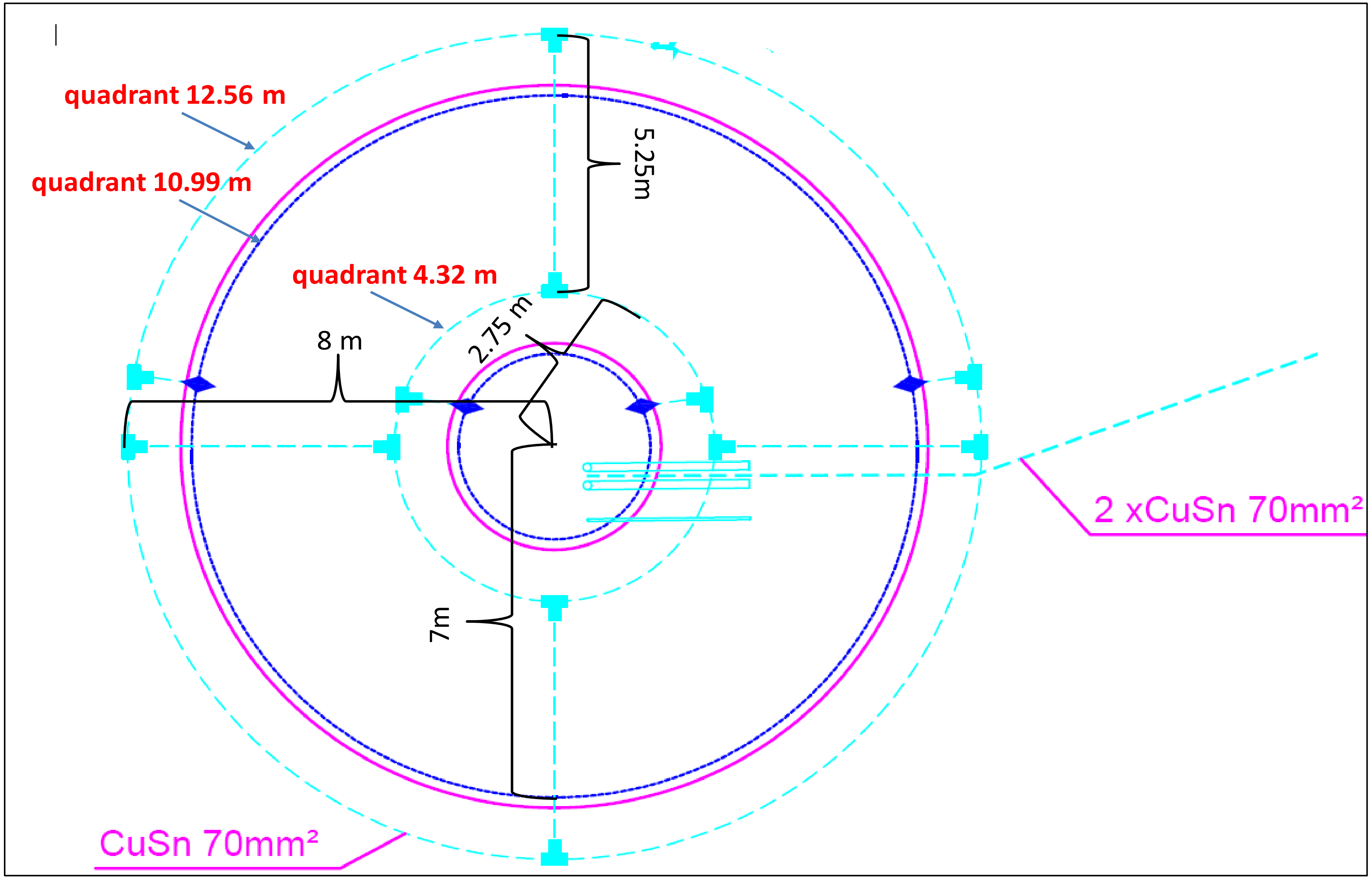


Wind turbine electrical grounding.

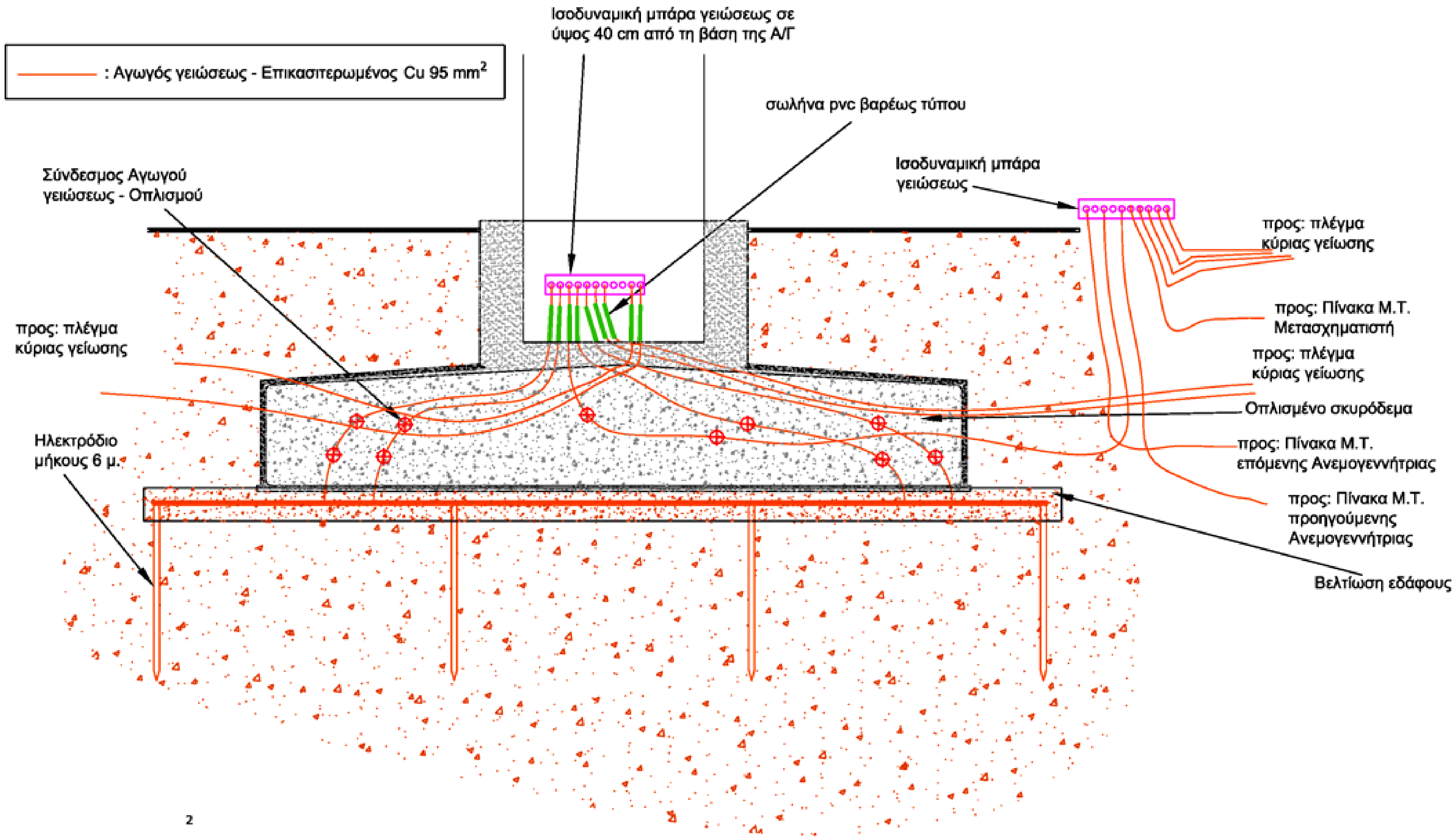




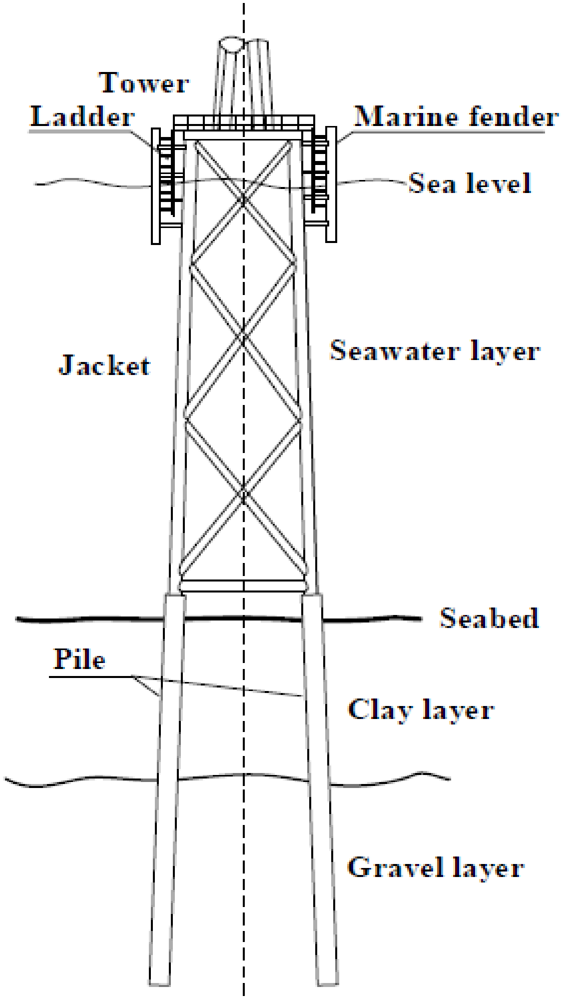
Wind turbine electrical grounding.



