INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the
Research and Development of Wind Turbine Systems
ANNEX XI

26th Meeting of Experts

Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems

Cologno Monzese, March 8 - 9, 1994

Organized by : ENEL S.p.A.

Scientific Coordination :

B. Maribo Pedersen
Dept. of Fluid Mechanics
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INTRODUCTORY NOTE

Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems

by

Emilio Garbagnati (1), Luigi Pandini (2), Alberto Pigini (3)

Wind turbines are tall structures and are often located in high level thunderstorm areas and positioned on the top of hills. Consequently they are highly exposed to lightning and cases have been reported of damages and malfunctioning following lightning strikes. The damages have involved from one side the blades and the structure and from the other side have affected the performance of the inner electric/electronic parts.
In the following the main aspects of interest are mentioned.

Risk to be stricken by lightning

The economic impact of lightning depends on the probability that a given wind turbine is struck by a lightning. This probability depends on:

- the lightning flash density of the territory;
- the geometry of the wind turbine;
- the installation site orography;
- the presence of adjacent structures.

Several models and criteria are available for the evaluation of the probable number of strokes to wind turbines.

The following questions may be of interest:

- are there examples of applications of the models to the structures considered?
- are there sufficient field data to check the theoretical evaluation? Is there the necessity of other "ad hoc" experimental installations for obtaining additional data?
- is protection of the wind turbine and/or wind turbine components against direct

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(3) Alberto Pigini, CESI S.p.A.

strokes by appropriate intercepting structures a feasible and economical approach?

Field experience related to lightning effects

Lightning effects can be subdivid into:

- direct effects, as burning, eroding, structure deformation due to arc attachment, damages to the blades, damages to the bearings;
- indirect effects, mainly resulting from the interaction of the electromagnetic fields accompanying lightning with electric circuits and apparatuses related to the wind turbine;
- effects involving safety, as touch voltage and step voltage in the vicinity of the structure.

The following points are of interest:

- what is the field experience about damages and malfunctioning due to lightning?
- what are the precautions considered in the design phase against lightning effects?

Tests to check the performance against lightning

Tests are very useful both to set up correct design criteria and to verify the adequacy of the design.
As well known, it is not possible to represent with a unique test all the aspects related to lightning.

The following tests can be considered:

Attachment point tests

The objectives of the tests are the determination of the impact point of the lightning on the wind turbine (e.g. blades, nacelle) and the verification of possible punctures deriving from voltage stresses (e.g. puncture of composite materials in the presence of close metallic object).
These tests are usually made on the full structures or on a significant mock-up. The simulation of the lightning channel is obtained by the application, by means of an impulse generator, of suitable voltages to appropriate electrodes (rod, plane, etc.), far from the test object.

Direct effect tests

The objective of the tests are the determination of the effects which lightning currents may produce on the different components. These effects are related to heating of the channel on the impact point (e.g. on the blades) and to the flowing of the current itself (e.g. through the bearings).

These tests are usually made on representative components by applying appropriate current waveshapes by means of suitable current generators.

The test current should be conducted into and out of the test object in a manner similar to the way lightning current would be conducted in the actual condition. In particular, when the heating effect due to the arc is to be taken into account, the test current is usually injected from a test electrode separated from the test object by a small air gap.

Indirect effect tests

The objective of these tests is to characterize induced voltages and currents in the electrical wiring related to the wind turbine and to verify circuits and components which may be susceptible to lightning induced effects. The circuits involved can be both those inside the generator and those of the related apparatsuses on the power network side.

Preliminary information can be obtained by appropriate measurements during "attachment tests" and "direct effect tests".

Ad hoc tests can be made on the full structure or on significant parts by injecting through the structures suitable current impulses.

The following points are of interest:

- what are the waveshapes and test set-up considered more representative for the different kinds of test?
- are there standards or specifications to be taken as reference?
- what is the test experience with the different design solutions?

Electromagnetic Compatibility of Control Systems

Electromagnetic disturbances can affect the reliability of electronic control systems and, consequently, the functional performances of the controlled process. Therefore, proper EMC requirements are generally applied in the design and testing of control systems for the different applications.

IEC product standards and basic test procedures have been already published and are in progress for several applications, e.g. industrial processes, HV substations and power installations; in these standards the different disturbances affecting the electromagnetic environments are considered (LF and HF, conducted and radiated), including the lightning phenomena and associated effects. Test procedures and examples of EMC requirements are given in the IEC publications of the series 1000-4, 801 and 255.

The adoption in the European Communities of the Council Directive 89/336/EEC on EMC, applicable to electrical and electronic equipment and installations, has considerably increased the CENELEC and IEC activities.

Attention should be addressed to the need of EMC requirements dedicated to control systems associated to wind turbine generators, or, as alternative approach, to adopt available product standards referring to comparable electromagnetic environment, properly modified for this subject.

A second point of discussion could be the definition of control systems performance criteria, to be associated to the different electromagnetic disturbances (continuous and transients), with particular reference to direct and indirect effects of the lightning phenomena.

LIGHTNING PROTECTION OF WIND TURBINE GENERATOR SYSTEMS.

SERVICE EXPERIENCE FROM NORWAY AND PROPOSED SOLUTIONS TO REDUCE LIGHTNING DAMAGE.

BY

ASLE SCHEI
TRANSINOR As
NORWAY

26TH MEETING OF EXPERTS

Lightning Protection of Wind Turbine Generator Systems and

EMC Problems in Associated Control Systems,

Cologno Monzese, March 8th-9th, 1994

1. INTRODUCTION

This paper presents an overview of the service experience with respect to lightning damages to wind turbine generator systems in Norway during the period 1986 to February 1994. The systems covered except one (V-å) are all located on the north-west coast of the southern part of Norway, where exposure to positive lightning strokes during the winter season is very well known.

After the presentation of typical lightning data and service experience, the paper try to analyze the reason of the damages and put forward proposals to modify the systems with the aim to obtain better service reliability. Today the failure rates due to lightning are far too high (one per year and wind turbine system) to be acceptable. The aim is to open up for discussion of the problems and the ideas of how to solve them.

2. LIGHTNING STROKE DATA

Fig.1 shows a map of the southern part of Norway with the percentage of positive flashes to earth indicated. It is seen that on the north-west coast outside Trondheim, where the wind turbines marked T, Sm, Va and N-T are located, the percentage of positive strokes in average is in the range of 25-30. During some days in the winter season this percentage is up to 80. In this area the average earth flash density is approximately o.2 strokes per $km^2$and year, which means in average on stroke per km^2every 5 years.

Lightning data prepared by CIGRE Study Committee 33 are shown in Fig.2. It is seen that the average amplitude of the stroke is approximately the same (30kA) for positive and negative strokes, whereas the average charge and (I^2x time) integral for positive strokes is ten times the corresponding values for negative strokes. This corresponds also to the experience of the power utilities which indicate more severe damages to the high voltage distribution network (22kV) during the winter-than during the summer season.

Fig.3 shows similar data from the sea coast of Japan. With respect to the severity of possible lightning damage by positive and negative strokes, it is important to recognise the very big difference in tail duration. For 50% and 16% probability the duration ratios between positive and negative strokes are 21 and 28 respectively.

The above lightning data indicate that more comprehensive lightning protection systems may be necessary in areas like the coastal areas of Norway and Japan, than in areas mainly exposed to negative lightning.

3. OPERATION EXPERIENCE

Table 1 presents an overview of the operation experience of wind turbine generator systems located at six different places along the Norwegian west coast. Except for T1 and Va, which are simpler and less sophisticated than the other wind turbines, the table indicates roughly one damage per year in average. All damages have occurred during the winter season, during which the percentage of positive lightning strokes is greater than during the summer season, as indicated in point 2.

The main difference in the picture of damages between Sm and the other turbines is the many damages to the blades of Sm. In case of Sm all damages involved also the blades, whereas the blades were involved in only one damage out of five in case of T2, and in none of the three damages of N-T3. The main reason for this difference is most likely the different design of the blades, even if some differences in the local conditions, such as neighbouring tall towers in case of T2, may have had some influence. The blades of Sm has built in steel wires for regulation of the tip of the blades. These steel wires are on earth potential, which means that the tip of the blades will act as lightning rods and attract lightning, see Fig.4. In on case all these blades were damaged most likely due to high internal pressure caused by the lightning current, see Fig.5.

In three cases, however, blades made of fibreglass without built in metal parts have been damaged (T2, V-å and Va).

Further, Table 1 illustrates that the most frequent damages are generally to the telecommunication and control circuits, independent of the blade design.

Turbine T1 has a much lower failure rate than all the others except Va which may , at least to some extent, be caused by the fact that T1 is the only one with nacelle made of steel.

To obtain an acceptable operation reliability of wind turbines in Norway, it is absolutely necessary to develop better lightning protection systems that involve the blades as well as the different eclectic power and control systems.

4 MAIN REASONS TO THE LIGHTNING PROBLEMS.

The main reasons to the lightning damages are basically twofold. Firstly, the blades are very often not able to conduct the lightning current without being damaged, and secondly the lightning current path to earth is partly via the steel tower and partly via earthing cables inside the tower causing induced overvoltages in the electric systems.

Also in case the lightning hits the lightning conductor at the top of the nacelle, current will partly flow through cables inside the tower, as illustrated in Fig.6. From the point of view of induced overvoltages in the electric systems this arrangement is not good.

The type of blade shown in Fig.4 (Turbine Sm) will certainly attract lightning more than a blade without built in metal parts on earth potential. However, laboratory tests described in reference (1) shows that blades of insulating material will attract lightning similar to metal blades when polluted with salt water.

5. POSSIBLE MEANS TO REDUCE THE PROBABILITY OF LIGHTNING DAMAGES.

5.1 Blades.

The blades could be made of steel or aluminium instead of electric insulating material.

Perhaps the tip of the blade shown in Fig.4 could be made of aluminium with a lightning conductor cable inside the blade from the tip to the nave?

What is the experience with:

* Screen mesh on fibreglass blades, covered with epoxy and paint ?

* Aluminized glass cloth or metal-glass cloth ?

* Conductive paint ?

* Will metal blades cause too much TV interference in case of wind turbine parks ?

5.2 Nacelle

The nacelle should be made of steel and the lightning current should be transferred from the nacelle to the steel tower. No lightning current should flow directly via cables or equipment inside the nacelle. This means that a lightning rod on the top of the nacelle with a cable inside connected to the steel tower and prolonged further down to earth, as shown in Fig.6, is not a good arrangement.

The current from the nacelle should be transferred to the steel tower and as much as possible distributed along the circumference of the tower. This could be arranged by sliding contacts (sliprings) that will be electrically in parallel to the tooth rack. Perhaps the tooth rack itself and the sliding surfaces may carry this current. If so the sliding contacts may be left out.

No earthing cables should be inside the tower because the lightning current in these cables will induce overvoltages in parallel power/control cables and in other installations by radiation.

It is considered to be a good lightning protection procedure to have all the electrical and mechanical components of the wind turbine inside an electrically continuous metal enclosure as indicated above. In that way the electromagnetic field caused by the lightning current will theoretically be zero inside the nacelle tower.

5.3 Transfer of current from the blades.

The lightning current from strokes to the blades should be conducted to earth without passing inside the nacelle. The current should be transferred via a slipring arrangement on the low speed shaft to the ring with sliding contacts at the bottom of the nacelle, as mentioned under point 5.2 above. In that way the current will be distributed along the tower circumference, shunting the bearings of the wind turbine.

5.4 No earthing cables from the nacelle to the tower bottom.

Today a separate earthing cable (shown in Fig.6) as well as one or more earthing cables as part of the power cables, are connecting the nacelle structure to the bottom earthing system. Such cables should not be used as explained above. For safely of personnel (safety regulations) working inside the structures, however, a portable earthing lead could be used to connect the tower structure to the nacelle structure when work is going on.

5.5 Overvoltage protection.

All cable screens (power, control, communication) should be connected to the main earthing system at the tower base.

All cable conductors at the tower base (power, control, communication) should be protected with suitable surge arresters (varistors) between each conductor and earth and in some cases (control, communication) also between the conductors.

In the nacelle the cable screens should be insulated from the nacelle structure and the cable conductors should be protected with suitable surge arresters (varistors) between each conductor and the nacelle structure and in some cases (control, commination) also between the conductors.

Sensitive electronic equipment should be shielded against electromagnetic radiation by installation in suitable metal cabinets, carefully designed to be electromagnetically "tight". All cable penetrations should be electromagnetically closed to lightning radiation.

In addition multipath protection by surge protecting devices both lateral and longitudinal, are recommended.

The generator should be "earthed" to the nacelle structure and the surge arresters (phase-to-earth) installed in a separate cabinet to prevent damage of the generator terminals in case of arrester failure.

5.6 Telecommunication.

It may often be difficult to prevent damage to telephone equipment connected to the outskirts by cable or overhead line. In such cases mobil telephone connection may be preferable.

5.7 Earthing.

If not to far away (less than approximately 2 km) the wind turbine earthing system should be connected to an earth electrode in the neighbouring sea, or to other local area with good earthing possibilities. The connections between these earthing electrodes should preferably be by a burried conductor, but may also be made by an overhead conductor. The reason for the effectiveness of this earthing even 2 km away is the long front time of the positive strokes (Fig.3).

5.8 Lightning rod at the top of the nacelle.

Will a lightning rod at the top of the nacelle, high enough to protect the blades from direct lightning strokes, cause problems to the wind turbine for instance due to reduced efficiency (turbulence) ?

6. REFERENCES

1. A study on lightning damages to WECS with artificial lightning strokes.
By Keiichi Tsuchiya et.al.
Published: Wind energy, Technology and implementation,
EWEC '91.Amsterdam.
The Netherlands,October 14-18, 1991.

Table 1: Overview of wind turbine generator systems and related damages due to lightning. All stell towers.

Wind turbine	Operation start	Damaged	Type of blade		Nacelle		Type of damage											Damages pr. year of operation
			Fiberglass without metal	Fiber glass with metal	Fiber glass	Steel	Blade	Sensors: Wind data	Sensors: Temp.	Modem	Remote control	Control circuits	Computer	Phone	Generator	Arrester 220 V	Gear	
T1	1986	4/2-93	x			x				1)	1)			1)		x		0.14
T2	26/6-89	12/11-91	x		x			x	x			x					x	1.18
"		30/12-91	x		x		x					x			(x)			
"		4/2-93	x		x						x							
"		10/3-93	x		x					x	x			x				
"		16/9-93	x		x						x							
Sm	12/11-89	9/4-90		x	x		x							Mobil				0.96
"		25/2-92		x	x		x	x	x								x?	
"		10/1-93		x	x		x		x	x			x	x				
"		21/1-94		x	x		x		x					x				
N-T3	Sept.91	14/12-93	x		x					x	x			x				1.32
"		22/12-93	x		x					x	x			x				
"		9/1-94	x		x						x			x				
V-8	Aug.91	23/12-92	x		x		x					x		x				0.76
Va	13/2-87	21/2-89	x		x		x	x	x	1)	1)	x		1)	x	x		0.14

1) Not installed, (x) Probably secondary failure

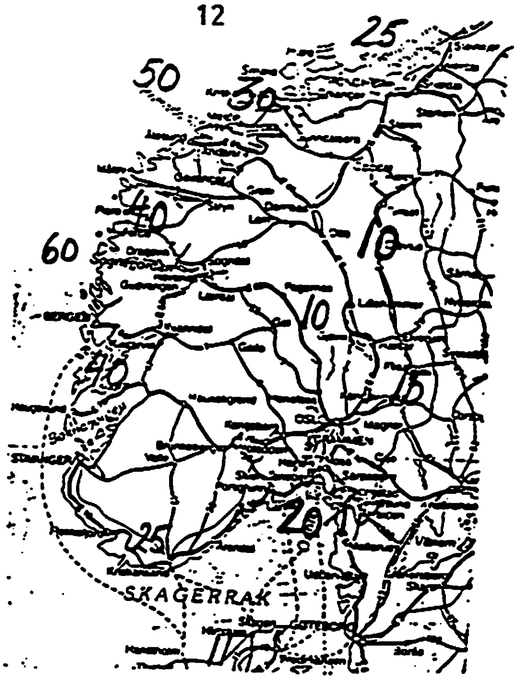


Fig. 1. Lightning flashes to the southern part of Norway in the period 1981-1990. Percentage of positive flashes to earth.

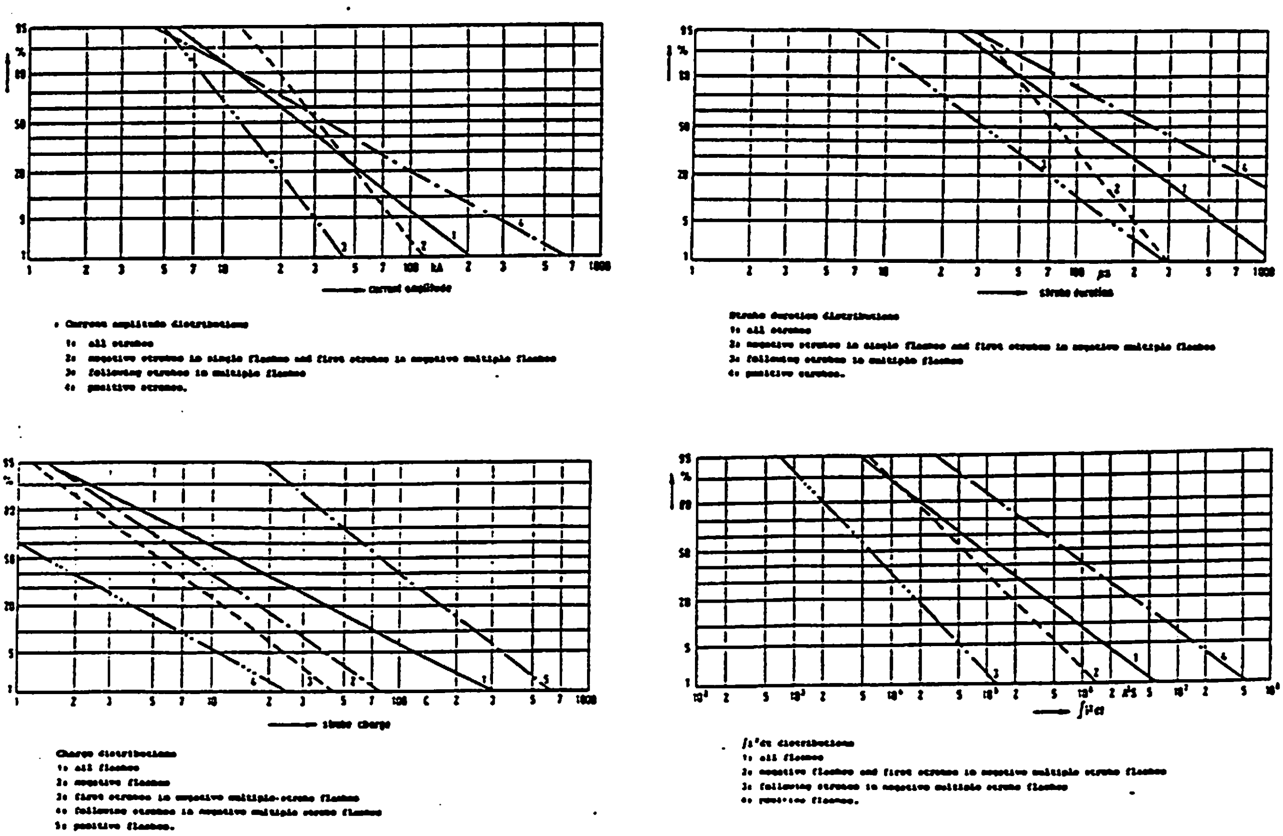


Fig. 2. Probability distributions of lightning stroke data (from CIGRE SC33)

91 SM 496-0, T-PD July 1992

Characteristics of Winter Lighting Current on Japan Sea Coast

Table 1. Parameters characterizing the current waveform of winter lightning

Parameter	Polarity	Number	50% value	16% value
Front duration Tf(μs)	Positive	24	178	1410
	Negative	37	11	67
	Total	61	37	398
Tail duration Tf (μs)	Positive	21	596	3980
	Negative	37	28	141
	Total	58	89	631
Front steepness G(kA/μs)	Positive	24	0.2	2.2
	Negative	37	1.2	7.1
	Total	61	0.5	5.0