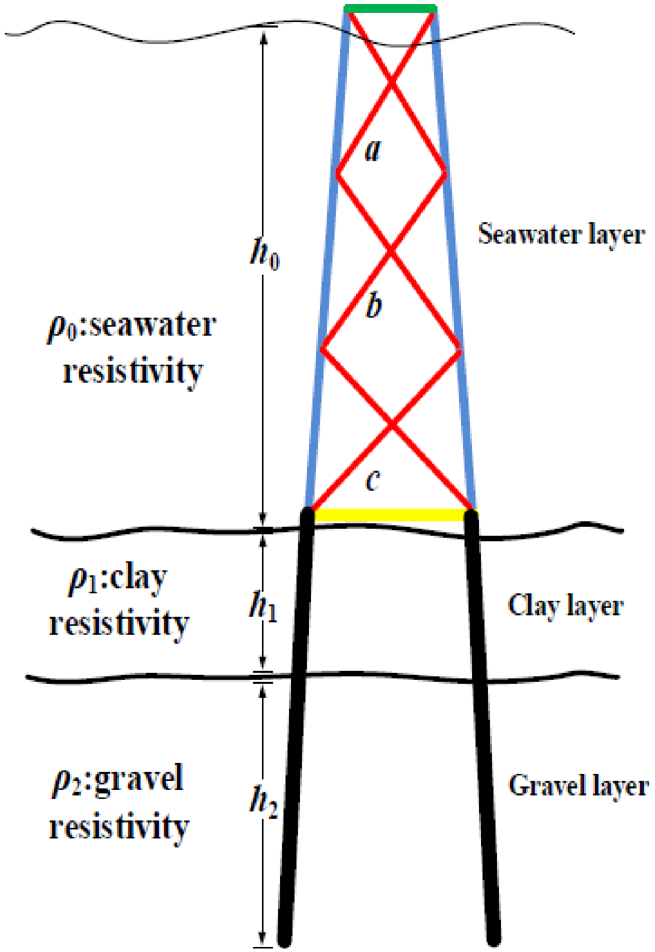
Wind turbine electrical grounding.



Wind turbine electrical grounding.



(a)



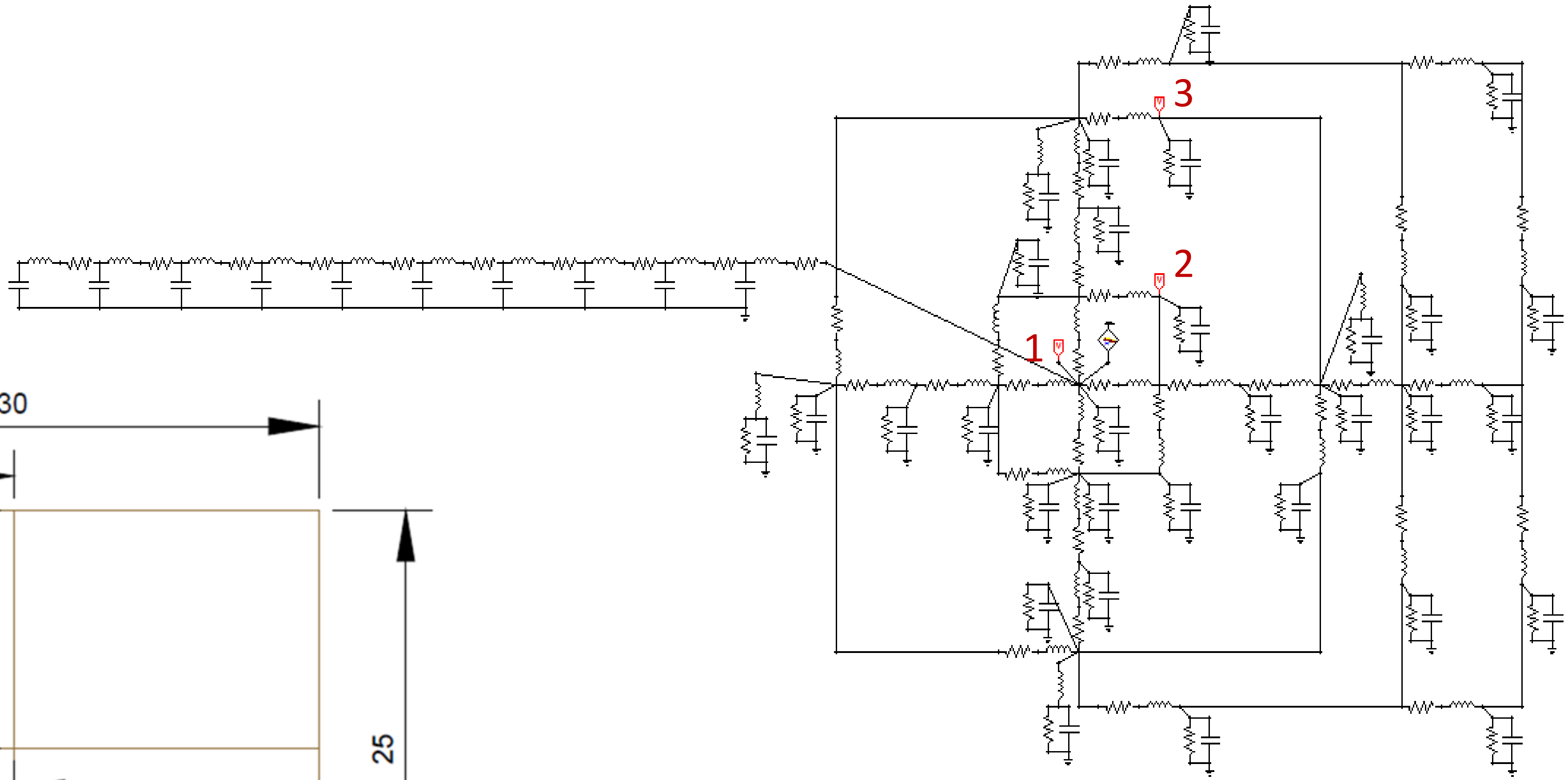
(b)

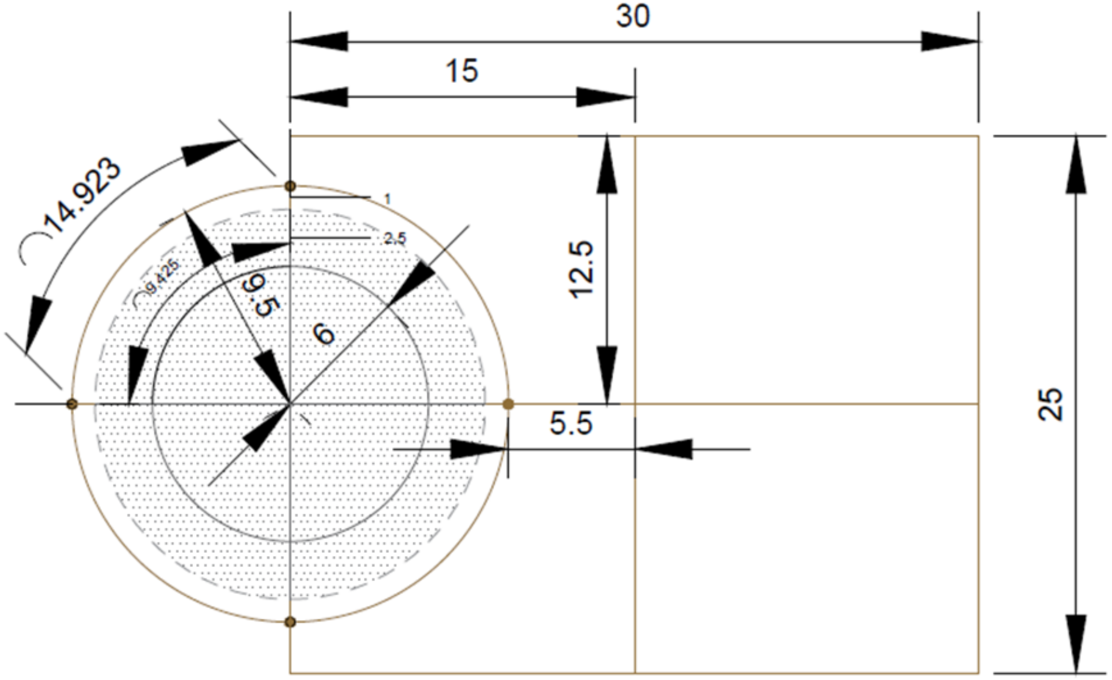
Jacker foundation

a) Structure diagram
b) Schematic diagram

A modeling analysis of grounding resistance and sea surface potential on jacket foundation offshore wind turbines Doi.org/10.1051/e3scof/20187201004