IEEE Power Engineering Review, July 1992

Fig.3

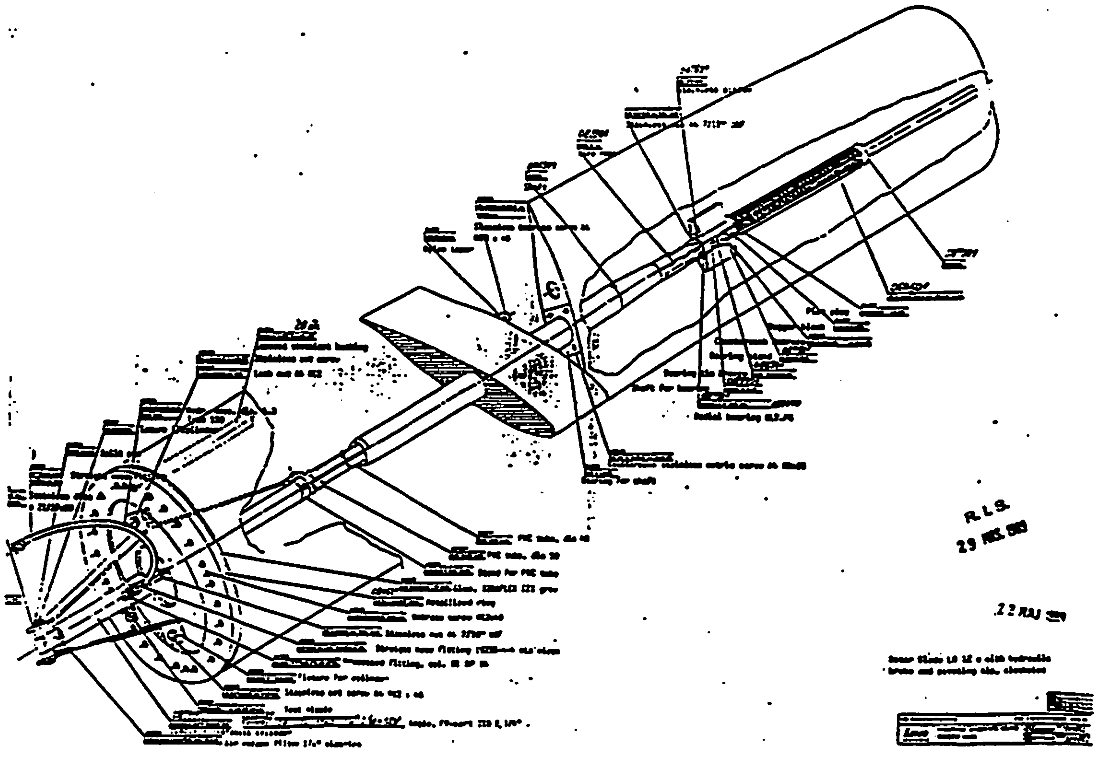
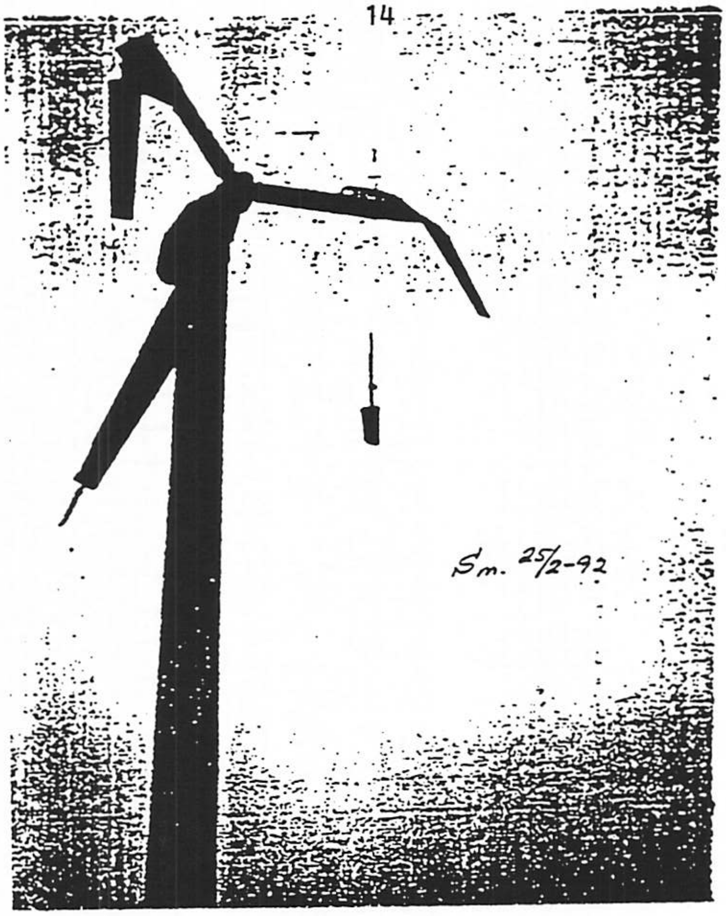


Fig.4



Sm. 25/2-92

Fig.5

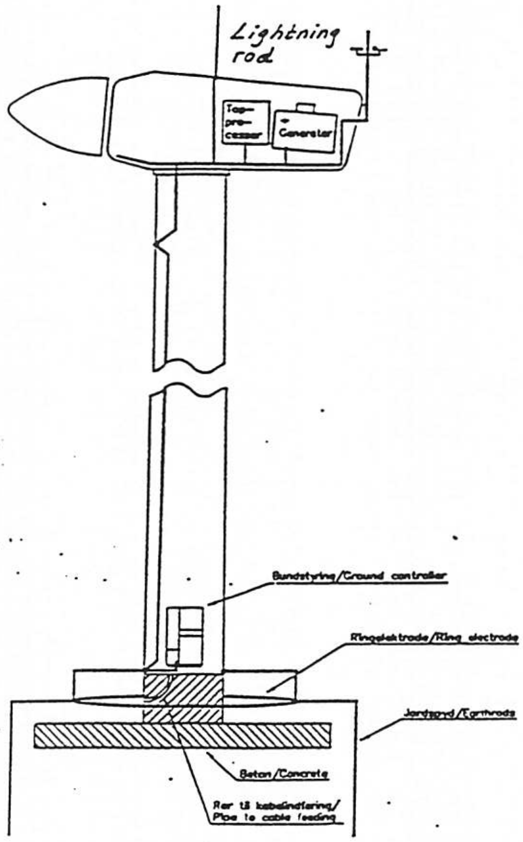


Fig.6

LIGHTNING AND THE IMPACT ON WIND TURBINE GENERATION

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Abstract

The utility power industries have been studying the nature of lightning and its impact on power sytems for many years. This study allows them improve reliability and power quality of the power systems. Lightning is known to be one of the causes of electrical breakdown in transmission lines and telecommunication lines. The reliability of power sources from the utility affects many people directly or indirectly. A breakdown in any part of the power network may eventually cost millions of dollars if it triggers the interruption of industrial processes.

With the increasing penetration of wind power generation into the utility grid, the lightning problem forces the utility engineer to start thinking about minimizing the casualties of lightning on the wind turbine generation systems on the wind farm. It is necessary for the power engineer to learn and better understand about the nature of the lighting, as well as the protection against lightning.

This paper deals with the cause and effect of power disturbance due to lightning on wind power generation. The protection of the system from the lightning is similar to insurance requirements. We have to understand the nature of the lightning and the statistical data of the lightning before we finally decide on how much we should invest on lightning protection. The data of lightning occurrences on the wind farm and the preventative measures practiced by the wind farm will be presented as well.

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Topical Experts Meeting on

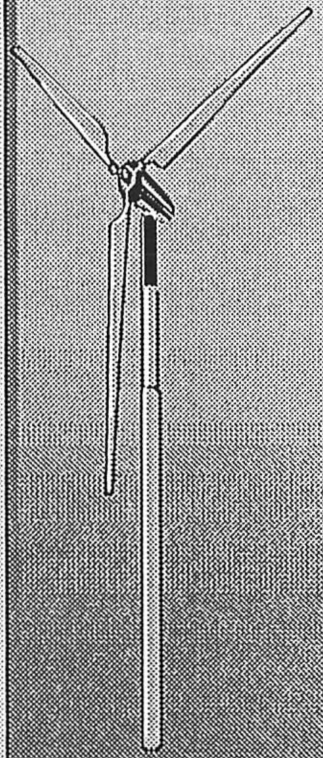
Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems

Eduard Muljadi Sandy Butterfield

NATIONAL RENEWABLE ENERGY LABORATORY
Wind Technology Division

March 8-9, 1994

in
Milan, Italy



SEQUENCE OF PRESENTATION

- NATURE OF LIGHTNING
- LIGHTNING PROTECTION
- SAFETY ASPECTS
- MECHANICAL ASPECTS
- ELECTRICAL ASPECTS
- CASE STUDIES

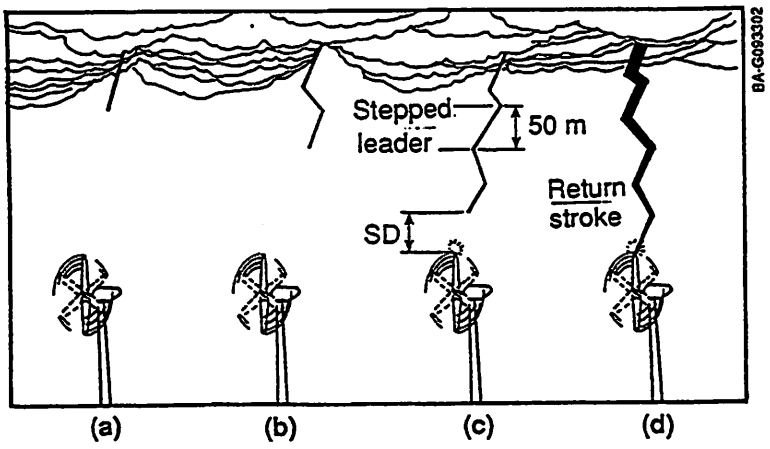
NREL Wind Technology Division

NATURE OF LIGHTNING

- PHYSICS OF LIGHTNING
- INCIDENCE OF LIGHTNING

Physics of Lightning

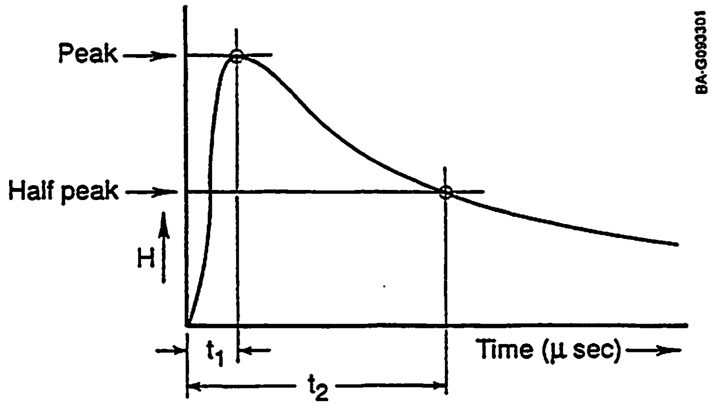
- Cloud-to-ground lightning starts with a preliminary breakdown within the cloud.
- Preliminary breakdown is continued with stepped leader (a branched discharge propagates horizontally and downward).
- The length of individual steps in the stepped leader is 30-90 m with intervals from 20 to 100 μs.
- When the tip of the stepped leader approaches the ground, the electric field above the ground becomes very large and there is one or more upward discharges beginning from the ground and initiating the attachment process.
- The return stroke begins when the stepped leader touches the upward discharge.
- Striking distance (SD) is the distance between the tip of the stepped leader and the object about to be struck when the upward discharge is about to begin.



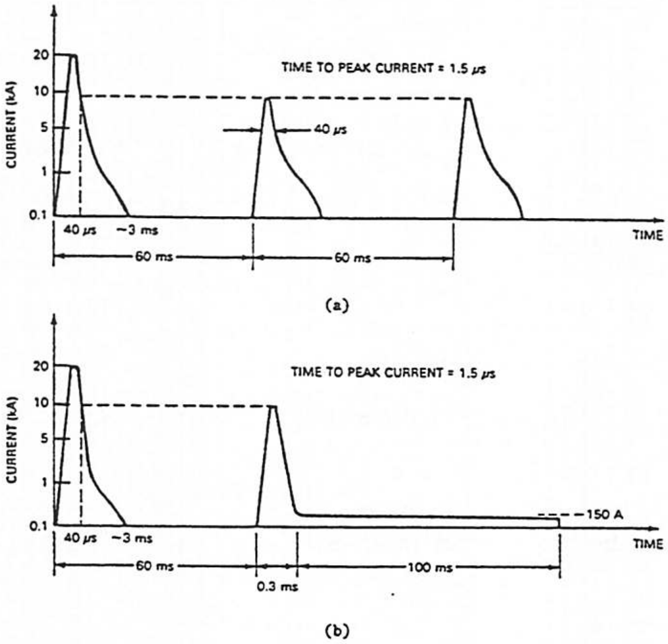
Development of a Stepped Leader.

Lightning Current

- Lightning current can be as high as several hundred kiloamperes.
- Lightning current has a very short rise time (approximately 20 kA/μs) and a slower fall time.
- The first return stroke may be followed by several return strokes as long as there is electrical charges in the cloud. The pause between return strokes is 40-80 ms.
- Some return strokes may be followed by a long steady discharge (approximately 200A).
- The voltage surge developed between the tip of the air terminal to the ground can be computed from the inductance of the ground conductor and the rate of rise of the lightning current.



Typical Lightning-Current Wave Shape.



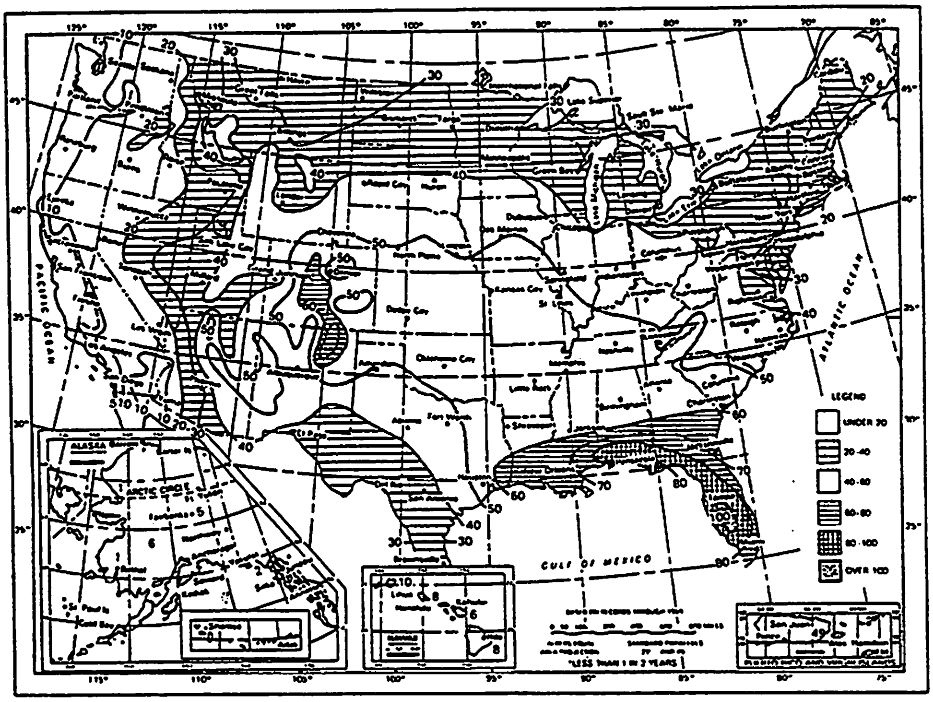
Ref. 2

physics of lightning

Time History of Typical (Basic) Lightning Models*
(a) Flash without any Continuing Current Stages
(b) Flash with Final Stage Continuing Current

Lightning Incidences

- The annual number of thunderstorm varies with the location; in United States, the highest density is in Florida and the lowest is in California.
- Around the world the highest density can be found around the equator.
- Lightning flash density in the western interior of Florida is about 18/km2, while in the northeastern states it is about 4/km2.
- A thunderstorm is divided into the initial phase, the active phase (27% of the time), and the final phase.
- 71% of lightning strikes occur in the active phase; 42%-52% are from the cloud to the ground.
- About 50% of lightning currents are higher than 20 kA



Ref. 3

incidences of lightning

Isokeraunic Levels for the United States

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LIGHTNG.SG1
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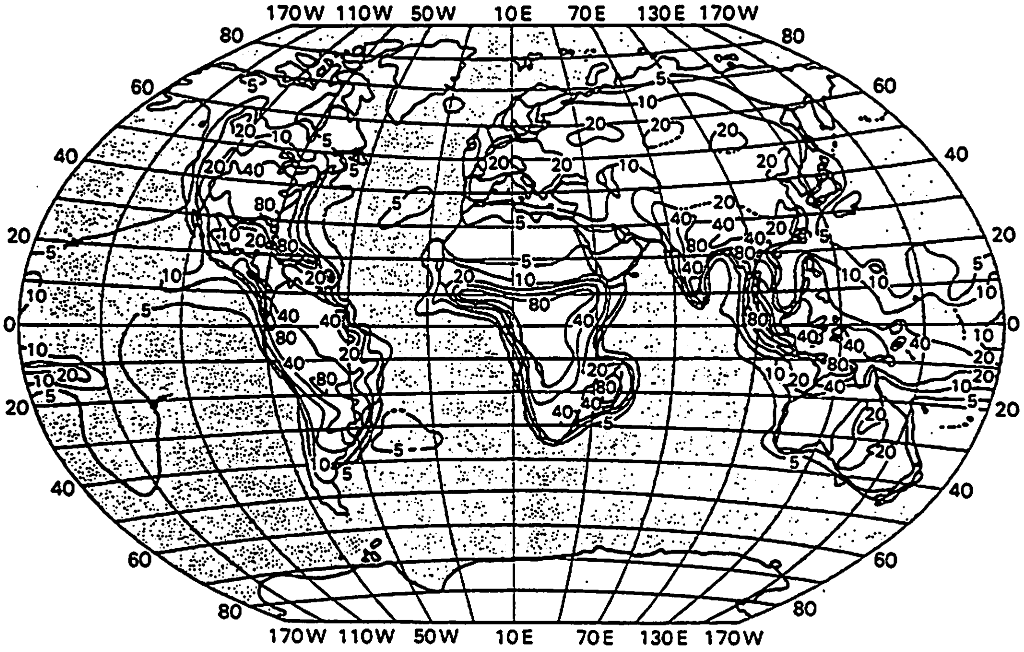

Ref. 3

incidences of lightning

Isokeraunic Levels for the World

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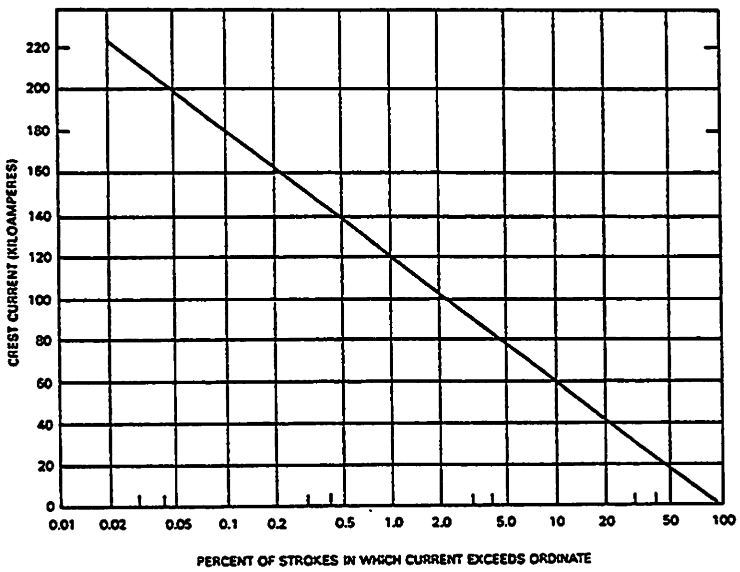
LOW-VOLTAGE SURGE-PROTECTIVE DEVICES

ANSI/IEEE
C62.42-1987



Ref. 2

incidences of lightning

Distribution of Lightning Stroke
Crest Currents to Aerial Structures*

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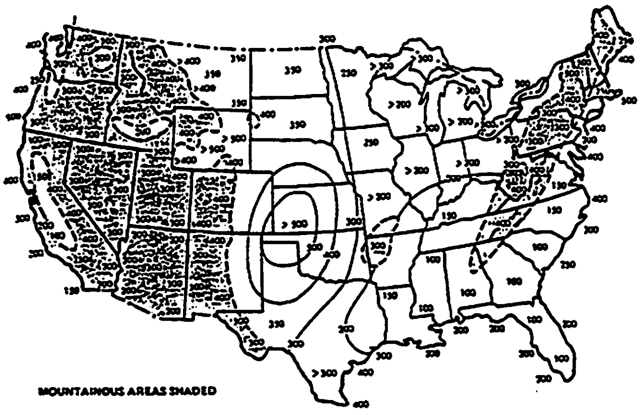

U.S. annual average wind power (W/m^2) at 50 m. (Courtesy of DOE.)

Ref. 4

incidences of lightning

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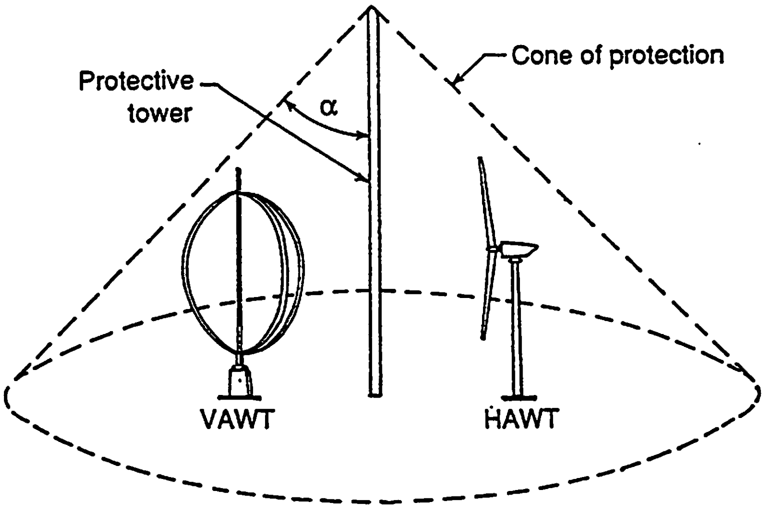
LIGHTNING PROTECTION

- TRADITIONAL CONCEPT
- GEOMETRICAL CONCEPT
- SURGE ARRESTER

Traditional Concept

- Traditionally, the protected zone of a lightning rod is considered to be the volume of a covered cone which has its apex at the top of the mast. The acceptable size of the angle between the cone and the vertical line through the apex is 45 degree. A more important case (such as a building containing explosives) should be protected with an angle alpha lower than 45 degree.
- With a ground wire connected between two lightning rods, the zone of protection is covered by a triangular prism with the upper edge along the wire.

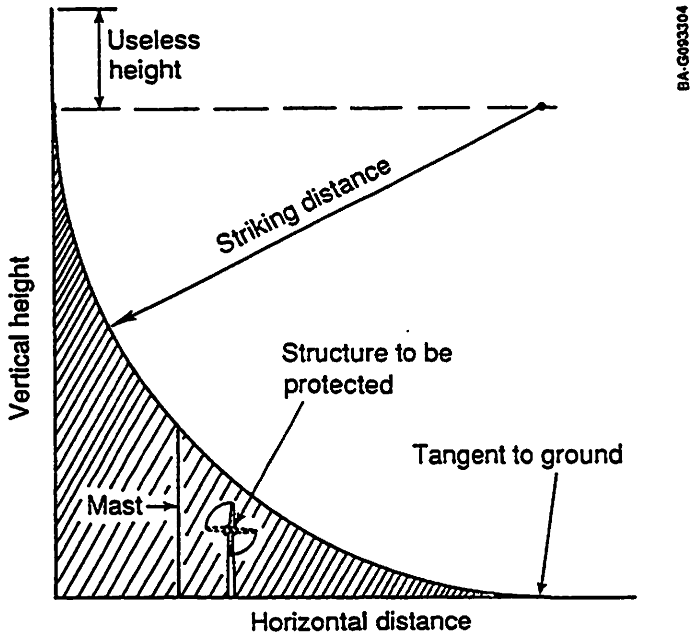


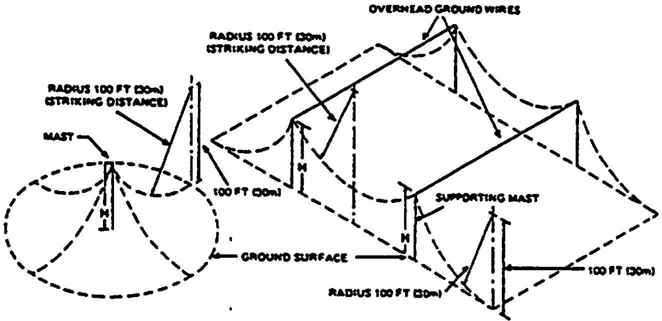
Cone of Protection Method.

traditional concept

Geometrical Concept

- The geometrical concept of lightning protection assumes a striking distance of 30.5 m (100 ft).
- The zone protected by a single mast is bounded by an arc of radius equal to the striking distance tangent to both the mast and the ground. Thus for a mast higher than striking distance, the lightning may hit the mast between the tip and 30.5 m height.
- In three dimensions, the protection may consist of masts and overhead ground wires. For simplicity, we can visualize a sphere of radius equal to the striking distance rolled over the area with mast and overhead ground wires; the zone protected is the volume that is not touched by the surface of the sphere.





(A)
SINGLE MAST
ZONE OF PROTECTION DEFINED BY DASHED LINES

(B)
OVERHEAD GROUND WIRES
ZONE OF PROTECTION DEFINED BY GROUND WIRE(S) AND DASHED LINES

Ref. 5

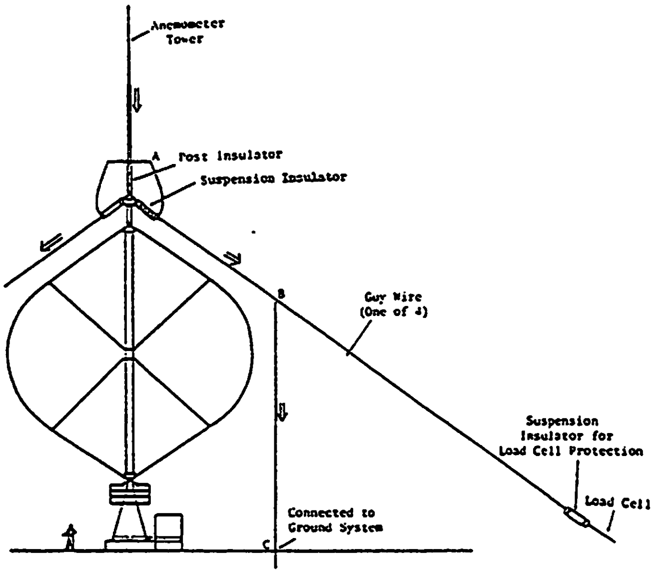
geometric concept

Lightning Protection

- Lightning protection in a wind turbine should be provided to conduct lightning to the ground without creating damage.
- It is important to install and maintain ground connections to provide a good conduction to the ground. Loose contacts and oxidation of the connectors may affect the surge impedance of the system.
- The resistance of the ground should be as low as possible.
- Grounding rods and grids can be used as the ground for lighting protection.
- If the ground resistance is high, some chemical (ordinary salt) can be added periodically to maintain a low ground resistance.
- The path of the lightning current should be made as low resistance as possible to reduce excessive heat generated by the lightning current. The inductance should be made as low as possible to reduce the voltage surges. Any additional bending in the ground conductor will increase the inductance.

Wind Turbine

- The highest point of a vertical axis wind turbine (VAWT) is the mast. It can be protected by employing the mast and the guy wires as parts of the protection.
- With the guy wires included (equivalent to an overhead ground conductor), the geometrical concept of lightning protection can be accomodated.
- The highest point of a horizontal axis wind turbine is (HAWT) the blade. Because the blades are not made from a conducting material, a lightning current path should be accomodated.
- A conducting material should be added on the surface of the blade to avoid the lightning current from flowing inside the blade. Lightning current flowing inside the blade may generate excessive heat and explode the blade.



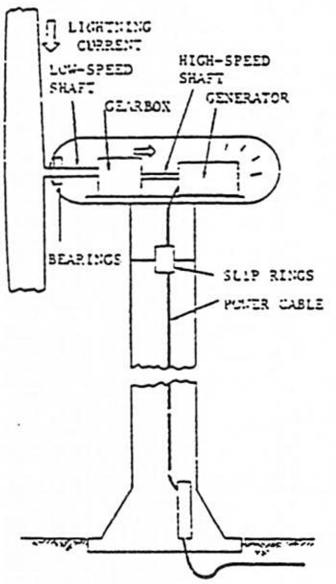
Lightning Protection Using Insulators

Ref. 6

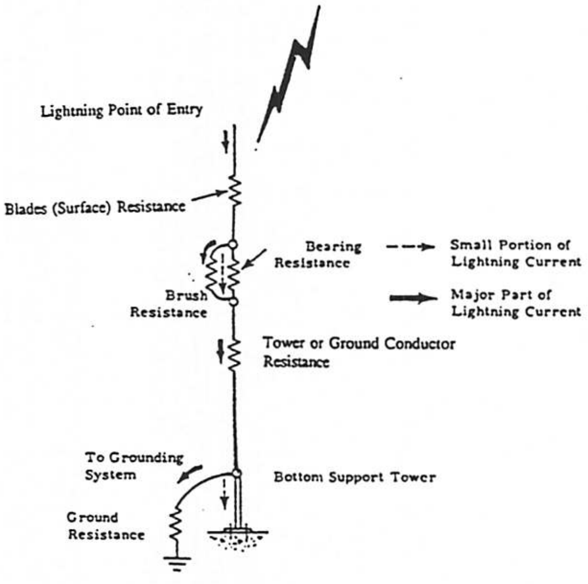
lightning protection

Horizontal Axis Wind Turbine

- **Lightning senses the wire and other metalic conductors inside the blade like an X-ray senses our bones inside the body. Thus, instrumentation wires, metalic conductors, and moisture inside the blade may encourage the lightning current to flow through the cavity within the blade.**
- **Applying a slip ring (for both VAWTs and HAWTs) diverts the current from flowing through the bearing. Thus, bearing damage can be avoided.**
- **A HAWT's generator may be exposed to a very high surge voltage when the lightning strikes the blade or other parts at the top of the tower. Thus, the insulation of the winding may be subjected to a high-voltage surge.**



Possible Lightning Path to Generator.

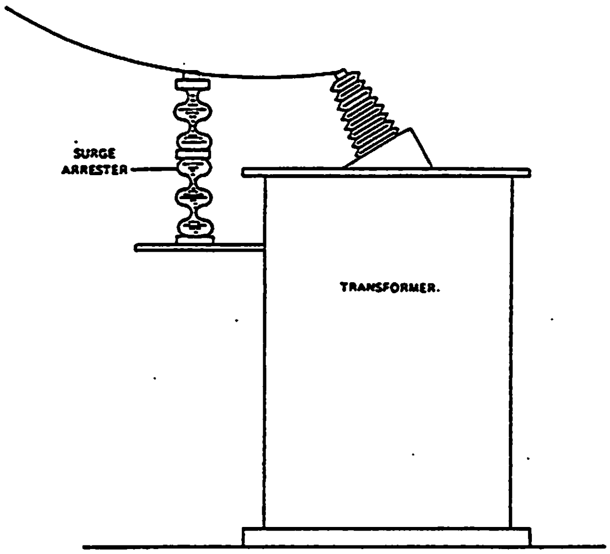


Schematic of Brush Design Showing Current Paths of a Lightning Strike

Surge Arresters

- Voltage surges may come from lightning strikes on the wind turbine, a nearby wind turbine, or a utility transmission line.
- A surge arrester can be used as a way to clamp the voltage from excessive values, thus protecting the sensitive equipment from failure.
- Wherever possible, the surge arrester should be installed on the generator side, the utility side, and the controller side.
- A surge arrester alone cannot protect the system against lightning. It has to be installed in conjunction with lightning protection.

IEEE
Std 142-1982



Ref. 7

Surge Arrester Location on Transformer

Representative Performance Data for Surge Arresters

Arrester Rating (kV)	Station Type: Spark-over† (kV)	Station Type: Discharge Voltage (kV)* at 5kA	Station Type: Discharge Voltage (kV)* at 10kA	Intermediate Type: Spark-over† (kV)	Intermediate Type: Discharge Voltage (kV)* at 5kA	Intermediate Type: Discharge Voltage (kV)* at 10kA	Rotating Machine: Spark-over‡ (kV)	Rotating Machine: Discharge Voltage (kV)* at 1.5kA	Rotating Machine: Discharge Voltage (kV)* at 3 kA
3	12	8.5	9	12	10	10.8	12	8	8.8
4.5							16	12	13
6	24	17	19	24	19.6	21.6	20	16	17.5
7.5							25	20	22
9	35	24	26	35	29	32	30	24	26
12	45	32	35	45	36.5	40.5	39	32	35
15	55	40	44	55	46	51	48	40	44
16.5							52	44	48
18							57	48	53
19.5							62	52	57.5
21	72	55	60	72	63	70	66	56	61.5
22.5							71	60	66

From ANSI C62.2-1969.

*Average voltage drop with an 8 by 20 μs discharge current wave at the stated peak current.

†Average sparkover on an impulse wave, based on a voltage rise to sparkover of 100 kV/μs per 12 kV of arrester rating.

‡Average sparkover on an impulse wave, based on 10 μs to sparkover.

IEEE Std
141-1976

Ref. 8

NREL Wind Technology Division

SAFETY ASPECTS

- DIRECT LIGHTNING STRIKE
- TOUCH VOLTAGE
- STEP VOLTAGE

NREL Wind Technology Division

Safety Aspects

- A direct strike may hit a person in the wind farm if the person is standing outside the protected zone (geometrical concept).
- Touch voltage can be developed during the lightning strike when a person touches the tower. The touch voltage is determined by the lightning current, and the resistance of the ground, and that of the human body. The current division that flows in the body and the ground is proportional to the inverse of its resistances.
- Step voltage can be developed during the lightning strike when a person stands near the down conductor or tower. The voltage between two feet is determined by the difference in distance between the two feet with respect to the grounding rod, the size of the lightning current, and the body resistance.

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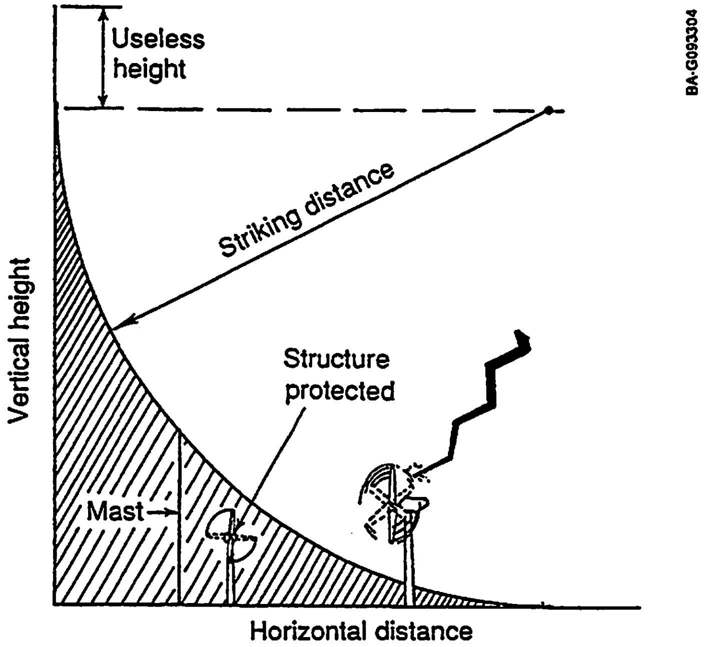

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LIGHTNG.SG1
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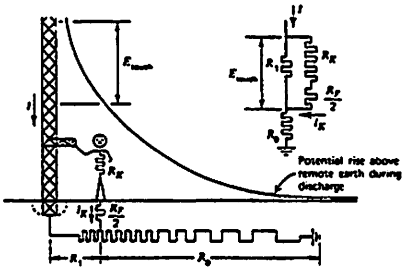

Touch voltage

Ref. 9

touch voltage

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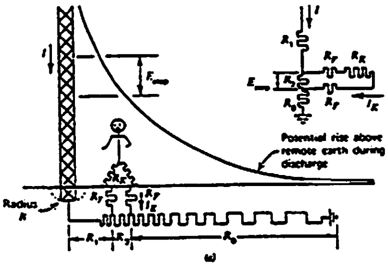
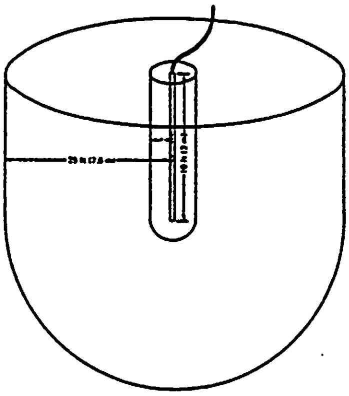


Step voltage

Ref. 9

step voltage

IEEE
Std 142-1982 GROUNDING OF INDUSTRIAL AND COMMERCIAL POWER SYSTEMS



Electrode Resistance Development

Electrode Resistance at a Radius r ft from a 10 ft (3 m) Long by $\frac{5}{8}$ in (16 mm) Diameter Rod (Total Resistance at r = 25 ft (7.6 m) = 100%)

Distance from Electrode Surface r (ft)	(m)	Approximate Percentage of Total Resistance
0.1	(0.03)	25
0.2	(0.06)	38
0.3	(0.09)	46
0.5	(0.15)	52
1.0	(0.3)	68
5	(1.5)	86
10	(3.0)	94
15	(4.6)	97
20	(6.1)	99
25	(7.6)	100
(100)	(30.5)	(104)
(1000)	(30.5)	(117)

Ref. 7

IEEE
Std 142-1982

GROUNDING OF INDUSTRIAL AND COMMERCIAL POWER SYSTEMS

Resistivity of Soils and Resistances of Single Rods

Soil	Resistivity ($\Omega \cdot$ cm) Avg	Min	Max	Resistance of $\frac{5}{8}$ in (16 mm) X 10 ft (3 m) Rod (Ω) Avg	Min	Max
Fills, ashes, cinders, brine waste, salt marsh	2370	590	7000	8	2	23
Clay, shale, gumbo, loam	4060	340	16 300	13	1.1	54
Same, with added sand and gravel	15 800	1020	135 000	52	4	447
Gravel, sand, stones, with little clay or loam	94 000	59 000	458 000	311	195	1516

Effect of Moisture Content on Soil Resistivity

Moisture Content (% by weight)	Resistivity ($\Omega \cdot$ cm) Top Soil	Sandy Loam
0	$>1000 \cdot 10^6$	$>1000 \cdot 10^6$
2.5	250 000	150 000
5	165 000	43 000
10	53 000	18 500
15	19 000	10 500
20	12 000	6300
30	6400	4200

Effect of Temperature on Soil Resistivity*

Temperature (°C)	(°F)	Resistivity ($\Omega \cdot$ cm)
20	68	7200
10	50	9900
0 (water)	32	13 800
0 (ice)	32	30 000
-5	23	79 000
-15	14	330 000

*Sandy loam, 15.2% moisture.

Ref. 7

IEA ANNEX XI
LIGHTNG.SG1
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ELECTRICAL ASPECTS

- ELECTROMAGNETIC COMPATIBLITY
- ELECTROMAGNETIC
- ELECTROSTATIC
- OTHER DISTURBANCES

NREL Wind Technology Division

Electromagnetic Compatibility

- Electromagnetic compatibility, EMC, is the ability of active device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.
- Electromagnetic susceptibility is the inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance.
- Electromagnetic compatibility level is the specified maximum electromagnetic disturbance level expected to be impressed on a device, equipment, or system operated in a particular condition.
- Electromagnetic compatibility margin is the ratio of the immunity level of a device, equipment or system to a reference disturbance level.

Ref. 15

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Immunity

- Immunity to disturbance is the ability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance.
- Immunity level is the maximum level of a given electromagnetic disturbance incident on a particular device, equipment or system for which it remains capable of operating at the required degree of performance.
- Immunity limit is the specified immunity level.
- Immunity margin is the difference between the immunity limit of a device equipment or system and the electromagnetic compatibility level.