Wind turbine electrical grounding





Transient behavior of wind turbine grounding, Chaliamani Iliana, Thesis, Upatras 2017

Developing voltages in kV, Lightning strike at the base of wind turbine

	Lightning I=10kA 1,2/50μs		Lightning I=30kA 1,2/50μs		Lightning I=100kA 1,2/50μs	
	With rod	Without rod	With rod	Without rod	With rod	Without rod
point 1	40	75	65	110	220	320
point 2	6.5	8	11.5	19	30	37
point 3	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

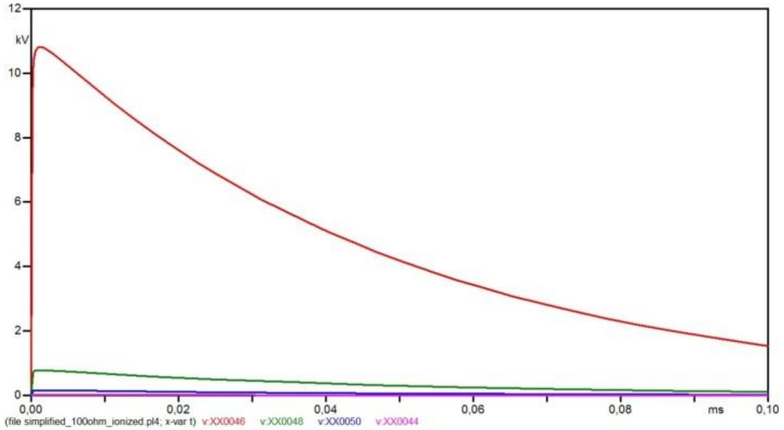
Developing voltages in kV, Lightning strike at the top of wind turbine

	Lightning I=10kA 1,2/50μs		Lightning I=10kA 1,2/50μs		Lightning I=100kA 1,2/50μs	
	With rod	Without rod	With rod	Without rod	With rod	Without rod
point 1	70	95	70	95	440	550
point 2	15	19	15	19	62	80
point 3	< 0.2	< 0.2	< 0.2	< 0.1	< 0.1	< 0.1

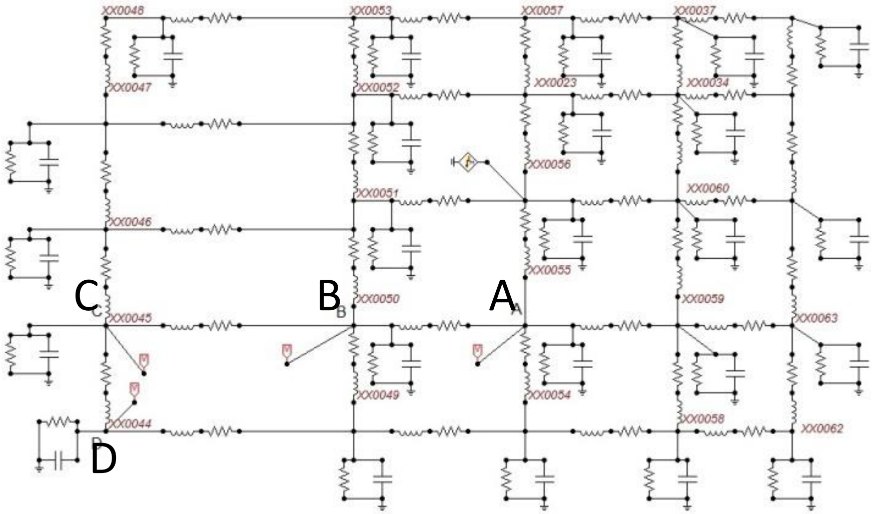
Mean decrease with rod ~30%

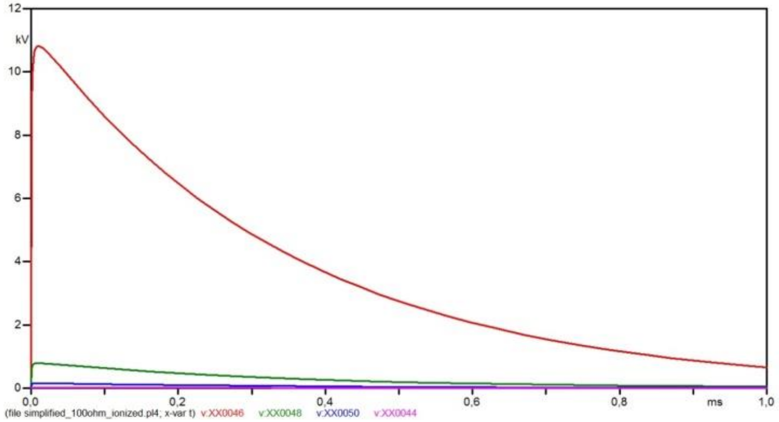
Transient behavior of wind turbine grounding, Chaliamani Iliana, Thesis, Upatras 2017

Lightning protection of wind turbines



Transient voltages for A, B, C, D, 100Ωm, 100kA, 1.2/50μs, E_c=300kV/m, V_{Apeak}=10.81kV