Ref. 15

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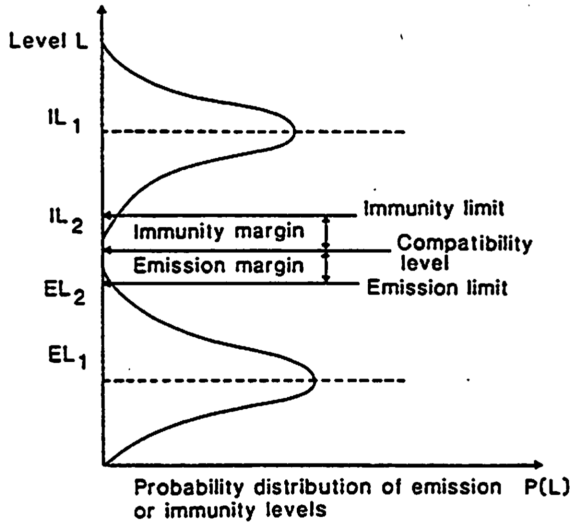
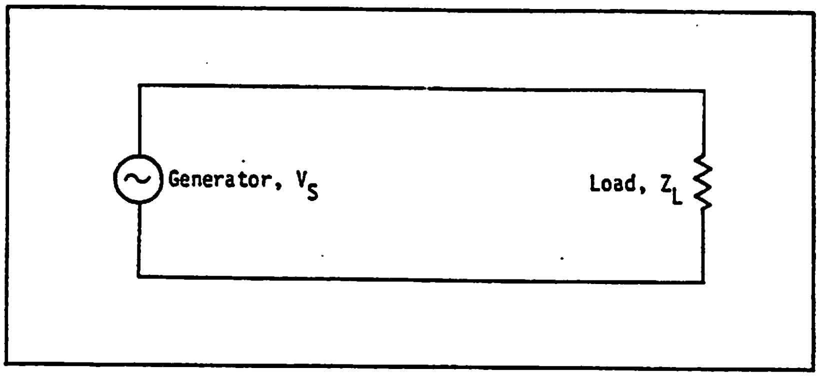


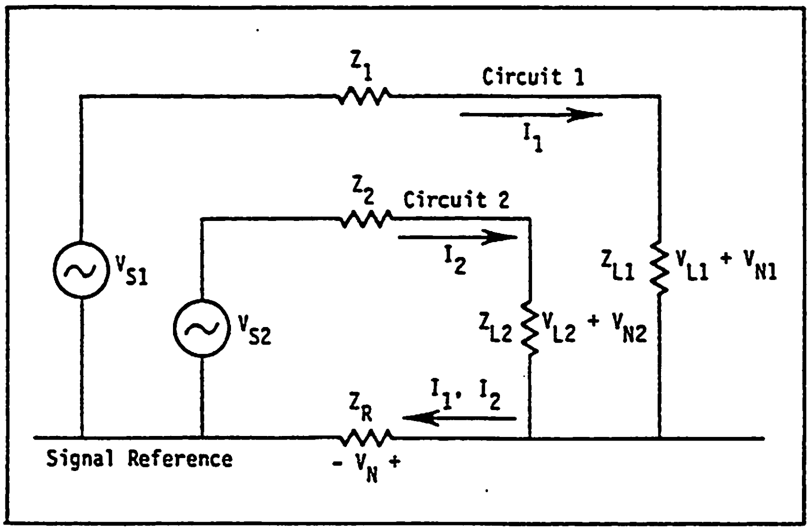
An illustration of the concepts of immunity/emission limits and how they relate to the compatibility level, adapted from reference [1]. (Reproduced by permission of IEEE)

Ref. 15



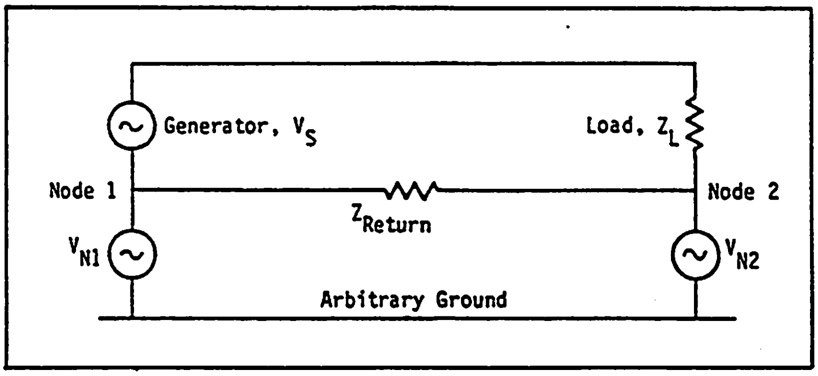
Idealized Energy Transfer Loop.

Ref. 10

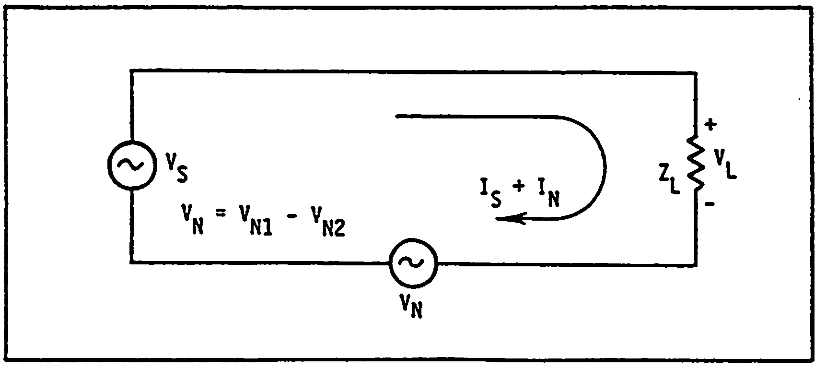


Coupling Between Circuits Caused by Common Return Path Impedance.

Ref. 10

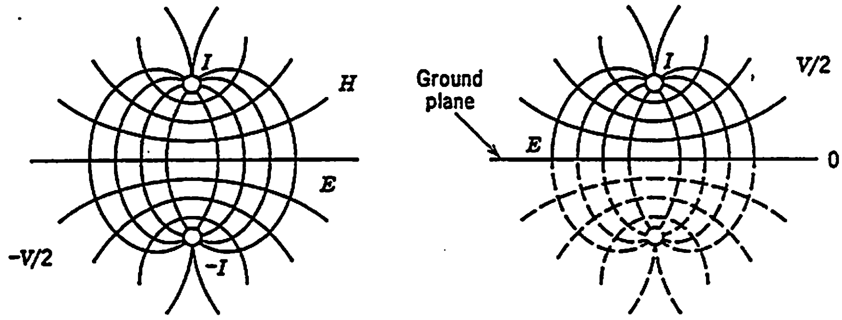


Energy Transfer Loop with Noise Sources in Ground System.



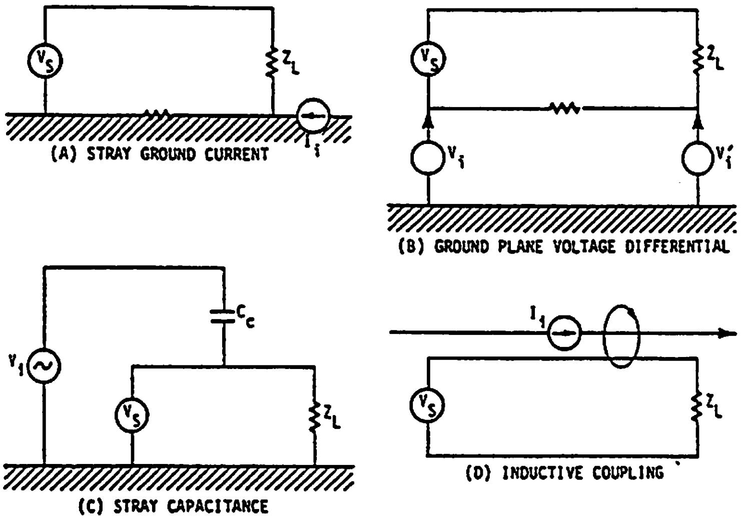
Equivalent Circuit of Non-Ideal Energy Transfer Loop.

Ref. 10



The electric E field and the magnetic H field around conductors in a simple transmission line.

Ref. 1

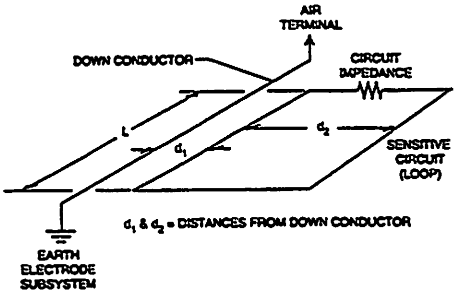


Ref. 10

Electromagnetic

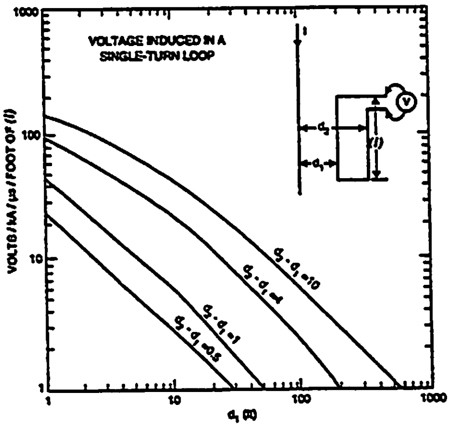
- Lightning current generates a very strong electro- magnetic field.
- The induced surge voltage generated around a loop circuit nearby depends on the strength, the rate of change of the magnetic field, and the area enclosed by the loop.
- Sensitive equipment and electronic circuits on the printed circuit board may be affected by induced voltage surges.
- The rate of rise and the number of return strokes of the lightning contribute to a wide spectrum of harmonics and noise that may affect the nearby circuits (controllers, measuring/monitoring devices etc,.).

IEEE
Std1100-1992



Source: Based on [B37] and [B38].

Inductive Coupling of Surge Current to Adjacent Sensitive Circuits



Source: Based on [B37] and [B38].

Normalized Induced Voltage Into Sensitive Circuits

Ref. 11

electromagnetic

Electrostatic

- Lightning current generates a very strong electric field.
- The surge voltage may be generated in the nearby circuit by capacitive coupling.
- Sensitive equipment and electronic circuits on the printed circuit board may be affected by voltage surges generated as the lightning current flows through a capacitive coupling.
- High-frequency electrical noise may be transfered easily through a capacitive coupling.
- Semiconductors that process signals are more susceptible to electrical disturbances than are power semiconductors.

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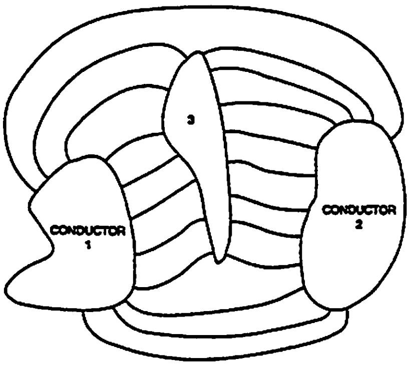
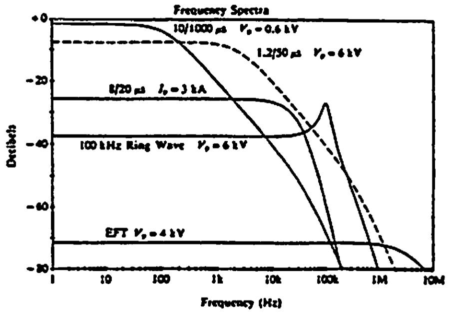


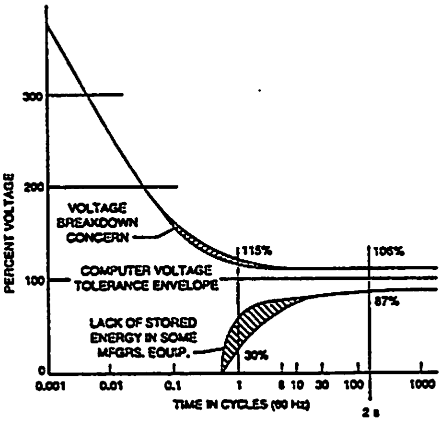
Electrostatic Field Between Charged Conductors

Ref. 11



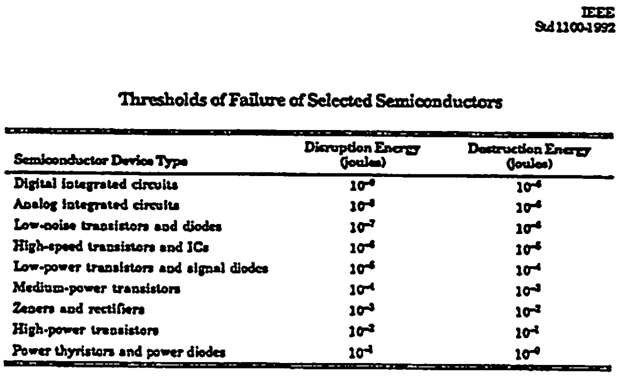
Frequency Spectra of Common Surge Test Waveforms

Ref. 11



Typical Design Goals of Power-Conscious Computer Manufacturers

Ref. 11



IEEE
Std 1100-1992

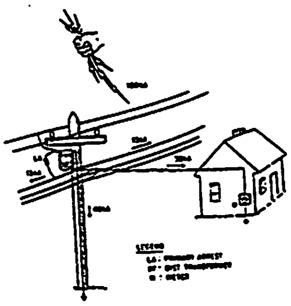
Thresholds of Failure of Selected Semiconductors

Semiconductor Device Type	Disruption Energy (joules)	Destruction Energy (joules)
Digital integrated circuits	10^{-9}	10^{-6}
Analog integrated circuits	10^{-8}	10^{-6}
Low-noise transistors and diodes	10^{-7}	10^{-6}
High-speed transistors and ICs	10^{-6}	10^{-5}
Low-power transistors and signal diodes	10^{-5}	10^{-4}
Medium-power transistors	10^{-4}	10^{-3}
Zeners and rectifiers	10^{-3}	10^{-2}
High-power transistors	10^{-2}	10^{-1}
Power thyristors and power diodes	10^{-1}	10^{0}

Ref. 11

Other Disturbances

- Lightning may hit the transmission lines and other parts of electrical systems. It travels in different paths affecting many parts of the system (if there is not enough protection or if the protection fails to operate).
- Lightning is only one of many disturbances that may disrupt the power production in wind power plants. A higher percentage of disturbances come from outside the wind power plant.
- Damage or disturbance caused by a voltage surge depends on the size and duration of the surge.
- Surges account for only 10%-14% of disruptive power disturbances while sags account for 30%-42%.
- Weather (wind and lightning) causes 51% of disruptive undervoltage.
- While lightning causes short disturbances, consideration should also be placed on persistence disturbances (conducted and radiated electromagnetic interfierence and radio frequency interference from other sources).

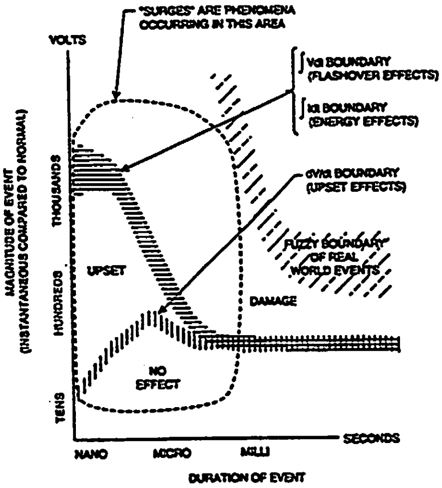


Division of Lightning Current Among Multiple Paths

Ref. 2

IEEE
Std 1100-1992

CHAPTER 3



Relationship Between Amplitude, Duration, Rate of Change of Disturbances, and Their Effects on Equipment

Ref. 11

IEEE
Std 1100-1992

Matching Sensitive Load and Power Source Requirements With Expected Environments

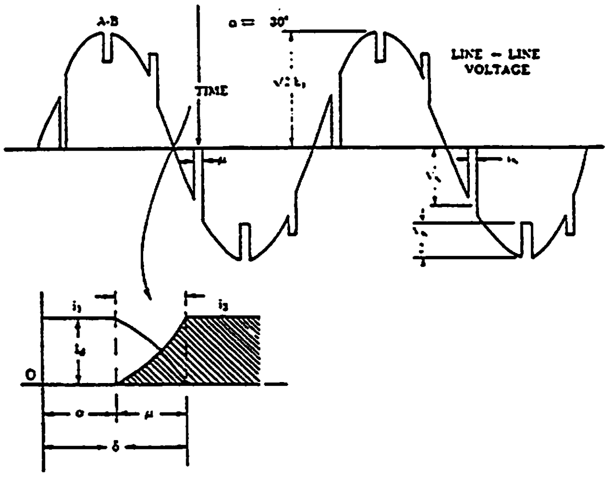
Voltage Parameter Affecting Loads	Typical Range of Power Sources	Typical Immunity of Electronic Loads		
		Normal	Critical	Units affected and comments
Over and Undervoltage	+6%, -13.3%	+10%, -15%	± 5%	Power supplies, capacitors, motors. Component overheating and data upset.
Swells/Sags	+10%, -15%	+20%, -30%	± 5%	Same as above.
Transients, Impulsive & Oscillatory, Power Lines	Varies: 100-6000 V	Varies: 500-1500 V	Varies: 200-500 V	Dielectric breakdown, voltage overstress. Component failure and data upset.
Transients, Impulsive & Oscillatory, Signal Lines	Varies: 100-6000 V	Varies: 50-300 V	Varies: 15-50 V	Same as above.
ESD	<45 kV 1000-1500 V	Varies widely 200-500 V	Varies widely 15-50 V	Signal circuits. Dielectric breakdown, voltage overstress, Component failure, data upset. Rapid changes in signal reference voltage.
RFI/EMI (Conducted) (normal and common mode)	10 V up to 200 kHz less at higher freq.	Varies widely 3 V typical	Varies widely 0.3 V typical	Signal circuits. Data upset, rapid changes in signal reference voltage.
RFI/EMI (Radiated)	<50 kV/m, <200 kHz <1.5 kV/m, >200 kHz	Varies widely w/ shielding	Varies widely w/ shielding	Same as above.
Voltage Distortion (from sine wave)	5-50% THD	5-10%	3-5%	Voltage regulators, signal circuits, capacitor filters, capacitor banks. Overheating, under-charging.
Phase Imbalance	2-10%	5% max	3% max	Polyphase rectifiers, motors. Overheating.

Ref. 11

Current Parameter Affecting Sources	Typical Range of Load Current	Typical Susceptibility of Power Sources		
		Normal	Critical	Units affected and comments
Power Factor	0.85-0.6 lagging	0.8 lagging	<0.6 lagging or <0.9 leading	Power source derating or greater capacity source with reduced overall efficiency.
Crest Factor	1.4-2.5	1.0-2.5	>2.5	1.414 normal; impact function of impedances at 3rd and higher harmonics (3-6% Z). Voltage shape distortion.
Current Distortion	0-10% total rms	5-10% total 0-5% largest	5% max total 3% largest	Regulators, power circuits. Overheating.
DC Current	Negligible to 5% or more	< 1%	As low as 0.5%	Half-wave rectifier loads can saturate some power sources, trip circuit breakers.
Ground Current	0-10 A rms + noise and surge currents	>0.5 A	<0.1 A	Can trip GFI devices, violate code, cause rapid signal reference voltage changes.

Frequency Parameter Affecting Loads	Typical Range of Power Sources	Typical Immunity of Electronic Loads		
		Normal	Critical	Units affected and comments
Line Frequency	± 1%	± 1%	± 0.5%	Zero-crossing counters.
Rate of Freq. Change	1.5 Hz/s	1.5 Hz/s	0.3 Hz/s	Phase sychronization circuits.

Ref. 11



NOTE: The two other phases are similar to A-B. Width of notches is exaggerated and ringing omitted for clarity.

Ref. 16

Voltage Notches

IEEE
Std 1100-1992

Expected Disruptive Power Disturbances per Year

Surges (> 100% of peak)	10 (14%)
Sags (> −20% rms)	30 (42%)
Swells (> +10% rms)	1 (1%)
Interruptions (one phase or more)	7 (10%)
Common-mode disturbances	24 (33%)
TOTAL	72 (100%)

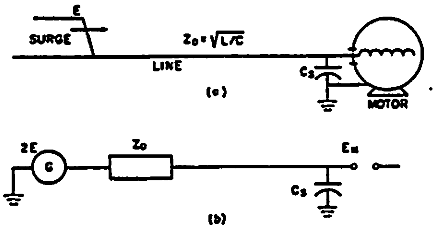
Causes of 100 Disruptive Undervoltages

Cause	Sags	Interruptions	Total
Weather (Wind and lightning)	37	14	51
Utility equipment	8	0	8
Construction or traffic accident	8	2	10
Animals	5	1	6
Tree limbs	1	1	2
Unknown	21	2	23
TOTAL	80	20	100

Ref. 11

Generator/Transformer/Controller

- **The generator should be protected from voltage surges that may damage the winding insulation. The voltage surges may come from lightning on the wind turbine or from external connection. An appropriate surge arrester should be provided on the generator. For a larger generator, wherever appropriate, a surge capacitor should be installed.**
- **The transformer should be protected from the voltage surges by a surge arrester on the utility side.**
- **Controllers and other sensitive parts should be protected by surge arresters (to provide protection against conducted disturbances) and should be shielded using metalic shielding (to provide protection against radiated disturbances). The use of fiber optic and opto isolator are encouraged.**



Application of Shunt-Connected Surge-Protective Capacitors for Wavefront Control
(a) Physical. (b) Equivalent

Capacitance of Surge-Protective Capacitors
per Line Terminal Connected Line to Ground

	Rated Motor Voltage		
	650 V and Less	2400—6900 V	11 500 V and Higher
Capacitance, µF	1.0	0.5	0.25

Rotating Machine 60 Hz 1 min High-Potential Test Voltages

	Rated Motor Voltage (volts)					
	480	2300	4000	4600	6600	13 200
Test Potential, kV Crest	3.11	7.92	12.73	14.43	20.1	38.8
Per unit of normal crest	7.94	4.21	3.9	3.83	3.72	3.59

From ANSI C50.10-1975 and ANSI C50.13-1975 for synchronous motors, and ANSI C52.1-1973 (NEMA MG1-1972) for induction motors.

Ref. 8

NREL Wind Technology Division

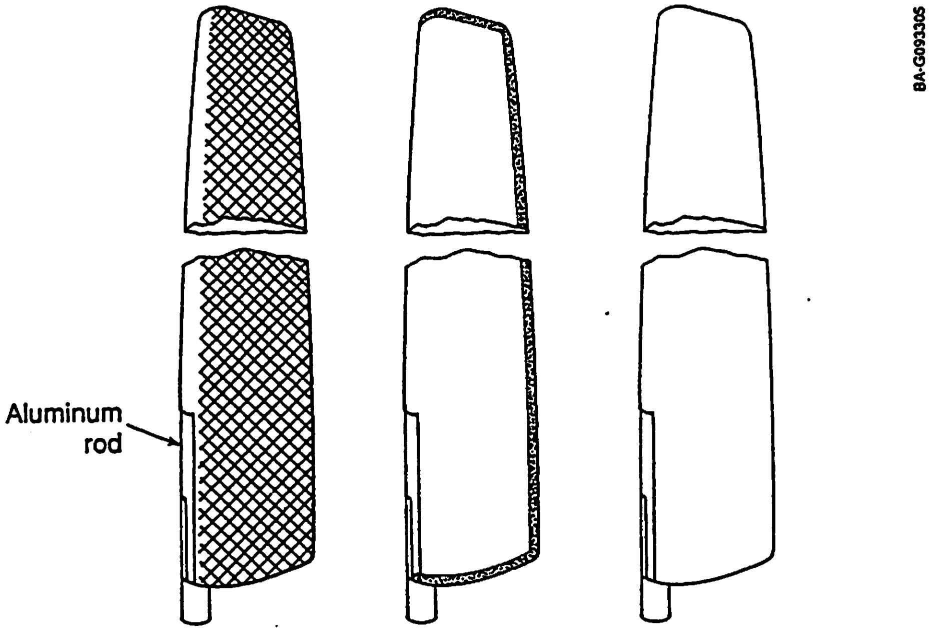
MECHANICAL ASPECTS

- BLADES
- BEARINGS
- STRUCTURES

NREL Wind Technology Division

Blades

- Instrumentation wire, metallic parts, and moisture inside the blade may provide the conducting path for the lighting current.
- The blade should be protected by providing a path for the lightning current to flow on the surface. Lightning current that flows in the cavity of the blade may explode the blade.
- Most blades are made of non-conducting materials. A path of conducting material can be installed on the surface (using copper wire, aluminum tape, mesh wire, etc.).
- The material conducting the lightning current must be able to withstand the heat and electromagnetic force generated by the lightning current.
- The conducting path should travel from the blade to the tower or ground conductor via a slip ring.

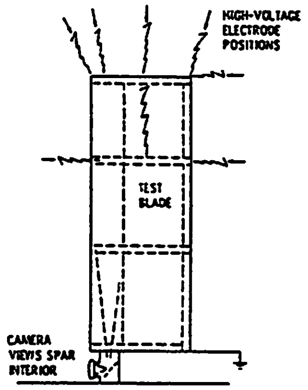


(a) Full surface coverage by aluminum screen.

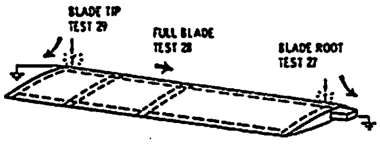
(b) Metal tip cap with trailing edge down conductor.

(c) No accomodations.

Ref. 12



(a) Test arrangement for high-voltage, long-arc tests.



(b) Test arrangement for high-current tests of blade.

Test sample and setup at Lightning and Transients Research Institute.

Ref. 12

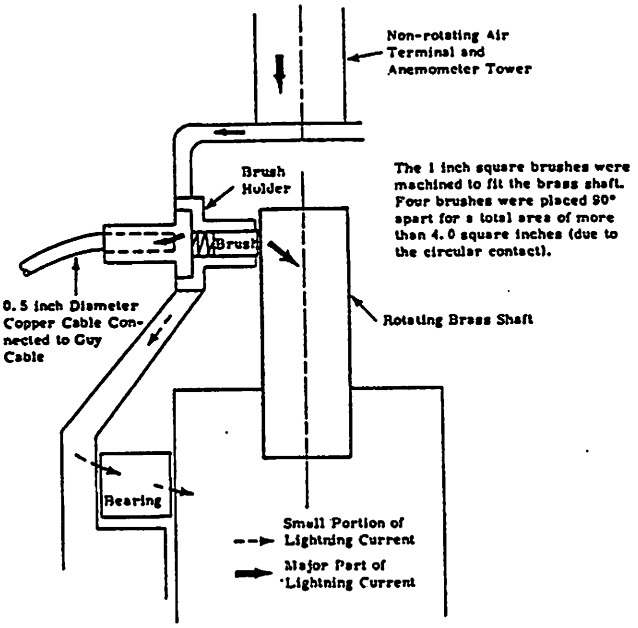
Ways to Provide External Conducting Path

PRODUCT	METHOD OF APPLICATION	COMMENTS
Conductive Tape	Position as required apply pressure. Soldering or welding to metal surfaces.	Apply to the leading and trailing edge. Aluminum tape has been shown to provide protection on fiberglass blades.
Conductive Paint	Brush or spray.	Paint with silver content has worked on helicopter blades. Other metals or alloys used in paint will require testing.
Alumnized glass cloth or metal-glass cloth	Put in place and secure to blade using an appropriate adhesive or process.	More than one layer may be required.
Diverter Strips	Apply to blade non-conducting surface and solder or weld to metal surfaces.	Results should be similar to tape. The TV interference may be less, but the cost of protection may be greater.
Screen mesh	Apply adhesive to nonconducting surface and weld or solder to metallic surfaces.	Wooden blades have been shown to have adequate protection with this method. The screen was covered with epoxy and paint.

Ref. 14

Bearings

- The lightning current should be diverted from the bearing by installing a slip ring.
- When the lightning current passes through the bearing, the bearing may be
  - melted
  - deformed
    - create noise
    - out-of-center balanced
    - increasing mechanical losses.
- The minimum precaution is to ensure that the lubrication is not dried by the heat caused by the lightning.



The 1 inch square brushes were machined to fit the brass shaft. Four brushes were placed 90° apart for a total area of more than 4.0 square inches (due to the circular contact).

Brush Lightning Protection System as Implemented on the 17-M VAWT. This illustration shows how the brushes were installed at the top of the turbine. It is not an exact copy of the hardware. Brush holders and brushes were installed at the bottom of the turbine to by-pass the lower bearings.

Ref. 14

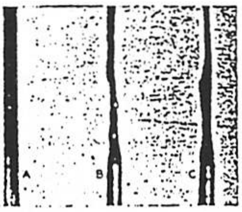
Structure

- Many wind turbines use the tower as the ground conductor.
- The structure must form a continuous conduction path. A gap or discontinuous path may create an arc and excessive voltage surges when the lightning strikes the turbine.
- Loose nuts and bolts may reduce electrical contact within the structure.
- Most damage on protected wind turbines is caused by inadequate grounding (loose contacts, a corrosive ground rod, etc.).
- In the case of a guy wire used as part of the lightning protection, care should be taken to ensure that the mechanical properties of the wire do not change due to the heat generated by the lightning current.
- The structure must be able to withstand the mechanical force generated by the magnetic field.

A—Original tube

B—After 3 successive discharges of 140,000 amperes

C—After 4 successive discharges of 135,000 amperes



Copper tubes crushed by lightning currents in laboratory (tubes had 14.3 millimeter inside diameter and 0.406 millimeter wall thickness)

Effect of high magnetic forces on thin copper strap after discharge from 265,000-amp. lightning generator

Ref. 13

CASE STUDIES

CASE STUDY I

- Location - Tehachapi, California, USA.
- Windfarm - 714 wind turbines.
- 7 to 8 lightning blade damages in 7.5 years.
- No air terminal.
- All metals are grounded to tower and the tower is connected to ground.
- Fiberglass blades have no protection (HAWT).
- Lightning arrester is used on the generators.
- The blade has a steel spar along the blade (tip deployment).
- Some of the blades have been split due to lightning damage.

CASE STUDY II

- Location - mostly in the Midwest, USA.
- Wind turbine manufacturer - 200 wind turbines (10kW).
- 3 to 10 lightning damages/year (generator rewound). Most of the damage was caused by loose contacts or oxidation of the ground connectors.
- No air terminal, no blade protection.
- All metals are grounded to tower and the tower is connected to the ground.
- Fiberglass blade (pultrusion, no cavity, HAWT).
- Use lightning arrester on the generators and controls.
- Variable-speed operation.
- 10 damages/year to the inverters, mostly due to the power quality of the utility (50% voltage surges and 50% voltage sags).
- Surge arresters are used on the generator; on the utility side and on the printed cicuit boards.

NREL Wind Technology Division

CASE STUDY III

- Location - mostly in the California, USA.
- Wind turbine manufacturer (300kW).
- Lightning damages/year - not available.
- Blades are made of fiberglass protected by copper wire (about 0.25 inches in diameter) molded by resin inside the blade. The wire is connected to the tower through a slip ring and the tower is grounded.
- Air terminal on the nacelle.
- All metals are grounded to the tower and the tower is connected to the ground.
- Surge arresters are used on the generators and controls.
- Lightning hits never destroyed the blades. They punctured the blade to the size of a match head (which is easy to repair).
- Some controllers were damaged by voltage surges due to utility surges.

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NREL Wind Technology Division

CASE STUDY IV

- Location - Tehachapi, California, USA.
- Windfarm.
- Up to 5 lightning strikes/100 turbines/year.
- No air terminal; no blade protection.
- All metals are grounded to the tower and the tower are connected to the ground.
- Fiberglass blades; Incidences: blades were shattered; the resin was ignited and the blade was burned.
- Lightning arresters on the generators (fixed frequency).
- Damage to the controller was due to the surges from lightning and the surounding power system (relays; lightning arrester being blown off; ground wire being blown off).
- Some of the lightning hits affected the controllers of the neighboring turbines due to voltage surges created.

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NREL Wind Technology Division

CASE STUDY V

- Location - Midwest, USA.
- Windfarm - 30 wind turbines.
- 3 to 4 lightning strikes per year.
- Air terminal on the nacelle, no blade protection.
- All metals are grounded to the tower or ground.
- Wood blades.
- Lightning arresters were used on the generators, and isolation transformer were used on the utility interface.
- Some of the blades split due to lightning damage.
- Lightning damaged the controller.

IEA ANNEX XI
LIGHTNG.SG1
Milan, 1994

NREL Wind Technology Division

CASE STUDY VI

- Location - Hawaii, USA.
- Windfarm - 13 turbines (600 kw).
- Lightnings strikes 6 times/year.
- No air terminal.
- All metals are grounded to the tower
- Wood-epoxy blades are protected by aluminum tape (6 inches wide along the trailing edge of the blade on the high-pressure side). It is connected to the tower via the slip ring.
- One of the blades had a manufacturing defect - a 3 inch crack with dirt and grease in it. When lightning struck the blade, heat generated and exploded the blade, even though it was protected with alumimun tape.
- Lightning arresters were used on the generator and surge arresters were used on the controller.

IEA ANNEX XI
LIGHTNG.SG1
Milan, 1994

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IEA R&D WIND - ANNEX XI

26th Meeting of Experts

Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control System.

Cologno Monzese, 8th-9th March 1994

LIGHTNING PROTECTION OF LARGE ROTOR BLADES DESIGN AND EXPERIENCE

by

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Vattenfall Utveckling AB, Sweden

INTRODUCTION

Wind Turbines become bigger and bigger. The cost involved with maintenance must be kept to a minimum. Damage due to lightning strikes can be very severe and expensive.

New materials are used in the rotor blades that may lead to new problems regarding lightning protection.

Sweden and Vattenfall have been involved in large Wind Turbines for many years. This paper describes the design and experience regarding lightning protection of rotor blades for Wind Turbines. Three examples will be described: The Maglarp Wind Turbine, the Näsudden II Wind Turbine and the experience from Lyse Wind Power Station.

MAGLARP

The Maglarp Wind Turbine, or WTS 3 which is the correct name, was erected in the south of Sweden in 1982. It was operated by the utility Sydkraft until 1993 when it was dismantled due to economic reasons. The prototype had been running over 28 000 hours up to then, producing over 37 000 MWh.

Design

The rotor blades were designed and manufactured by Hamilton Standard in USA. The blades were made of Glassfiber Reinforced Plastics (GRP) and Epoxy. Each blade was 39 metres long with a weight of 13 tons. The blades were manufactured using filament winding technique which resulted in a design with a hollow loadcarring structure. No conductive material was used in the blades exept for the retention rings at the blade root (fig 1).
Each blade was equipped with 36 strain gauges resulting in over 100 wires running from aprox. 75 % radius down to the blade root.

In order to protect this instrumentation, the blades were equipped with a lightning protection system (fig 2). The lightning protection consisted of aluminium tape, 150 mm wide and 0.13 mm thick. This equals to a crossection of 20 mm^2. The tape was mounted along the leading edge and the trailing edge. And chord wise at five different stations.The joints used were buttjoints with an additional piece on top.
A steelband was mounted around the tip cap and connected to the aluminium tape.

The system was tested, using 1000 000 Volts to verify the lightning path and 200 000 Amp to verify the capability to protect the GRP.

The blades were connected to the hub by flexible cables and to the nacelle using a big slipring with four spring loaded carbon brushes.

Experience

No big damage was found on the blades during the entire operation time. Small damages were however found every year. Sometimes up to 10 different burn marks were found. When the lightning "hit" a strain gauge, it more or less evaporated and also destroyed the wiring. The aluminium tape then got punctured from the inside.

The Aluminium tape cracked along the trailing edge within a couple of months. The bonding of the tape was insufficient and the wear along the leading edge was a big maintenance problem.

In 1986 it was decided to remove the lightning protection on the blades. The measuring period was over and the strain gauges mounted on the blades could be sacrificed. It was important to decrease the maintenance time for the Wind Turbine. Over two weeks were spent every year to repair the blade lightning protection, which of course was unacceptable.

The first year the outer 15% were removed, including the steelband around the tip cap.The result was good. The following two years the rest of the aluminium tape was removed exept at the blade root. The connection to the hub and to the nacelle was however kept intact.

The result was that all lightning damage on the blades more or less disappeared.

Also the connection between the hub and the nacelle was a problem.The wear of the carbon brushes was unacceptable and the carbon dust, together with some hydraulic leaks in the hub resulted in very dirty blades indeed. Later, the system was modified to bronze-brushes which seemed to work satisfactory.

Conclusion

The lightning protection of the blades worked as planned. No damage of the blades.

The maintenance was much more time consuming then expected.

The problem disappeared as the lightning protection was removed from the blades.

NÄSUDDEN II

Design

The Näsudden II wind turbine was erected in October 1992 on the island of Gotland in the Baltic Sea.

Rated power is 3 MW and it has been in operation aprox. 4000 hours up to now.

The wind turbine has been manufactured by Kvaerner Turbin in Sweden. The blades were designed and manufactured by MBB in Germany.

Each blade is 39 meters long and manufactured in Carbonfiber Reinforced Plastics (CRP) , GRP and Epoxy (fig 3).

The carbon fibre beams are located along the leading edge, trailing edge and two beams on each side of the blade. Since carbon fibre is a semi conductive material, it became quite clear that these parts needs a good lightning protection.

The lightning protection used on the Näsudden II Wind Turbine is a modified version of what MBB has used on the Monopterus Wind Turbines.

All carbon fibre beams are covered with a fine copper mesh, imbedded in the blade surface. The cross section of this copper mesh is aprox. 20 mm^2 (fig 4).

The blade tip is made of stainless steel and connected to the copper mesh by contact rivets.

12 copper wires connect the copper mesh with a U-shaped rail, mounted around the blade root. Two copper wires run inside this rail and provide a sliding contact between the blade and the hub when the blade is pitching (fig 5,6). (A similar system is used between the nacelle and the tower.)

The connection between the hub and the nacelle is made by five bronze brushes (fig 7).

Experience

The unit was erected in October 1993 has been in operation for more then one year. There has not been any signs of lightning damage. One possible maintenance problem could be to protect the leading edge against erosion. An erosion protection layer (polyurethane foil) has been mounted on the outer part of the leading edge on top of the lightning protection. The conductive path from the blade tip is however quite big (aprox 120 mm^2) and future will tell if this system is sufficient.

Conclusion

Rotor blades made of CRP needs a good lightning protection.

System chosen in this case has proven to work satisfactory.

CRP should, if possible, be avoided along the leading edge

LYSE WINDPOWER STATION

Design

Lyse Windpower station consists of two wind turbines; the Nordic 400 which is a Swedish stall regulated Wind Turbine with teetered hub and variable speed and the Bonus 450 Mk2 which is a Danish stall regulated Wind Turbine with a rigid hub and fixed speed (fig 8).

The rotor blades for both Wind Turbines are made by LM in Denmark. The aerodynamic profiles are different but the general build up of the blades are the same: GRP and Polyester. Both blades are about 17 meters long and have a aerodynamic tip brake (fig 9).

The blades don't have a lightning protection. Which is quite common for Wind Turbines of this size. A steel wire is running inside the blades to manoeuvre the blade tips. This steel wire is connected to the hydraulic piston in the blade root and into the nacelle either by the hydraulic hoses (Bonus) or by the electric sliprings (Nordic 400). This means that a conductive path is provides all the way out to the blade tip. Which could attract lightning.

In order to compare different solutions, it was decided to isolate the steel wire connection to the hydraulic piston with a composite isolator on the Bonus Wind Turbine.

Experience

The Wind Turbines were erected in June and august 1992.

Several lightning storms have been observed in the area. Some of them have resulted in grid losses. There has also been some damage to the meteorological equipment, located in the nearby meteorological mast.

Some computer problems were experienced on the Bonus Wind Turbine early 1993. Possibly due to lightning.

In December 1993 the Bonus Wind Turbine stopped due to tip brake error. The reason to this was that the isolator had melted and therefor released the tip brake (fig). No damage on the blade was found more then some possible burn marks around the blade tip shaft, which is made of CRP. The other two blades were OK.

No lightning problems have been found on the Nordic 400 Wind Turbine.

Conclusion

The idea to protect the blades by isolating the tip brake wires has not proven to be successful in this case.

No damage has been found in the rotor blades on either one of the two Wind Turbines.

SUMMARY

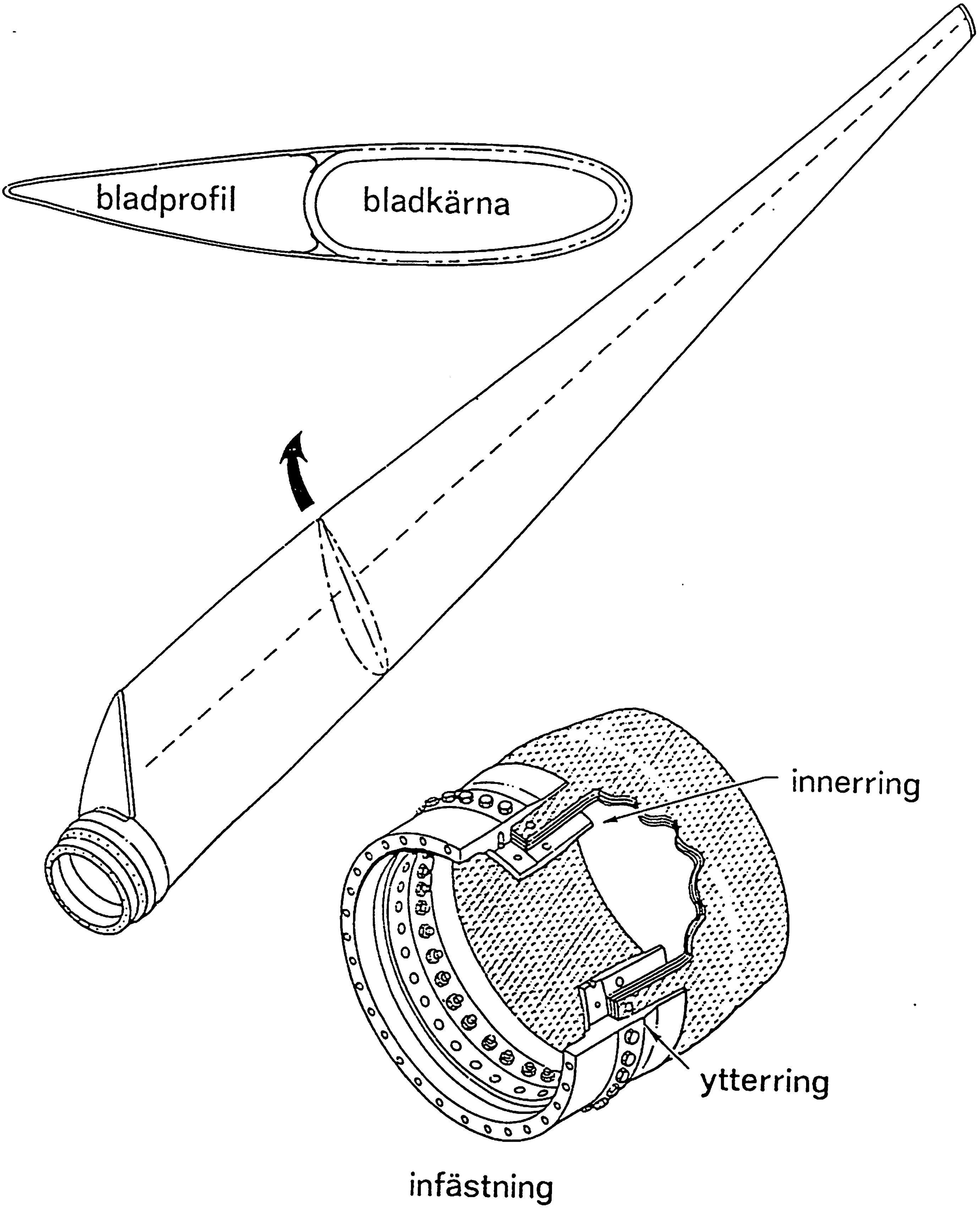
Lightning protection of large rotor blades is probably necessary.