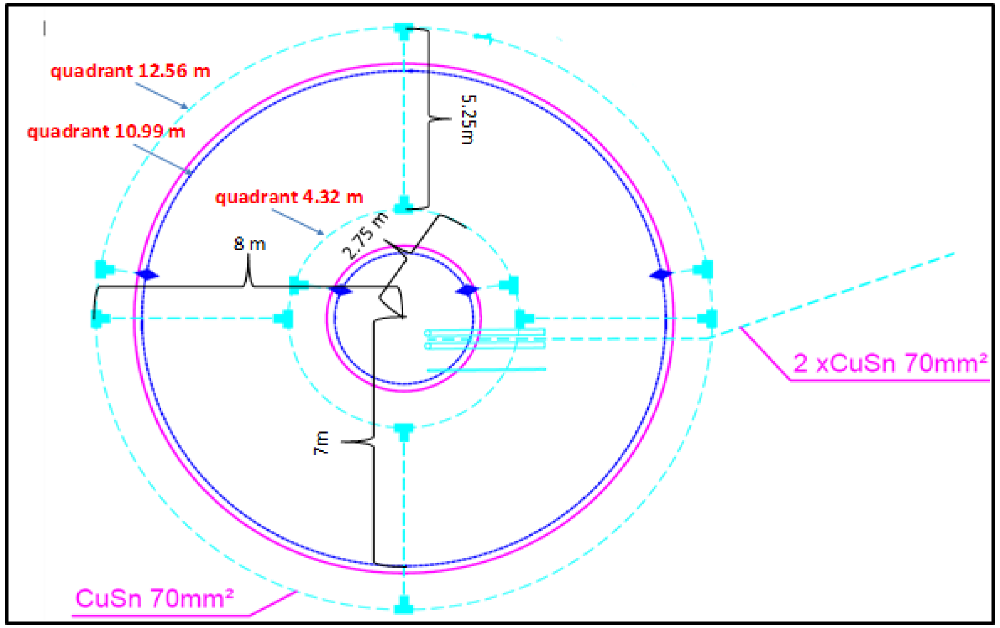


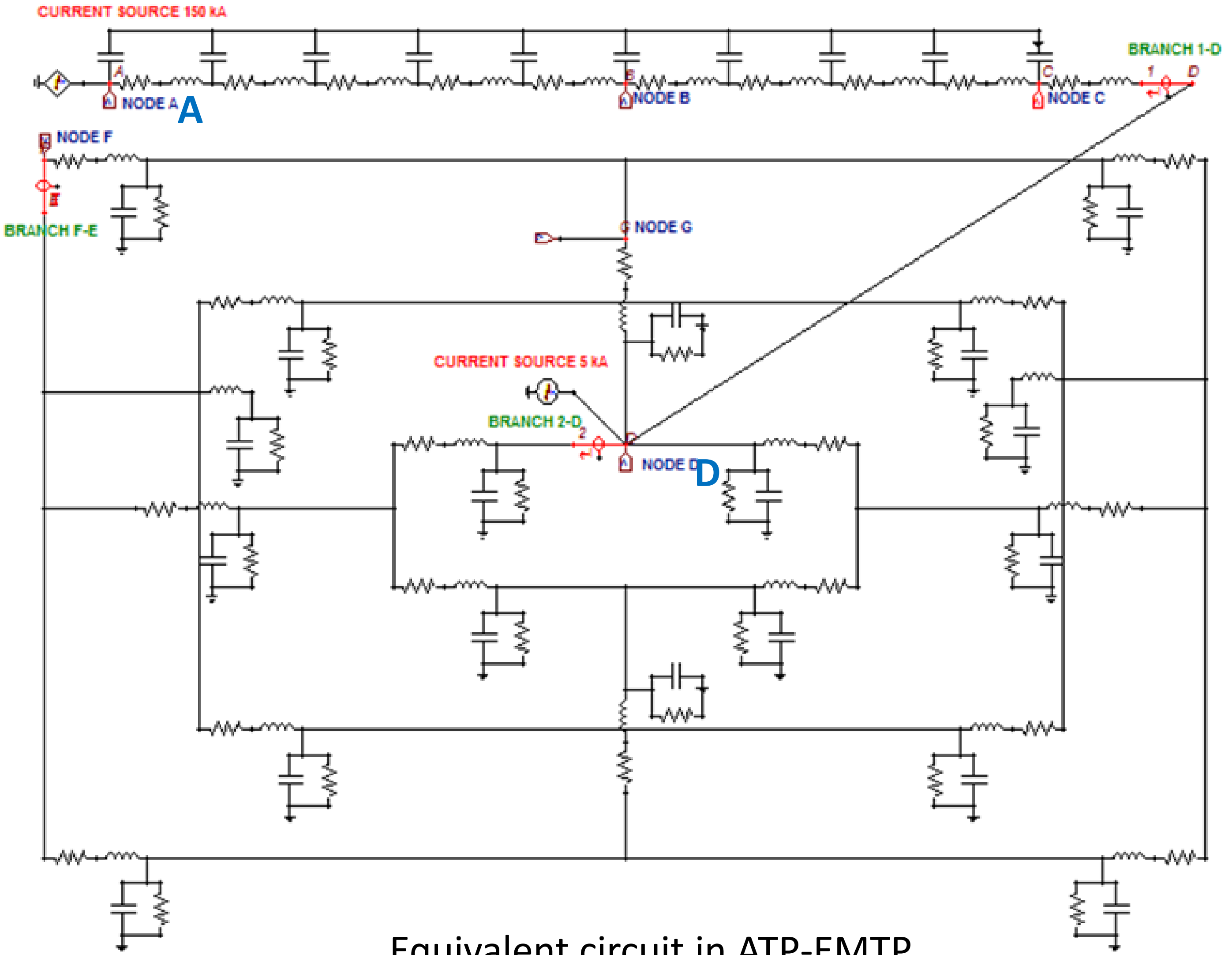


Transient voltages for A, B, C, D, 100 Ωm, 100kA, 10/350μs, E_c=300kV/m, V_{Apeak}=10.81kV

***Eleftheria Pyrgioti, Vasileios Bokogiannis,* "Lightning Impulse Performance of a Wind Turbine Grounding Grid Considering Soil Ionization" APL2011, Nov. 1-4, 2011, Chengdu, China**

Wind turbine electrical grounding



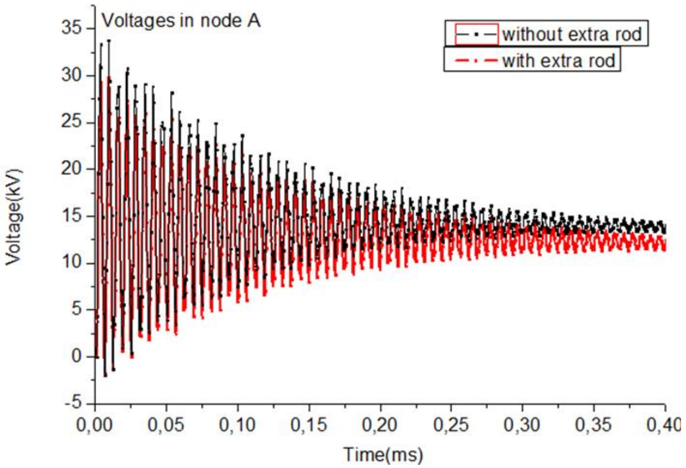


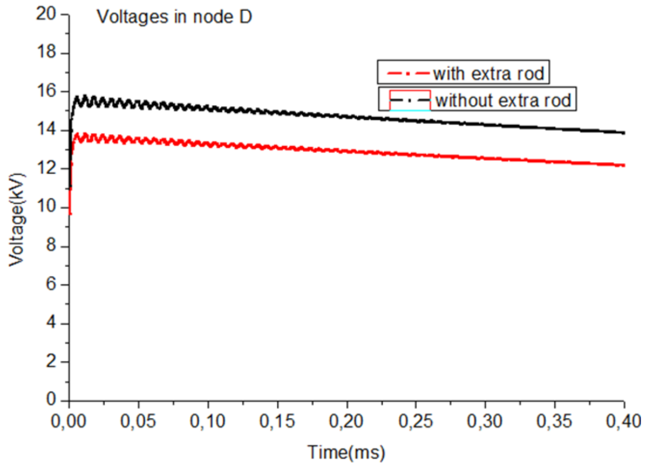
Equivalent circuit in ATP-EMTP

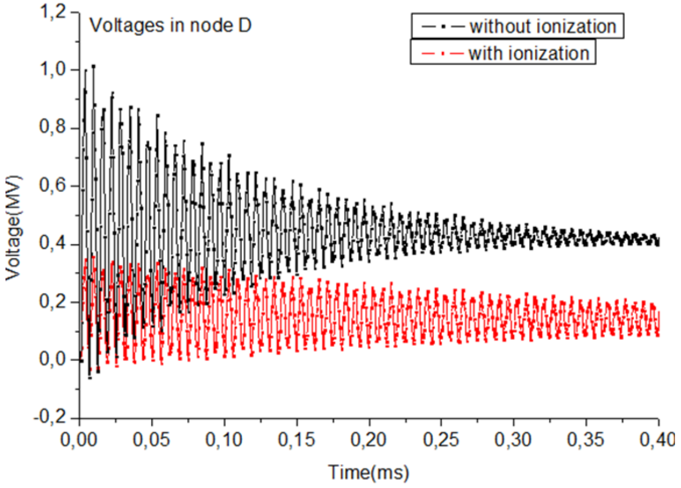
I. A. Naxakis, S. A. Pastromas, S. I. Xerra, K. N. Koutras and E. C. Pyrgioti: "EVALUATION OF WIND TURBINE EARTHING SYSTEM, (ISH 2019)

Wind Turbine Grounding

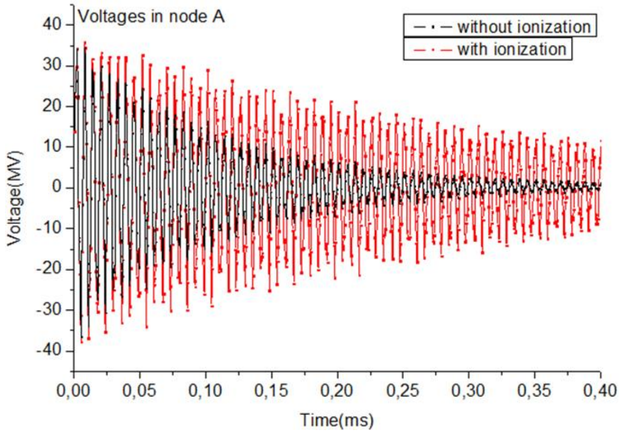
5kA in node D

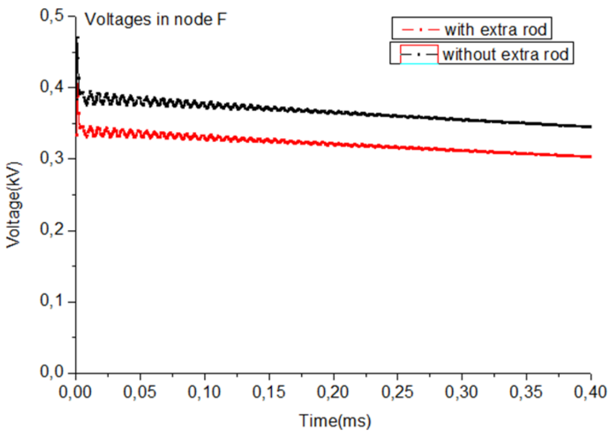


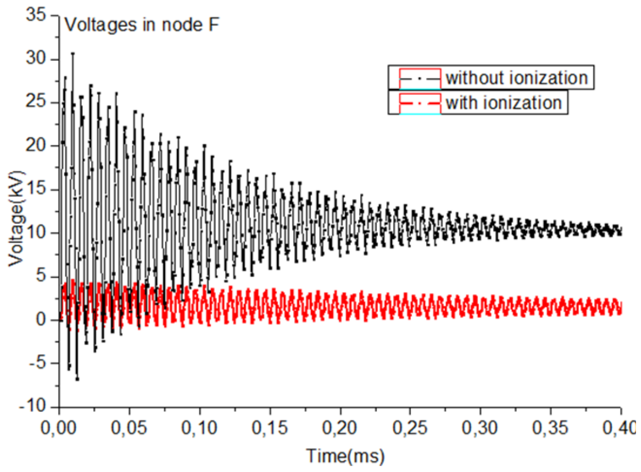




150kA in node A







I. A. Naxakis, S. A. Pastromas, S. I. Xerra, K. N. Koutras and E. C. Pyrgioti: “EVALUATION OF WIND TURBINE EARTHING SYSTEM, (ISH 2019)

Corrosion prevention

Corrosion protection must be provided through bimetallic contacts and cathodic protection.

Connections between metals with a potential difference greater than 0.5V are not allowed, e.g. aluminum-copper connection must be made with a stainless-steel connector. Alternatively the connection point must be protected by a waterproof housing.

Cathodic protection can be passive or active. Passivity is ensured by connecting to the installation a metal more electronegative than steel and aluminum, e.g. zinc or magnesium.