New materials like Carbonfiber Reinforced Plastics require lightning protection.

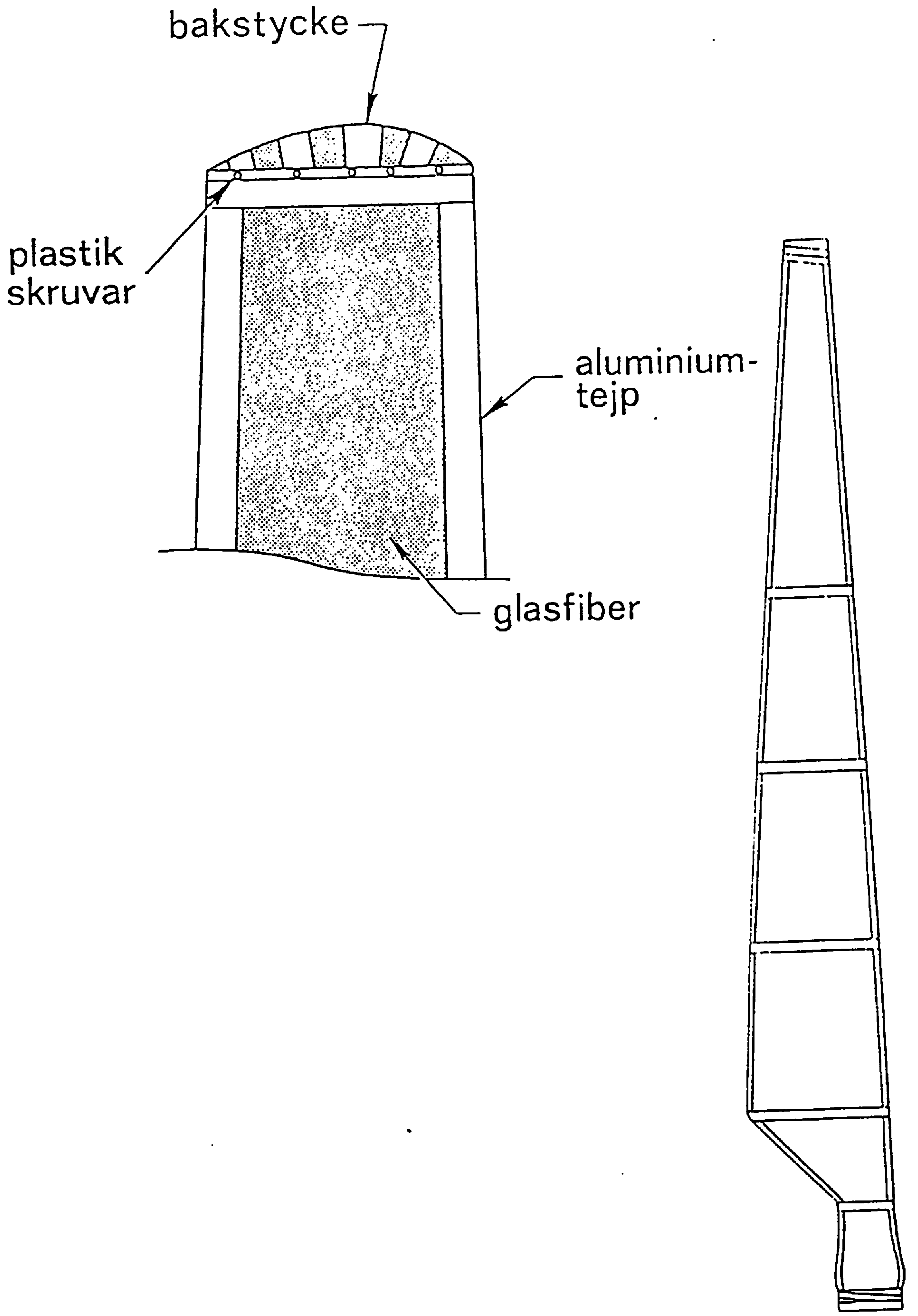
Maintenance problems must be addressed during the design of a lightning protection system.

The lightning protection system itself may attract more lightning.

On small rotor blades it may be more economic not to install lightning protection.



WTS 3
Rotorblad, bladstruktur
Figure 1



WTS3
Rotorblad, åskskydd

Figure 2

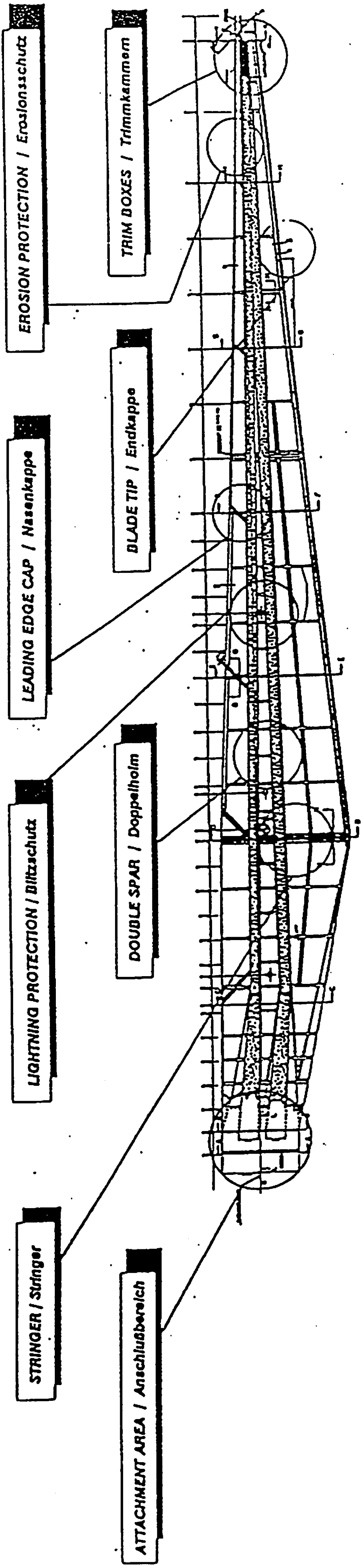


Abb. 2.1 Rotorblatt-Gesamtübersicht

Figure 3

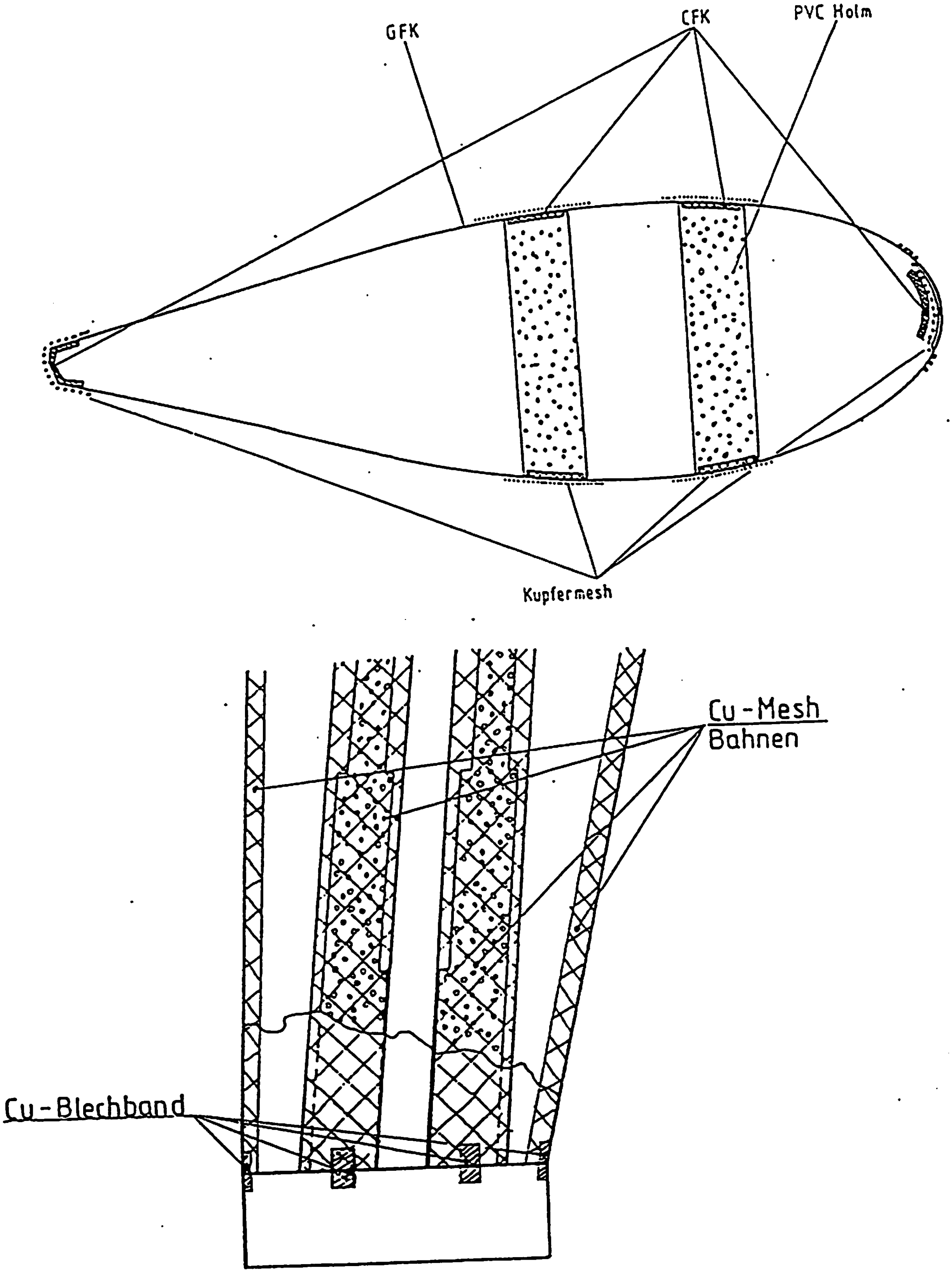


Abb. 2.5 Rotorblatt-Blitzschutz

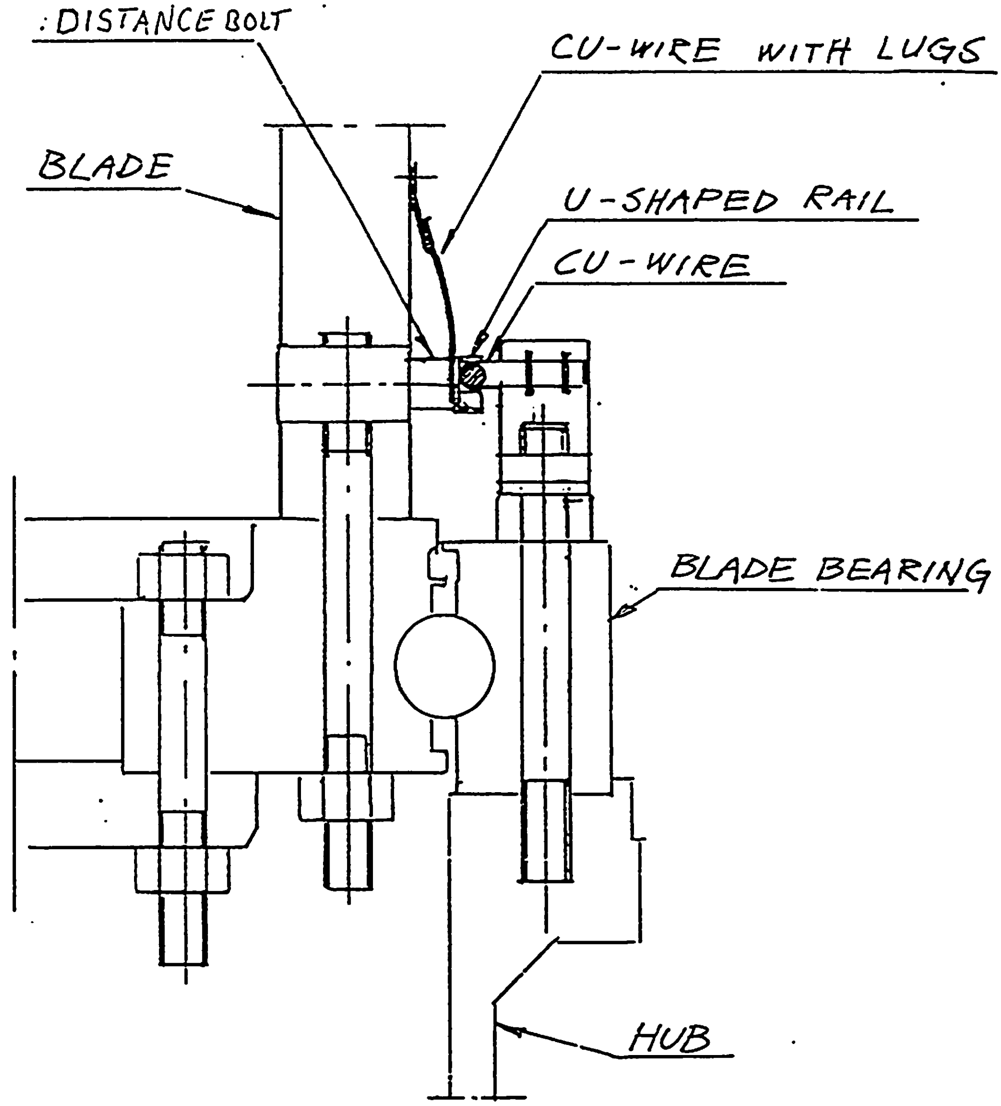
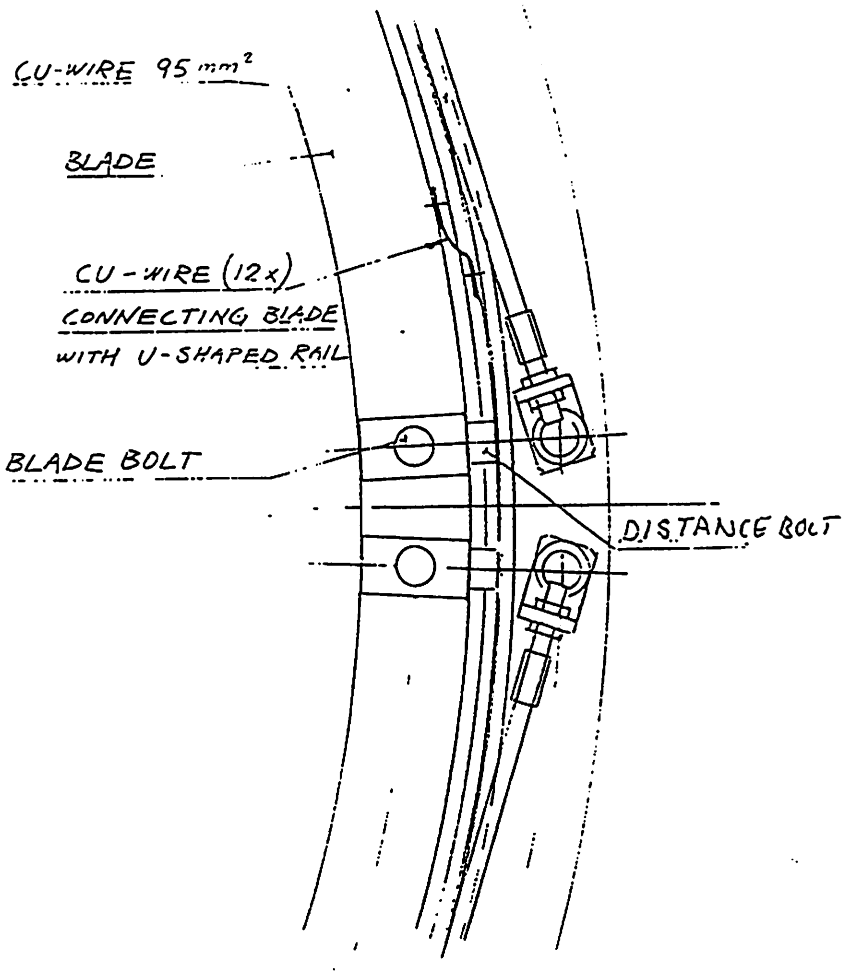
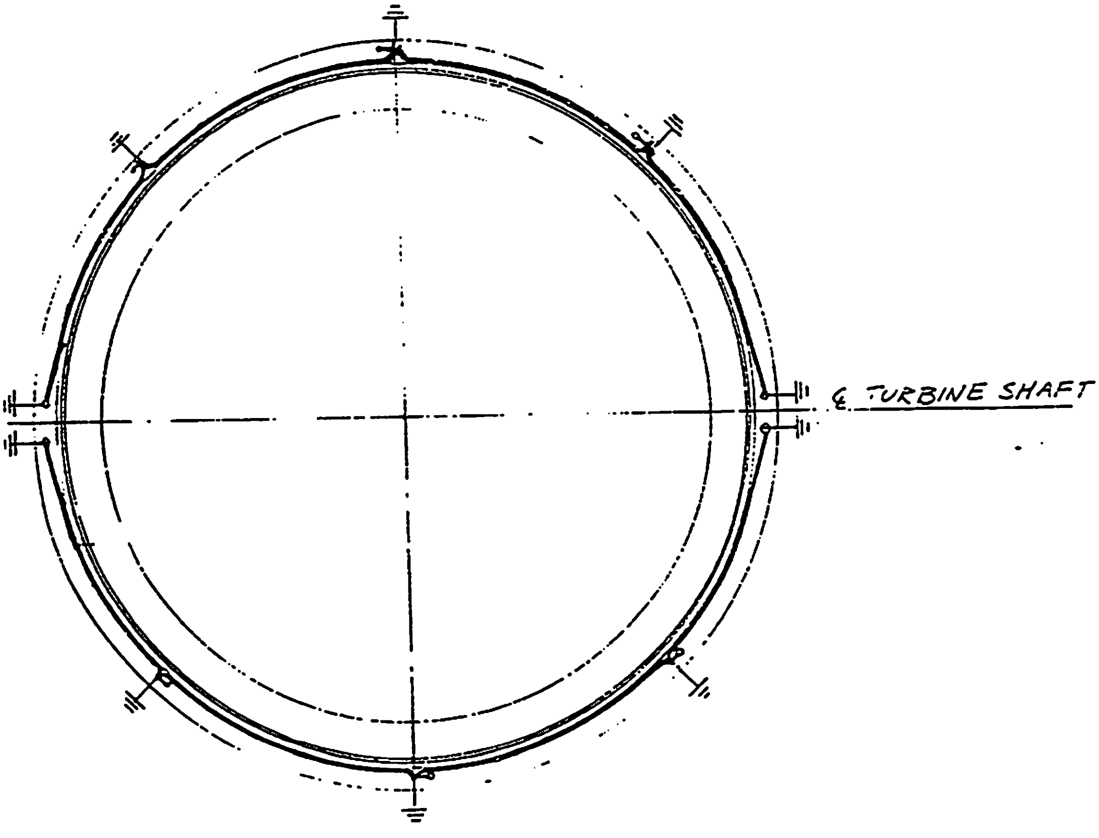