The active cathodic protection is ensured by applying potential difference ≈ 1V

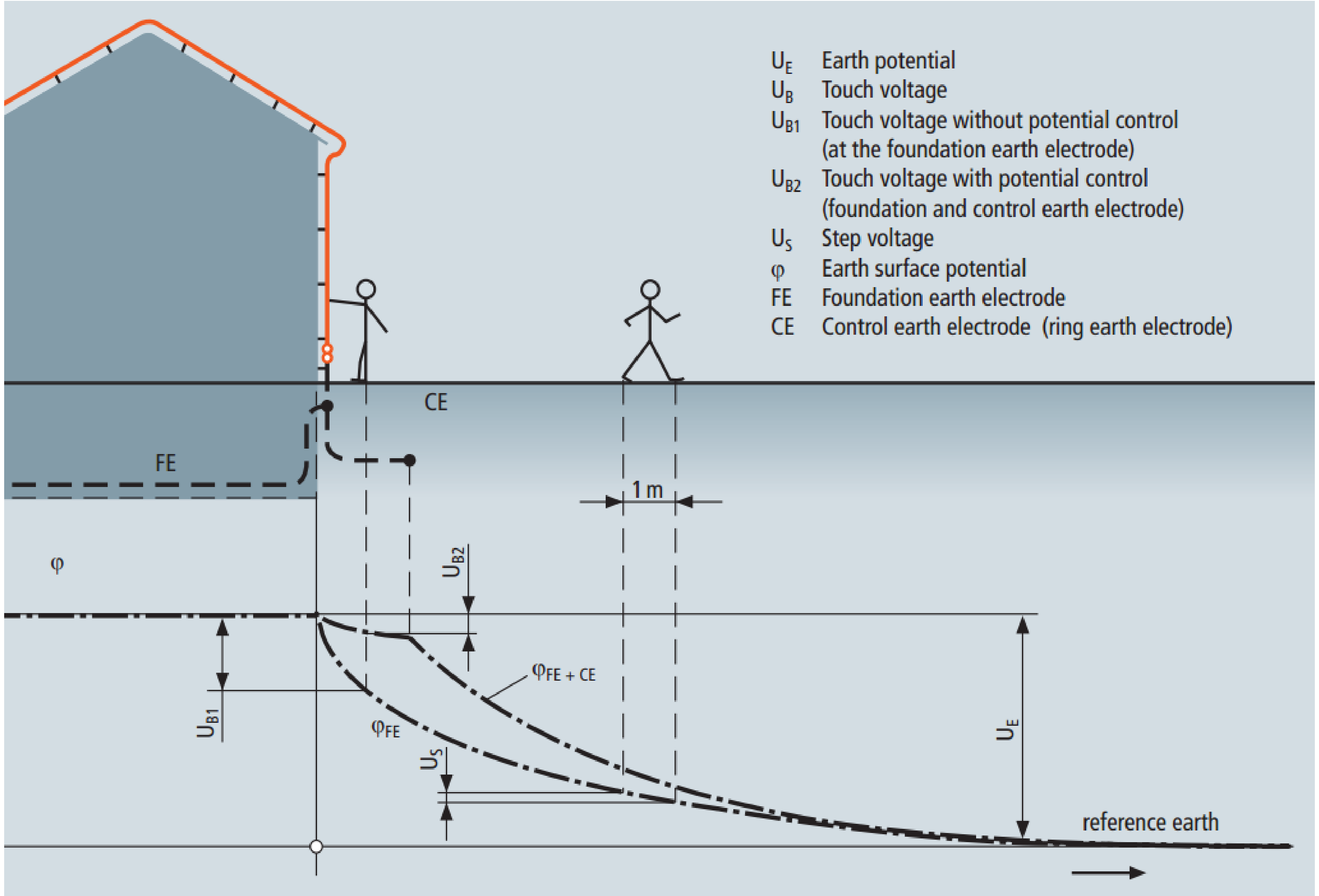
Alternatively and in special cases SPD protection-cutting devices are needed.
Attention! appropriate analysis is necessary to avoid sparks

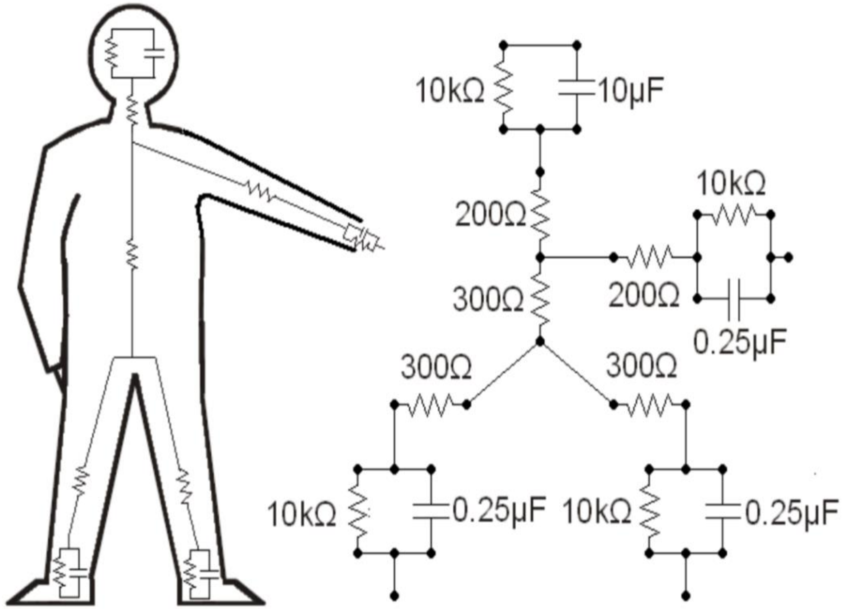
Corrosion prevention

Steady State Electrode	Material Potential (SEA WATER), Volts
Graphite	+0.25
Platinum	+0.15
Zirconium	-0.04
Type 316 Stainless Steel (Passive)	-0.05
Type 304 Stainless Steel (Passive)	-0.08
Monel 400	-0.08
Hastelloy C	-0.08
Titanium	-0.1
Silver	-0.13
Type 410 Stainless Steel (Passive)	-0.15
Type 316 Stainless Steel (Active)	-0.18
Nickel	-0.2
Type 430 Stainless Steel (Passive)	-0.22
Copper Alloy 715 (70-30 Cupro-Nickel)	-0.25
Copper Alloy 706 (90-10 Cupro-Nickel)	-0.28
Copper Alloy 443 (Admiralty Brass)	-0.29
G Bronze	-0.31
Copper Alloy 687 (Aluminum Brass)	-0.32
Copper	-0.36
Alloy 464 (Naval Rolled Brass)	-0.4
Type 410 Stainless Steel (Active)	-0.52
Type 304 Stainless Steel (Active)	-0.53
Type 430 Stainless Steel (Active)	-0.57
Carbon Steel	-0.61
Cast Iron	-0.61
Aluminum 3003-H	-0.79
Zinc	-1.03

http://metals.about.com/od/Corrosion/a/Galvanic-Corrosion.htm

Measures to limit the step and touch voltages



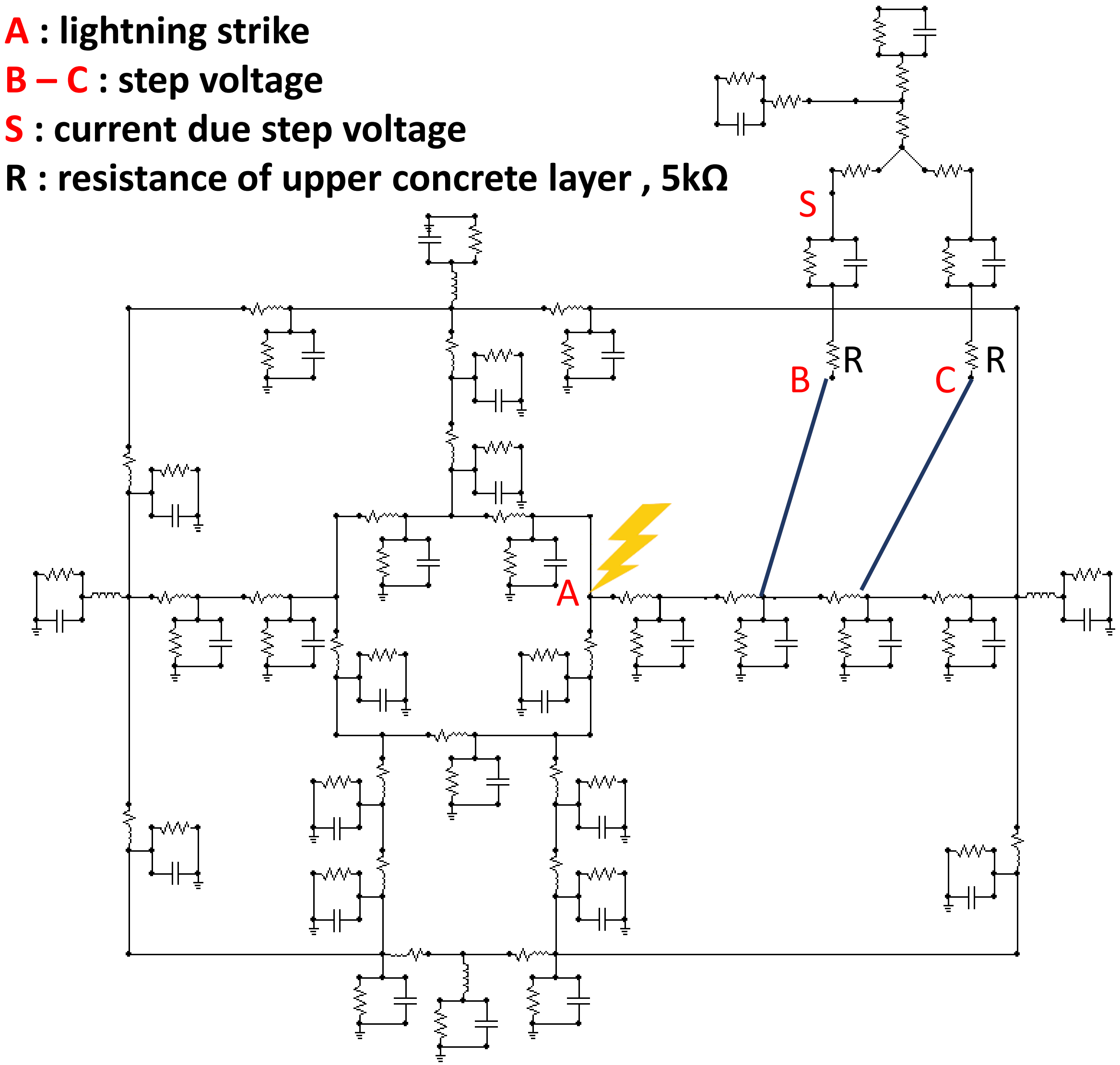


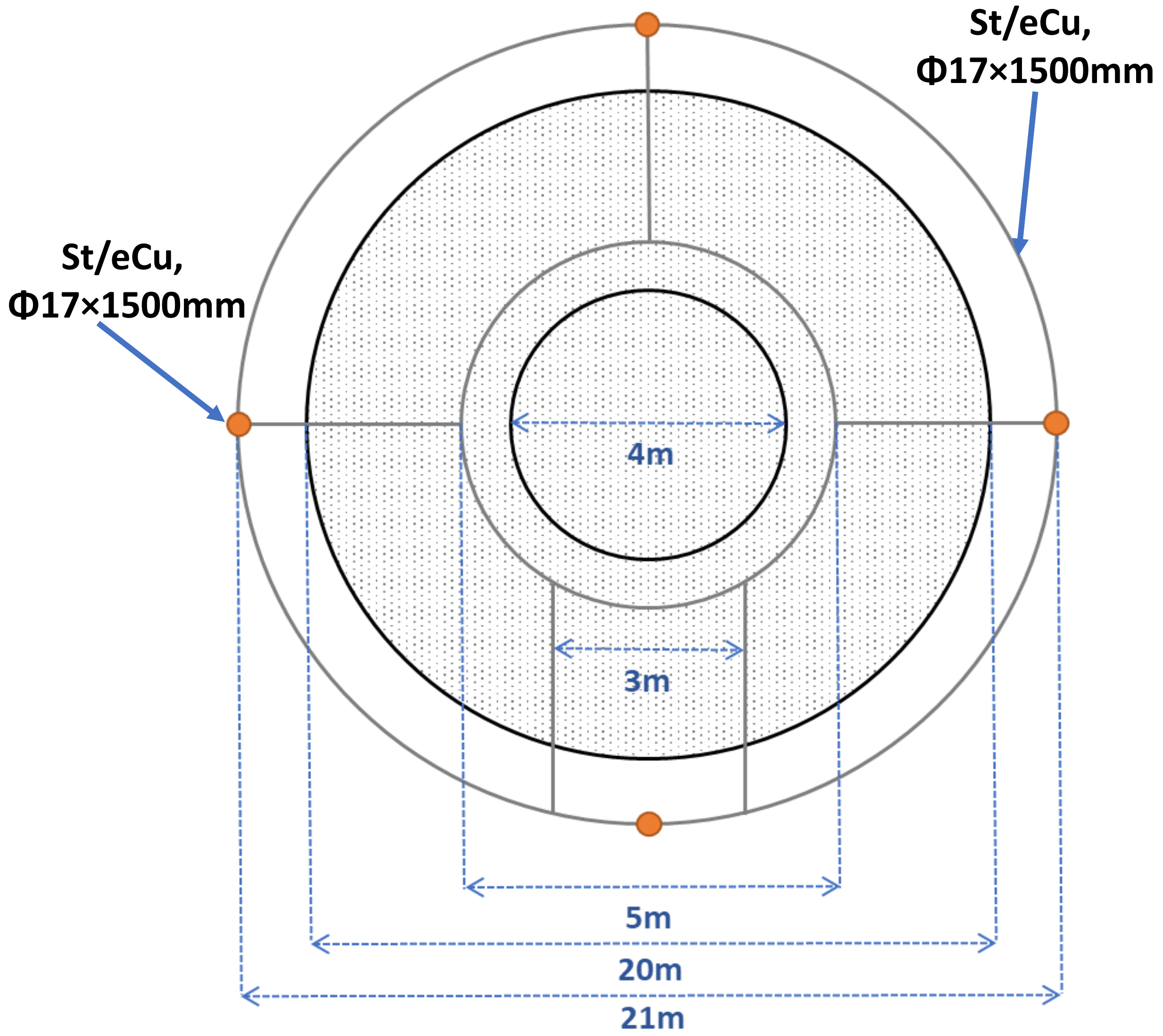
Equivalent electrical human model

LIGHTNING PROTECTION GUIDE 3rd updated Edition, DEHN + SÖHNE, 2014

Safety against touch and step voltages

- A : lightning strike
- B – C : step voltage
- S : current due step voltage
- R : resistance of upper concrete layer , 5kΩ





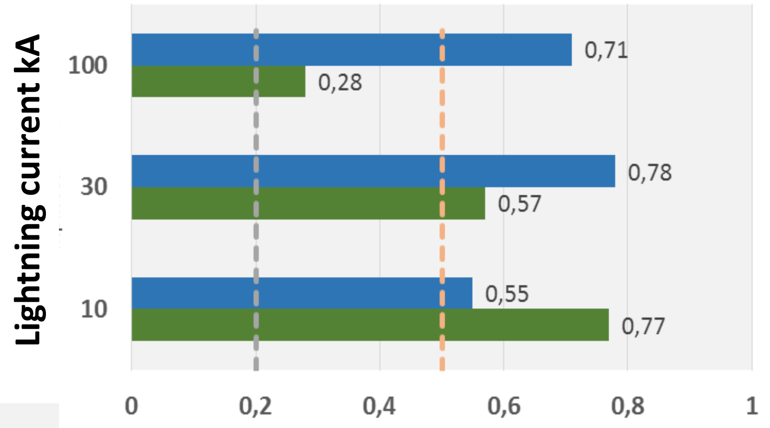
Transient behavior of wind turbine grounding M. Bombyla, Thesis, Upatras 2016

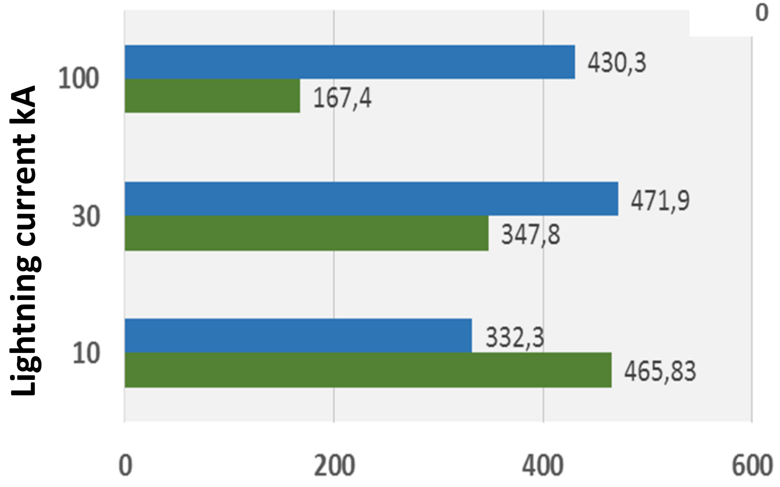
Safety against touch and step voltages

Zone 1 (0–2mA): current is not perceived
Zone 2 (2-200mA): muscle contraction, without pathological effect
Zone 3 (200–500mA): possible transient cardiac disturbances
Zone 4 (> 500): chance of heart palpitations