:DISTANCE BOLT
CU-WIRE WITH LUGS
BLADE
U-SHAPED RAIL
CU-WIRE
BLADE BEARING
HUB

Figure 5


CU-WIRE 95 mm²
BLADE
CU-WIRE (12x)
CONNECTING BLADE
WITH U-SHAPED RAIL
BLADE BOLT
DISTANCE BOLT


℄ TURBINE SHAFT

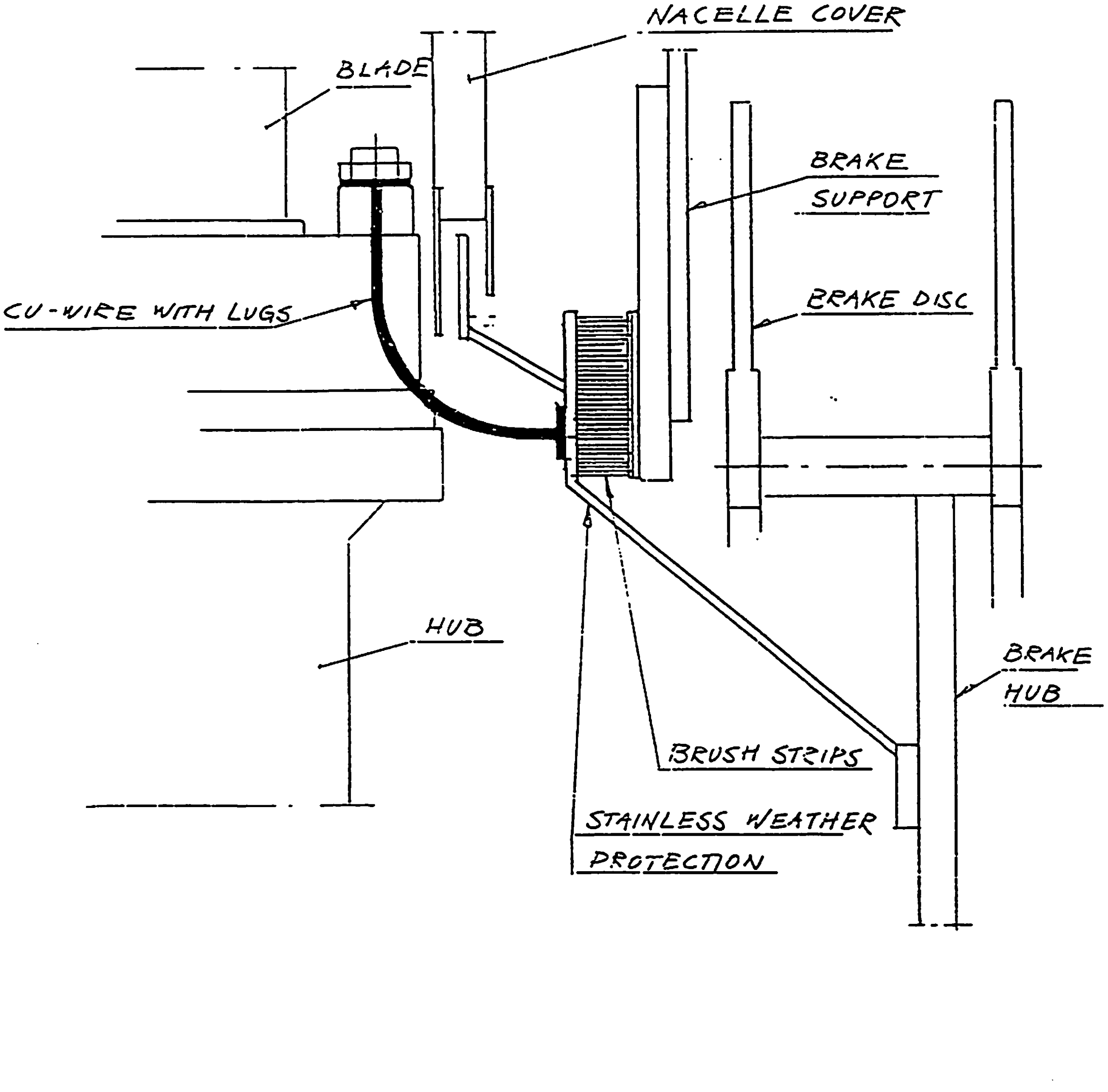
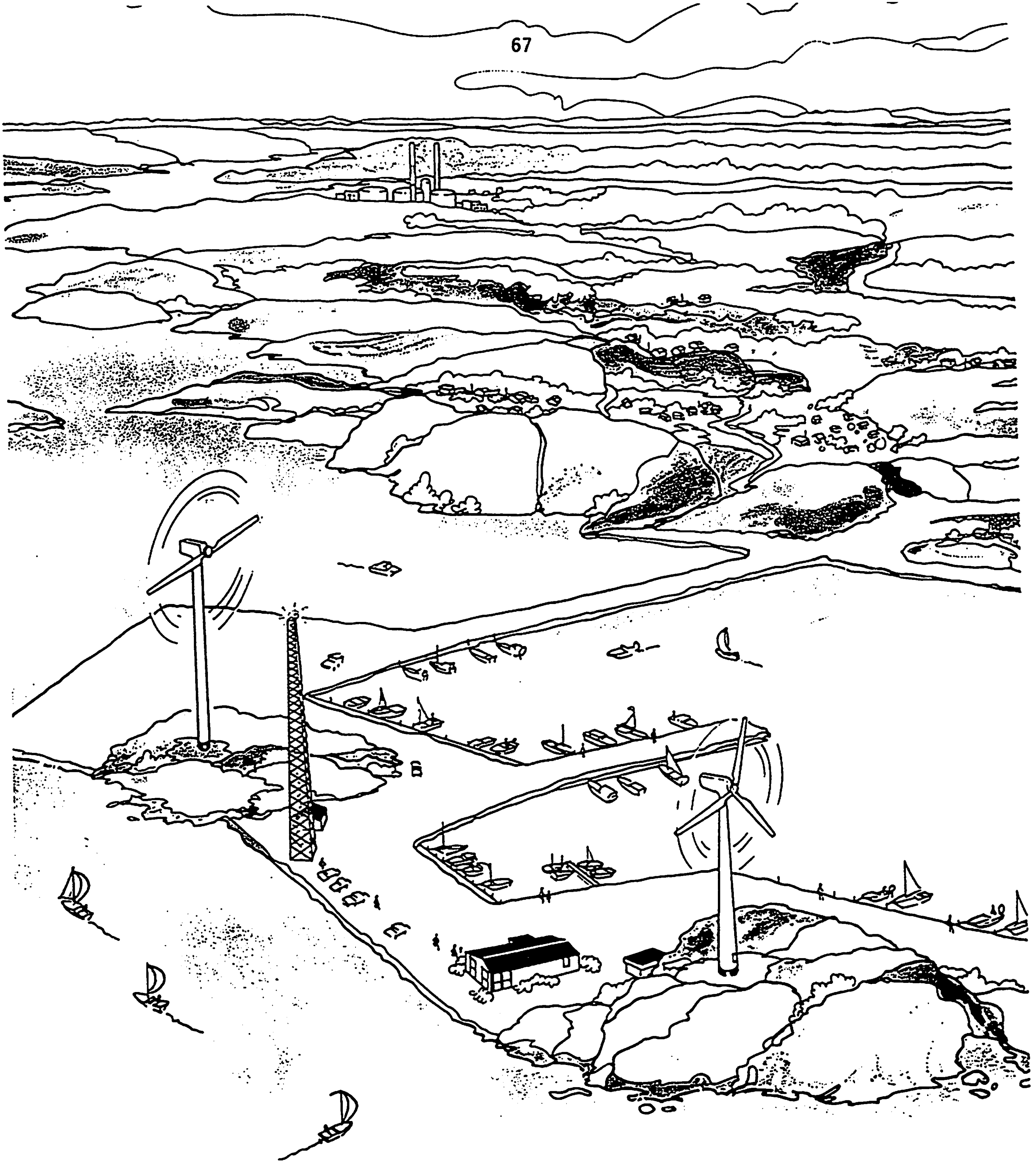

NACELLE COVER
BLADE
BRAKE SUPPORT
BRAKE DISC
CU-WIRE WITH LUGS
HUB
BRAKE HUB
BRUSH STRIPS
STAINLESS WEATHER PROTECTION

Figure 7



LYSE WIND POWER STATION

VATTENFALL

Figure 8

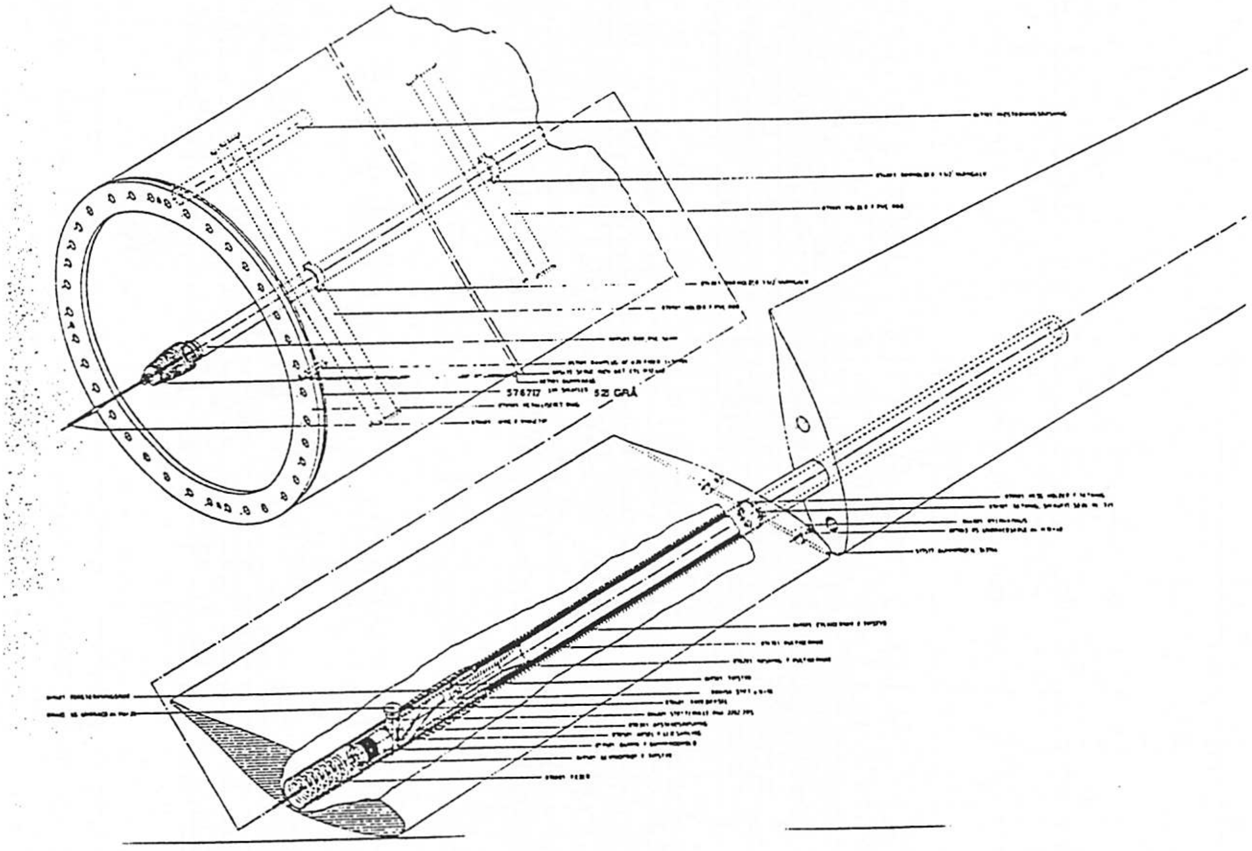


Figure 9

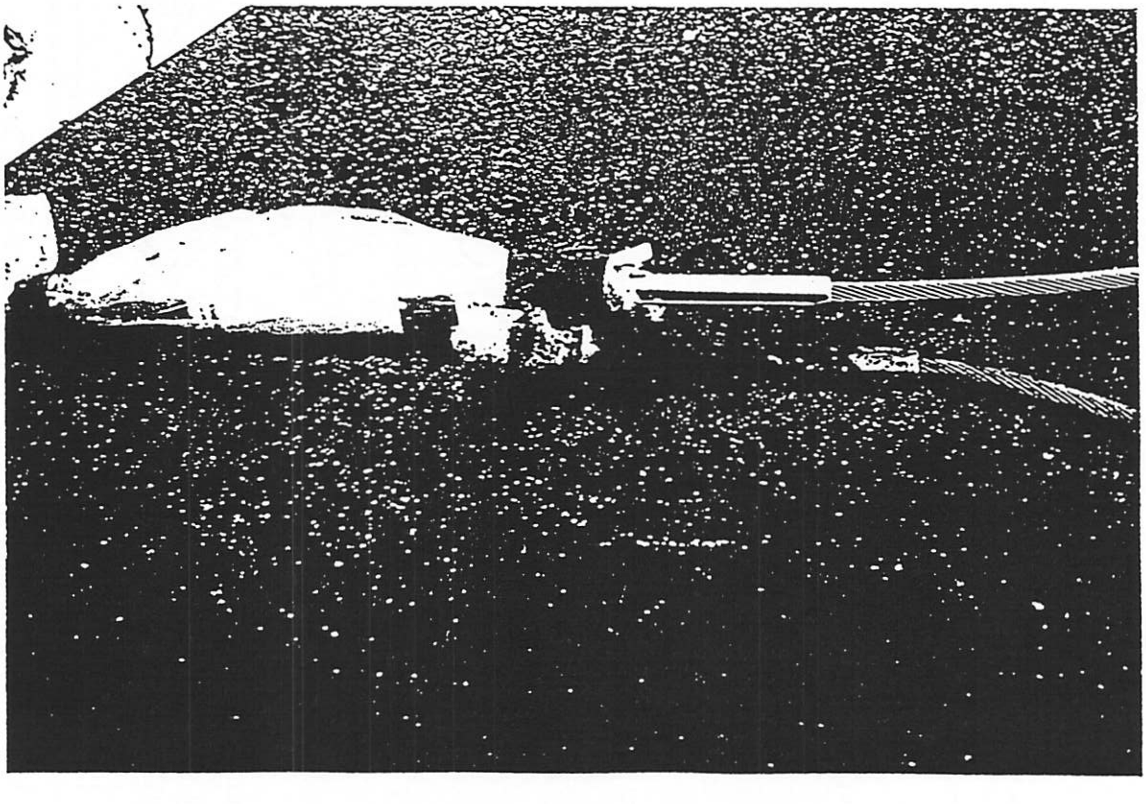


Figure 10

INTERNATIONAL ENERGY AGENCY

The Implementing Agreement for Co-operation in Research and Development of Wind Turbine Systems

26th Meeting of Experts

Lightning Protection of wind Turbine Generator System and EMC Problems in the Associated Control Systems.

Cologno Monzese, March 8th-9th, 1994.

Contribution:

LIGHTNING FLASHES TO NON-CONDUCTIVE (FIBRE GLASS) ROTOR BLADES OF WIND TURBINES:

by

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DK 2800 Lyngby, Denmark

INTRODUCTION:

In the past, there have been repeated discussions concerning the probabilities of lightning flashes to conductive and non-conductive objects, and concerning the way in which the interception efficiency is influenced by the resistances of the object, including the effect of the value of the grounding resistance. Opinions have ranged from the belief that non-conductive objects were self-protecting, to the belief that objects with and without lightning protection were exposed to approximately the same striking probability, regardless of the resistances in the object.

The same controversy has existed for wind turbines equipped with non-conductive rotor blades (f. inst. fibre glass).

In connection with an analysis of lightning damage to a fibre glass rotor blade of a wind turbine, evidence of importance for the solution of this controversy has been revealed.

DAMAGES TO FIBRE GLASS ROTOR BLADES:

From time to time non-conductive rotor blades are struck by lightning, suffering damages ranging from minor ones to total disintegration of the blade.

Rotor blades are normally equipped with steel wires for the control of the tips or the spoilers.

Such wires may act as receptors for lightning flashes (lightning rods), a phenomenon confirmed by the analysis of rotor blades damaged by lightning.

In connection with the analysis of lightning damaged blades, it has further been confirmed that normally major damages are associated with high values of the lightning current. This is indicated by the finding of mechanical damages together with discoloration of the steel wire due to excessive heat, and in addition damages to the wire arrangement.

Further, it has been found that complete non-conductive rotor blades without any internal conductive parts such as control wires, also suffer from lightning flashes. The reason for these flashes has been unknown, and the mechanisms governing the phenomenon have similarly been unknown.

However, in connection with an analysis of a special design of rotor blades, evidence was revealed of importance for the solution of the controversy of flashes to conductive and non-conductive objects. Furthermore, the analysis disclosed evidence of the phenomena involved and of concern for the development of methods for the estimation of the reception efficiency for conductive and non-conductive objects. These findings are reported in the following paragraphs of the paper.

THE MODELS USED TO DETERMINE THE LIGHTNING RECEPTION EFFICIENCY:

The EGM model:

For a great number of years the EGM (Electro Geometric Model) has been the prime model for evaluating the probability of lightning flashes to objects.
[Cf. lit. 1].

The model is an empirical, simple one representing a rather crude simulation of the last part only of the lightning flash. In spite hereof, the model has constituted a great step forward, and was for many years the basis for the dimensioning of lightning protection systems.

One of the major limitations of the simple EGM model is that it does not include the effect of the geometry and the height of the objects.

The LPM model:

In recent years, a new approach, the LPM (Leader Progression Model)[Cf. lit. 2], has been suggested and developed by L. Dellera and E. Garbagnati. The model is based on more details of the lightning processes of the flash. The model takes into account the field beneath a thundercloud, the field around the grounded object including the effect of height and geometry as a function of the surrounding field from the thundercloud and the downward-moving stepped leader.

The downward-moving leader is represented by the charge deposited in the progressing leader channel. The charge pr. unit length of the leader is a function of the final lightning current. When a sufficiently high field strength is reached on the top of the object as a function of all the aforementioned factors, an upward-moving leader is formed and provided that the upward- and the downward-moving leaders merge, the necessary preconditions are established for the flash.

Even though the model only includes some of the lightning flash mechanisms, an examination of the results of the model shows a much closer agreement between the behavior of natural lightning and the forecast determined by the model. Several improvements, however, are needed in order to ensure a sufficiently accurate model, including the selection of realistic and representative parameters, but even without these improvements the model has proven extremely valuable for the understanding of lightning phenomena and the protection measures necessary to provide an effective protection system.

From the model it follows that a flash to an object is always preceded by the formation of an upward-moving leader joining the downward-moving stepped leader descending from the thundercloud.

Provided that this assumption is correct, as experience seems to indicate, a non-conductive part of a construction should not be able to generate an upward-moving leader, and thus will not take part in determining the point of impact on the object. Only provided that by accident the non-conductive part is placed in or adjacent to the lightning channel, the non-conductive part will be struck by lightning.

The influence af the resistances of the object:

Neither the EGM model nor the LPM model takes into account any of the resistances of the object. Because the EGM model is empirical only, it will hardly be possible to incorporate the effect of the resistances. In contradistinction to this, the LPM model, however, is a semiempirical model which includes much more of the physical phenomena, it may therefore be relatively easy in addition to incorporate the effect of the resistances.

The resistances will effect the development of the upward-moving leader. If the resistance is too big, it will reduce the amount of charge in the upward-moving leader, and hence the length it will attain, and thus reduce the reception efficiency of the object in question.

The current necessary for the streamer development is in the order of 100 amp. but the time duration is short, and therefore the necessary charge is limited. The current necessary for the leader formation is considerably smaller, and therefore the conduction necessary to support the upward-moving leader may be much lower than normally anticipated. For wet and salt-contaminated constructions, even if the construction is inherently non-conductive, the formation of the upward-moving leader will proceed in the same manner as on a conductive object. However, when the lightning flash is established, the effect of the lightning current of course will be drastically different depending on whether or not a sufficiently effective lightning conduction on the object is provided.

As a matter of fact, an experimental proof of this phenomenon was disclosed accidentally in connection with an analysis of a lightning damage to non-conductive (fibre glass) rotor blades on a 200 kW wind turbine in Dennmark.

DESCRIPTION OF THE WIND POWER TURBINE AND THE DAMAGE TO THE ROTOR BLADES:

The lightning flash to the rotor blade took place medio March 1992. At the same time, rotor blades of two other wind turbines suffered similar damages (cf. enclosure 1).

The wind power turbine is one of several turbines (29) erected in the northwestern part of the island Zealand in Denmark (cf. enclosure 2).

The wind turbines are of 200 kW size with a three blade rotor, 35 meter in diameter. The rotor blades are polyester-fibre glass blades, each ~ 12 meters long and equipped with leading edge spoilers operated by means of steel wires internally passing along almost the full length of the rotor blade.

In order to prevent the wire from functioning as a lightning reception rod, an insulator is inserted in the wire at the hub end af the blade. The insulator used is of the type utilized in stays and shrouds in sailboats (yachts) in order to prevent attenuation of the wireless communication onboard.

In spite of the insertion of the insulator, a lightning flash to the rotor blade took place and damaged the above-mentioned insulator (cf. enclosure 3).

The pulling wire in the rotor blade is a stainless steel wire with a diameter of 4 mm ($\sim$ 12 mm^2). The insulation between the two electrodes of the ends of the wire consist of an air gap of ~ 4 mm in series with ~ 2 mm plastic insulation on each of the two electrodes. The electrodes with their insulation are imbedded in a brass-tube with internal threads.

The lightning flash has caused a puncture of the insulation of the electrodes, and burned a hole in both of the electrode insulations with a diameter of ~ 4 mm in the one and ~ 8 mm in the other electrode insulation. Apart from this, the blade has suffered no further damage.

The wire bears no sign of discoloration caused by the conduction of the lightning current. Consequently, the lightning current has been of limited value, and well below the meridian value. Based on this fact, and the size of the puncture, the lightning current has been estimated to be about 10 kA. The damage to the brass tube is caused by the air pressure development inside the insulator in the confined volume. Assuming the level of the lightning current and the associated charge, the air pressure has been estimated to be in the order of 100 atm. or higher.