Permissible step voltage limits

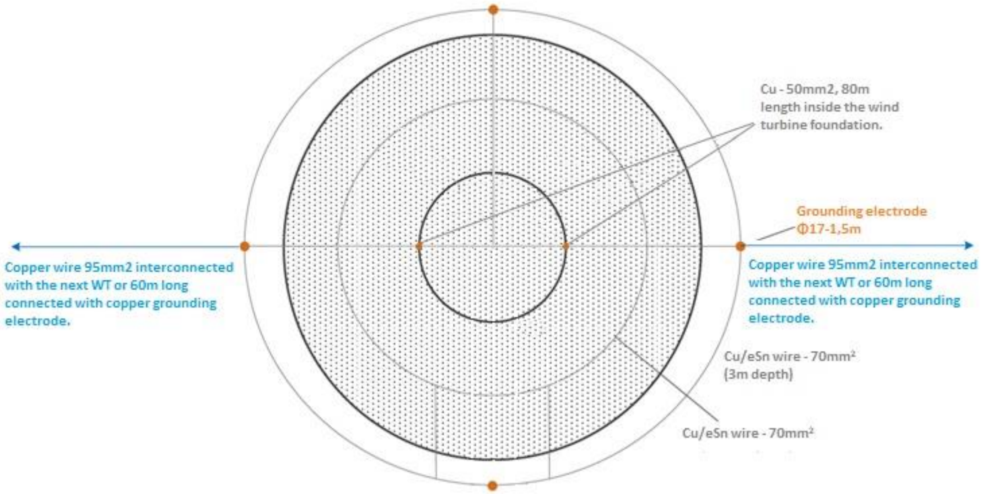
t_s (ms)	E_{step50} (V)	E_{step70} (V)
$\rho_{concrete} = \rho_s = 50\ \Omega m$		
0,5	105309,8	142531,4
1	74465,3	100784,9
3	42992,5	58188,2
5	33301,9	45072,4
$\rho_{concrete} = \rho_s = 300\ \Omega m$		
0,5	113091,3	153063,3
1	79967,6	108232,1
3	46169,3	62487,8
5	35762,6	48402,8

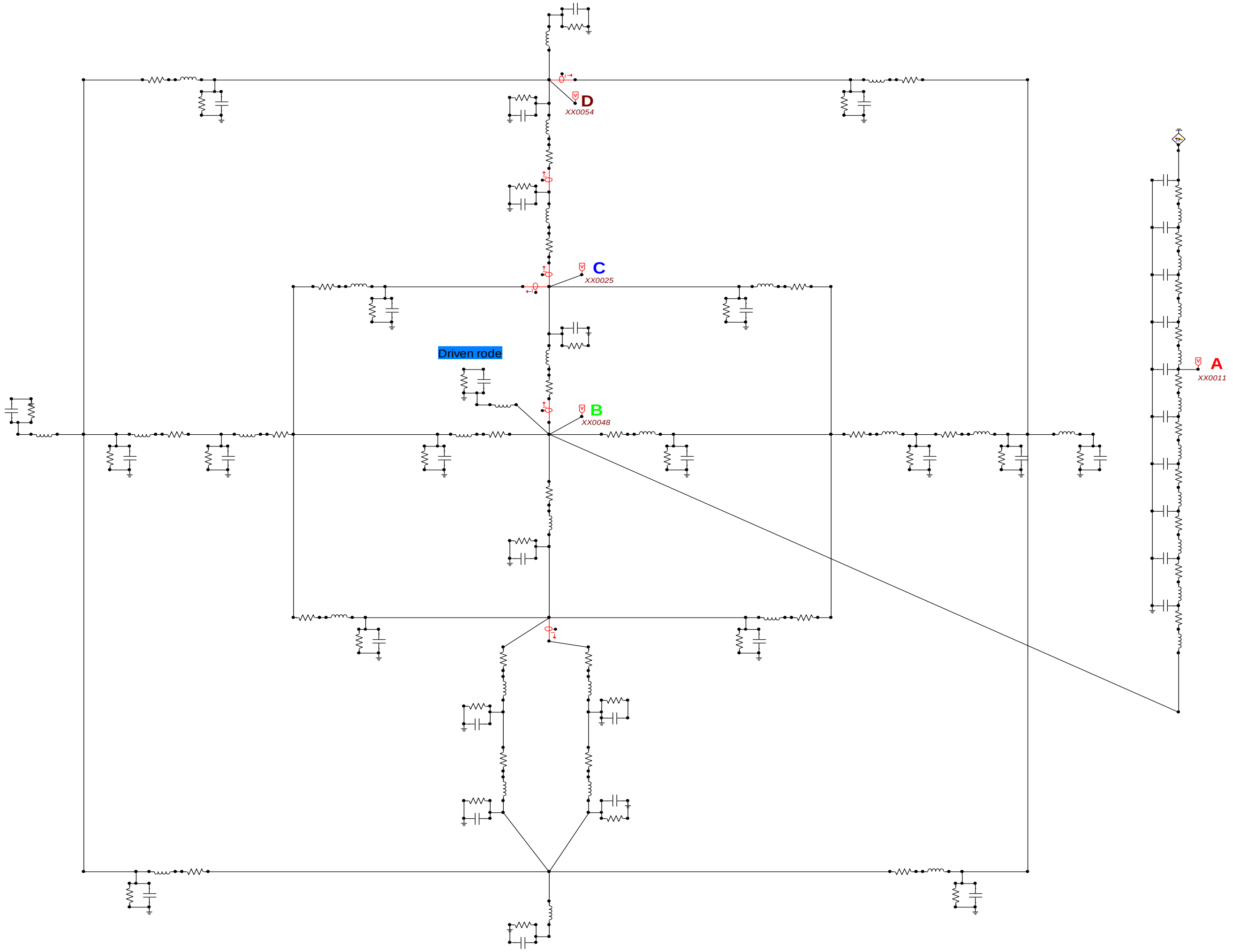




Transient behavior of wind turbine grounding M. Bombyla, Thesis, Upatras 2016

Wind turbine electrical grounding





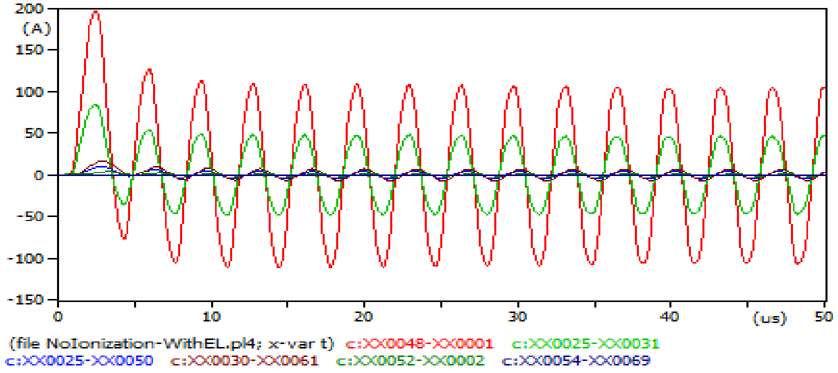
Wind Turbine Tower Technical Data & Calculated Values

Parameter	Value	Unit
H	80	m
rt	3.5	m
S	0.438	m^2
ρ	$1.5 * 10^{-7}$	Ωm
μ/μ0	100	-
Tower thickness	0.02	m
Lt	$5.59 \cdot 10^{-5}$	H
Rt	$2.74 \cdot 10^{-5}$	Ω
Z1	$5.59*10^{-6} + 2.74*10^{-6}$	Ω
C0	$1.17 \cdot 10^{-9}$	F

“Assessment of Wind Turbine Grounding System” *S. A. Pastromas, K. Maimaris, I. K. Stasinos, I. A. Naxakis, E. C. Pyrgioti* ICHVE 2018, Athens, Greece

Wind turbine electrical grounding

Currents (with central electrode)
ρ=50Ωm, ρ_{soil}=500Ωm, 10kA, 10/350μs



THEORETICAL STEP AND TOUCH VOLTAGES (R=10KΩ)

Voltage (kV)	Fault clearance time in ms			
	0,5	1	3	5
Estep, 50kg	53.43	37.78	21.82	16.90
Estep, 70kg	72.32	51.14	29.52	22.87
Etouch,50kg	52.27	36.96	21.34	16.53
Etouch,70kg	70.74	50.02	28.88	22.37

VOLTAGES AT WIND TURBINE PAD WITH I_p=10KA & 100KA

I/ρ - ρ_{soil} kA/Ωm	Voltages (kV)			
	Point A (point of attack)	Point B (WT base)	Point C (foundation limit)	Point D (soil)
10/50-500	350	3	0.17	0.001
100/250-1000	3500	25	2.00	0.009

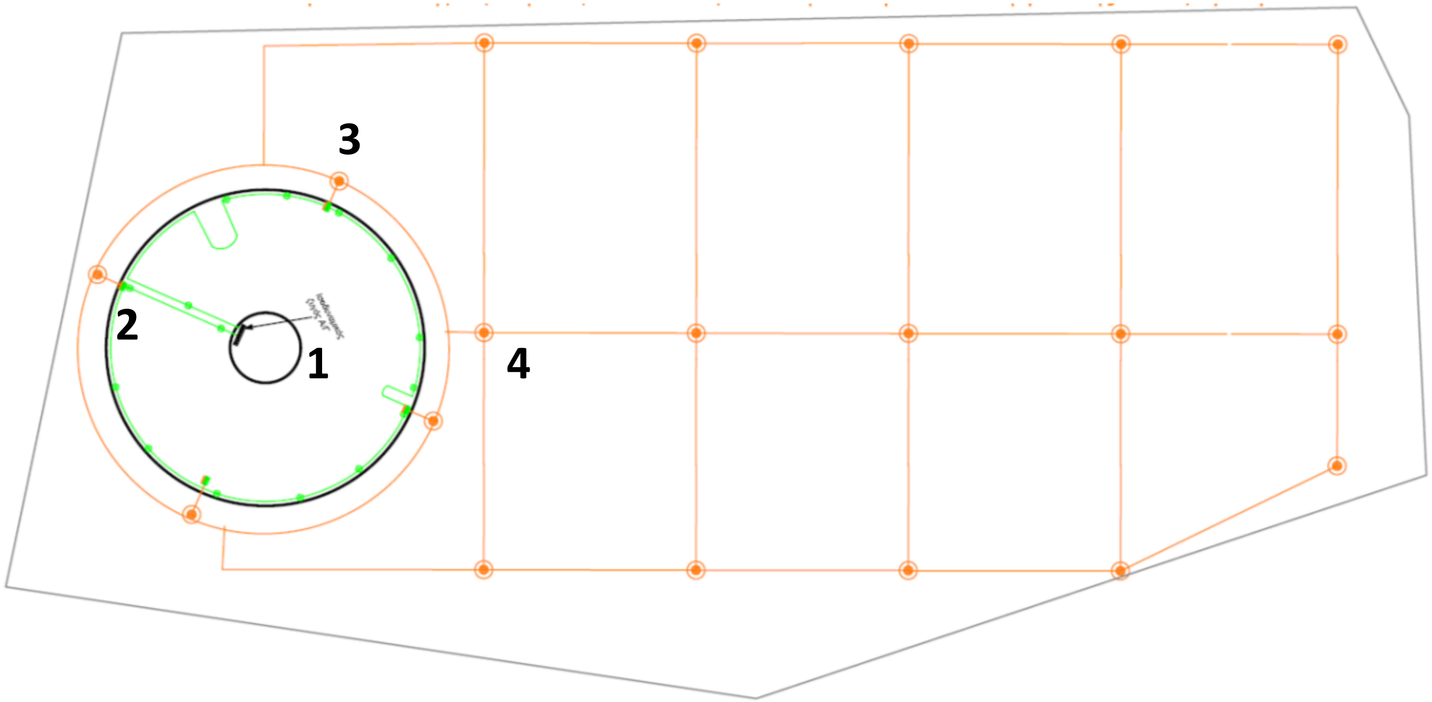
SIMULATION RESULTS FOR STEP-TOUCH VOLTAGES & CURRENTS (R=10KΩ)

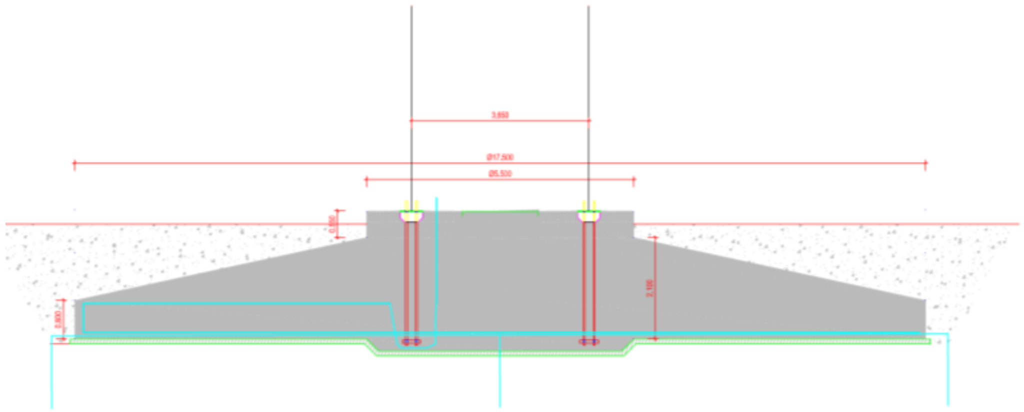
Ip (kA)	Voltages (kV)		Currents (A)	
	Touch	Step	Left leg	Right leg
10 (1-2m)	24.10	11.10	0.41	1.47
10 (2-3m)	-	5.84	0.93	1.49
100 (1-2m)	89.01	49.00	1.27	5.94
100 (2-3m)	-	28.39	3.48	6.19

The specific grounding system is safe for the personnel for low lightning current and for high it is not safe

"Assessment of Wind Turbine Grounding System" *S. A. Pastromas, K. Maimaris, I. K. Stasinos, I. A. Naxakis, E. C. Pyrgioti* ICHVE 2018, Athens, Greece

Wind turbine electrical grounding.

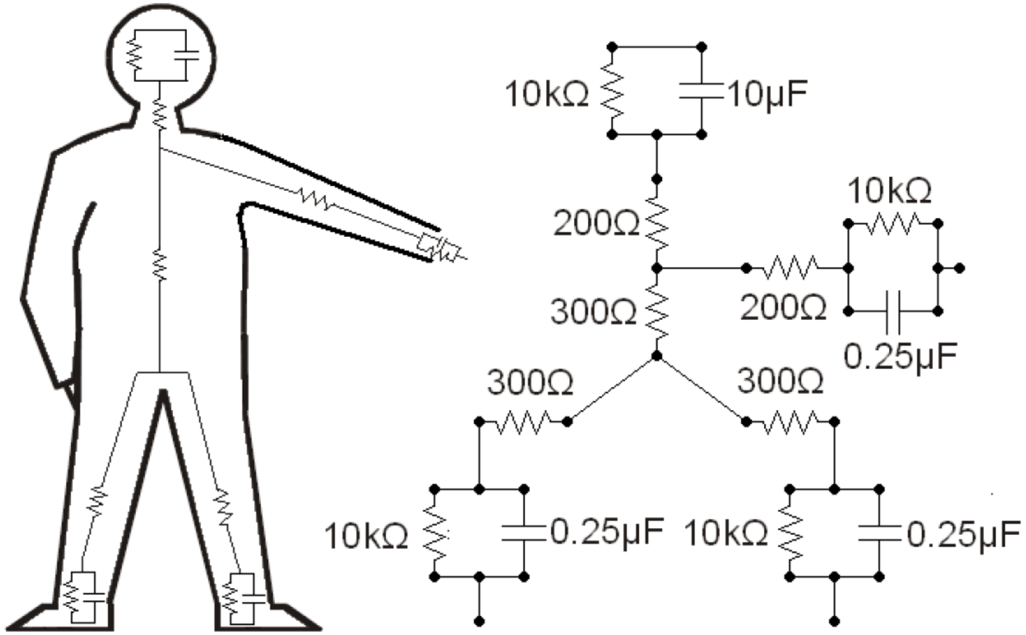




	Point	V_{max} (kV) ρ=50Ωm	V_{max}(kV) ρ=200Ωm
150 kA 1.2/50 μs			
Foundation grounding	1	4500	6000
	2	21	90
	3	7	12
Foundation grounding Plus Grounding grid	1	2700	6000
	2	22	86
	3	5	9
150 kA 19/485 μs	**Point**	**V_{max} (kV), ρ=50Ωm**	**V_{max} (kV) ρ=200Ωm**
Foundation grounding	1	1400	3400
	2	18	58
	3	6	9
Foundation grounding Plus Grounding grid	1	1500	3400
	2	17	55
	3	5	7

Lightning performance og wind turbines, A. Sarametidi, Thesis, Upatras 2017

Wind Turbine Grounding



Lightning strike 150 kA 1.2/50 μs - top of WT tower		
	Step voltage	
point	ρ=50Ωm	ρ=200Ωm
3	917 V	1166 V
4	3 V	4 V
Lightning strike 5 kA 1.2/50 μs - base of WT tower		
	Step voltage	
point	ρ=50Ωm	ρ=200Ωm
3	164 V	335V
4	2 V	3 V

$$Vstep50=(RB+6Cs\rho s)*0.116/\sqrt{ts}$$

$$Vstep50=\mathbf{3016\ V}$$

Lightning performance og wind turbines, A. Sarametidi, Thesis, Upatras 2017

Inspection-maintenance of lightning protection systems
EN (IEC) 62305(1-5)

- Inspection at the beginning of the construction works in order to supervise the foundation grounding
- Inspection after the end of the construction of the LPS

Periodic inspection depending on the type of protected construction, which will include at least:

- Conversion and corrosion inspection of air-termination system components, down-conductors, connections and grounding system
- Measurement of earth resistance, inspection of contacts and lightning equipotential bonding
- Inspection after changes or repairs due to lightning strike
- Protection measures to reduce the risk of touch and step voltages.

Measures for personal protection from lightning

- Use state-of-the-art warning systems
- Decide to suspend outdoor activities
- Move to a safe place, inside a large building or metal vehicle, not near metal installations, water, electrical or electronic installations, or under trees
- Reassess the risk, if half an hour passes without lightning activity, the area is considered safe, the interrupted work can be continued
- Do not touch two metal surfaces at the same time, as you may become part of the lightning discharge path.
- *"Deaths"* from lightning are most often reversible.
- The main symptoms are cardiac and respiratory arrest.
- Learn Cardiopulmonary Resuscitation.
- You can bring back to life victims of lightning strike. Do not be disappointed,
- up to 20 minutes without breathing does not always cause brain damage.

- Do not stop before the victim recovers or before the doctor arrives

NLSI National Lightning Safety Institute

Thank you!