Comparison of the estimated current value to the value measured by our Lightning Location System has failed due to lack of the precise knowledge of the occurrence of the flashes to the wind turbines.

ANALYSIS OF THE CAUSE OF THE LIGHTNING INCIDENT:

The mechanical velocity of the rotor blades is very much lower than the velocity of the leaders. Therefore, the blade can be regarded as stationary during the final stages of the formatiotion of the leaders and the succeeding return stroke. The time interval, however, betwen the first return stroke and the subsequent ones may be large enough to bring a new blade into the exposed space. Therefore, more than one blade might be struck by subsequent strokes of the same lightning flash.

In the paragraph on the LPM model, it was assumed that a precondition for a flash to a construction is the development of an upward-moving leader, approaching the downward-moving stepped leader from the thundercloud. This assumption seems to be confirmed by experience in the field.

On the basis of this assumption, the rotor blade of the wind turbine must have developed an upward-moving leader prior to the flash.

Due to the inserted wire insulation, the control wire in the rotor blade has not participated in the conduction of the current necessary for the formation of the leader.

The voltage rise over the insulation caused by the formation of the leader is relatively slow. Since the flashover voltage of the external insulation is much lower than the puncture voltage, an external flashover of the insulator would have taken place provided the voltage rise had been big enough.

In this case, the lightning current would have taken the path over the external insulation in the arc established by the previous flashover.

On the contrary, the lightning current has created a puncture to the internal insulation of the wire insulator. As the puncture voltage is much higher than the flashover voltage, a prerequisite for the occurrence of a puncture is that the applied voltage is sufficiently high and sufficiently steep, actually the conditions associated with a lightning flash.

Therefore, it can be concluded that the current necessary to feed the upward-moving leader, must have been conducted over the surfaces of the fibre glass rotor blade.

At a first glance, it may seem astonishing that sufficient current may be conducted via the surfaces of non-conductive items. From experience, however, the contaminated and moist surfaces are a significant factor often of crucial importance for the behavior of high voltage insulators and insulation in practice.

In the near future, an investigation will be undertaken to determine the surface conduction necessary to provide the current for the formation of the upward-moving leader, the amount of energy dissipated in the moist surfaces, the amount of contamination and water necessary, the effect of the internal and external surfaces, and the effect of aging of the surfaces by the influence of climatic conditions.

Furthermore, the investigation will aim at determining the effect of the impedances in the current path, including the surface conduction and the ground resistance, for the length of the upward-moving leader and thus for the effective attraction radius.

CONCLUSION:

The analysis of the wire insulation for a wind turbine rotor blade damaged by a lightning flash to the blade, has proven that non-conductive objects are exposed to lightning flashes, due to the formation of an upward-moving leader supplied by surface current in the wet and contaminated surfaces of the rotor blade. Therefore, non-conductive structures have to be protected by a lightning protection system. The same applies to non-conductive rotor blades for wind turbines. How such a protection should be provided is the subject of a research program with participation of the interested parties in Denmark such as users, insurance companies, manufacturers and research organizations, and financially supported by the Danish Ministry of Energy.

The results of this analysis have been compared with the available data from other damages in the field over the years, and the results hereof have so far supported the reported findings.

One further observation of importance from the analysis is that a thorough investigation of lightning damages may be extremely useful in order to make it possible to improve the understanding of the lightning phenomena. On the other hand it has also been proven that in practice it is difficult from the statistics and the recording of the individual damages to get sufficiently detailed information to allow for analyses capable of revealing fundamental properties, similarly to the one reported in this paper.

Unfortunately, the EGM model can neither give support to the evaluation of the interception efficiency of normal non-conductive structures nor be used for the evaluation of the effect of geometry and height of the objects.

For the LPM model, on the other hand, the effect of geometry and height is a built-in feature. In order to provide a more precise determination of the inception efficiency, however, the model may have to be further developed, but of even greater importance may be the selection of values for the parameters used in the model, appropriate to the task, a selection which may be more difficult than appreciated, mainly due to lack of sufficient reliable knowledge of the corresponding parameters in nature.

Finally it seems possible to improve the LPM model by incorporation of the resistive part of the object in the path governing the current to the upward-moving leader.

Literature:

Lit. 1: M. Darveniza, F. Popolansky, E.R. Whitehead:
"Lightning Protection of UHV Transmission Lines",
Electra No. 41, juli 1975, pp 39-69.

Lit. 2: L. Dellera, E. Garbagnati:
"Lightning stroke simulation by means of the leader progression model - part 1: Description of the model and evaluation of exposure of free standing structures",
IEEE Transactions on Power Delivery, act. 1990, vol. 5, N. 4, pp. 2009-2022.

Enclosures:

Enclosure 1. Lightning damages to wind turbines in the supply area of the Power Company NVE.

Enclosure 2. Map of the area indicating the positions of the wind turbines.

Enclosure 3. Photo 1 - 4 of the damaged wire insulation.

ENCLOSURE 1.

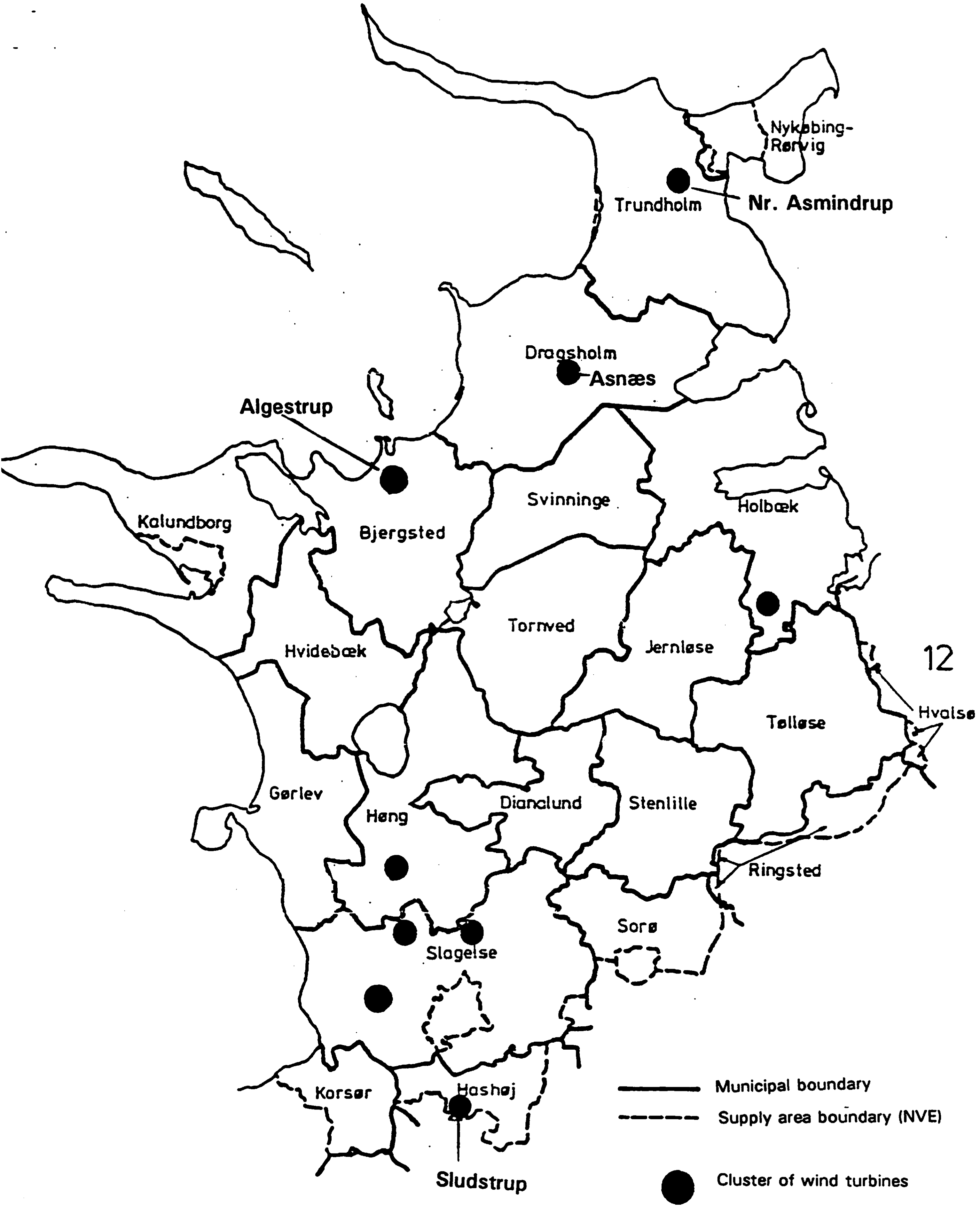
LIGHTNING DAMAGES TO WIND TURBINES IN THE AREA OF THE POWER COMPANY NVE

Date	Cluster	D/I	Damaged Parts
920319	Sludstrup 1	D	Wire in rotor blade
920316	Algestrup 1	D	Wire in rotor blade
920319	Algestrup 3	D	Wire in rotor blade and rotor blade
890628	Asnæs 1	I	Parts of the controls and fuses
890628	Asnæs 2	I	Parts of the controls and fuses
890628	Asnæs 3	I	Parts of the controls and fuses, cables, and probes
910823	Nørre Asmindrup 2		Parts of the controls
880630	Nørre Asmindrup 1		Main control and fuses

D/I = Direct/indirect lightning flash to the wind turbine.

MAP OF NVE SUPPLY AREA

ENCLOSURE 2.



ENCLOSURE 3.

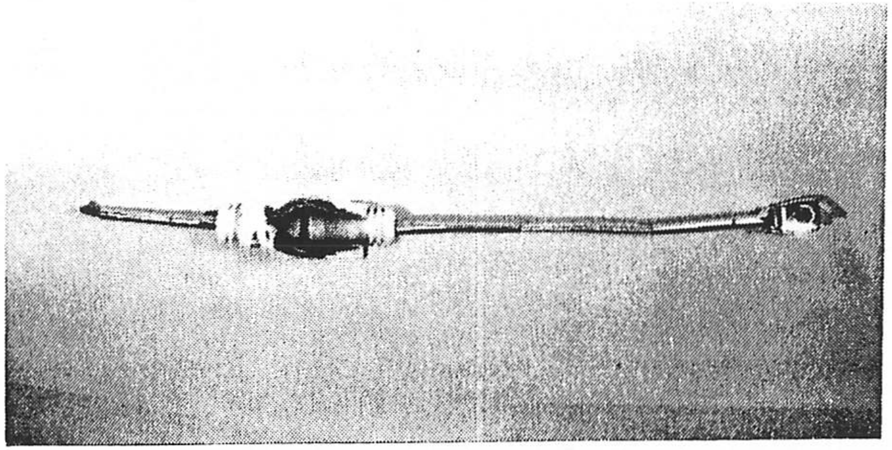


Fig. 1: The wire insulation with the burst casing.

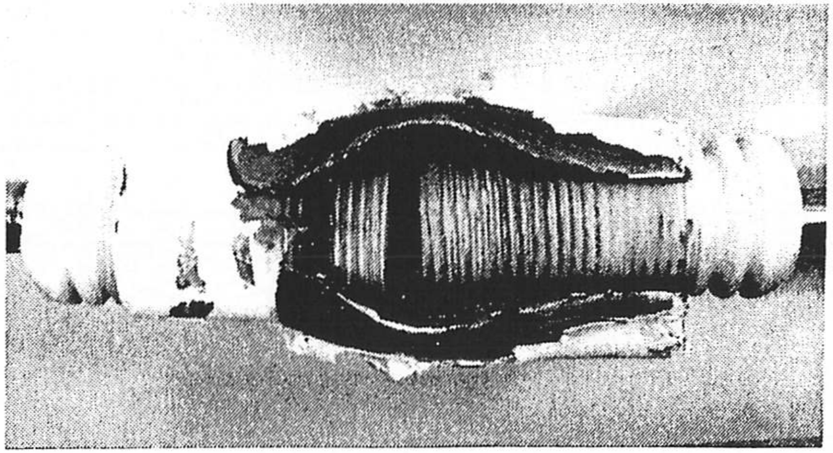


Fig. 2: Close-up of the wire insulation.

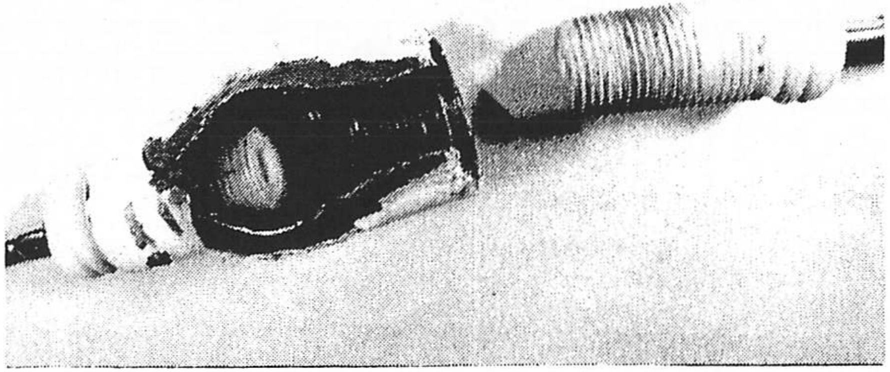


Fig. 3: The wire insulation with the burned hole in the insulation.

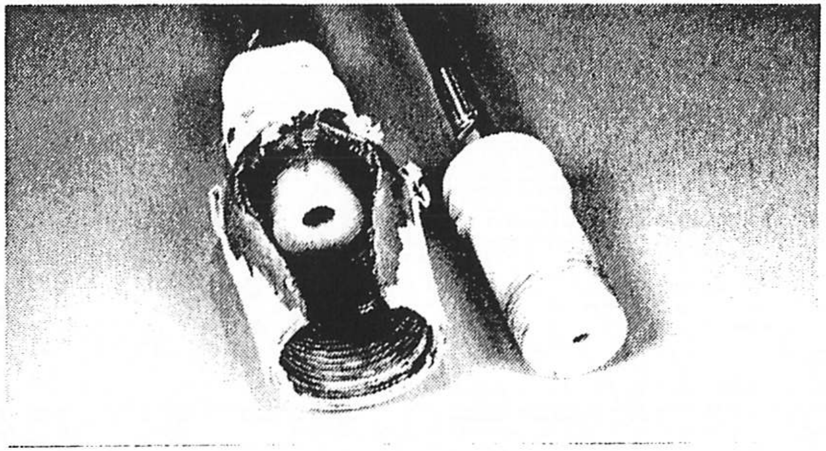


Fig. 4: The wire insulation with the burned holes in the insulation of the two electrodes.

CURRENT DISTRIBUTION AND INDIRECT EFFECTS ON A WIND POWER GENERATOR FOLLOWING A LIGHTNING STROKE

E. GARBAGNATI- ENEL CRE
L. PANDINI- ENEL CRA

1 - INTRODUCTION

Following a lightning stroke the current flows through the various parts of the wind mill, with possible damages (example damages to the bearing). Furthermore the current flowing generates electromagnetic fields which could affect the behavior of the electrical and electronic apparats inside the wind mill.

2 - TESTS PERFORMED

The tests were carried out injecting current impulses on the nacelle of the Gamma 60 wind mill generator, as shown in Fig. 1. In the tests the nacelle was mounted at the top of a 2 meter tower.

Currents with the following characteristics were injected:

- peak value 3.8 kA
- frequency: 16 kHz
- maximum steepness 0.38 kA/us

The current shapes are shown in Fig. 2.

3 - TEST RESULTS

3.1 Current distribution

The measured current distribution is shown in Fig.3. In particular the figure reports, for each measuring point, the percentage of the current flowing with respect to the injected one.

The analyses of the results obtained indicates that the largest fraction of the injected current (80 %) was flowing through the bearing closest to the blades. The performance of the bearing under the full lightning current is analyzed in a companion paper.

3.2 Indirect effects

Example of the magnetic field recorded is shown in Fig. 4
The measured magnetic field distribution is given in Fig. 5.
The results show that the magnetic field can reach values of several kA/m in proximity of the blades. These values are higher than those compatible with the immunity of the instrumentation for industrial application. However the magnetic field are much lower in the zones were electronic apparatus are installed, thus resulting not critical.

An example of the induced voltages on wiring is shown in Fig. 6. The measurements have shown that in the examined case the induced voltage reach maximum values of few tens of volts, thus being not critic for control systems for industrial application.

4 - CONCLUSIONS

The tests have shown that when the lightning strokes the blades a significant percentage of the current can flow through the bearings. This current may affect the bearing behavior.

The electromagnetic field inside the nacelle may be of concern. However a proper design may mitigate the problem.

Experimental checks on the complete wind generator after installation could help to complete the picture.

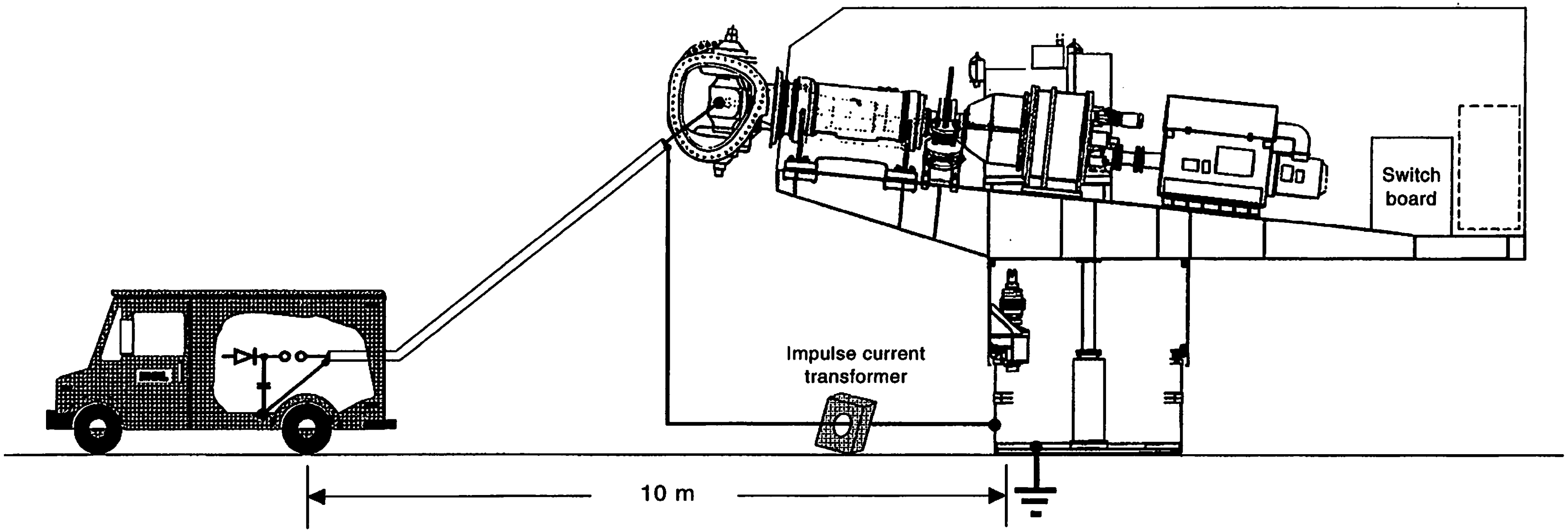
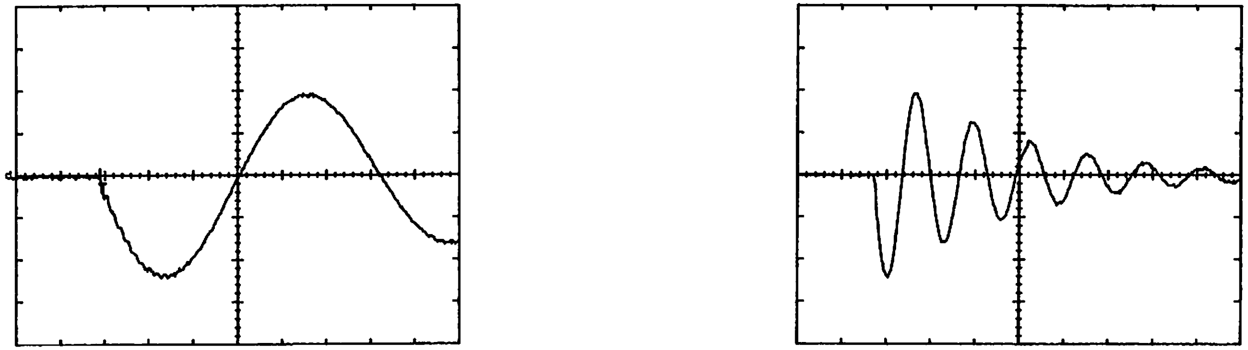


Fig. 1 - Test set up



Osc. 1: 1,5 kA/div - 10 µs/div

Osc. 2: 1,5 kA/div - 50 µs/div

Fig. 2 - Injected current

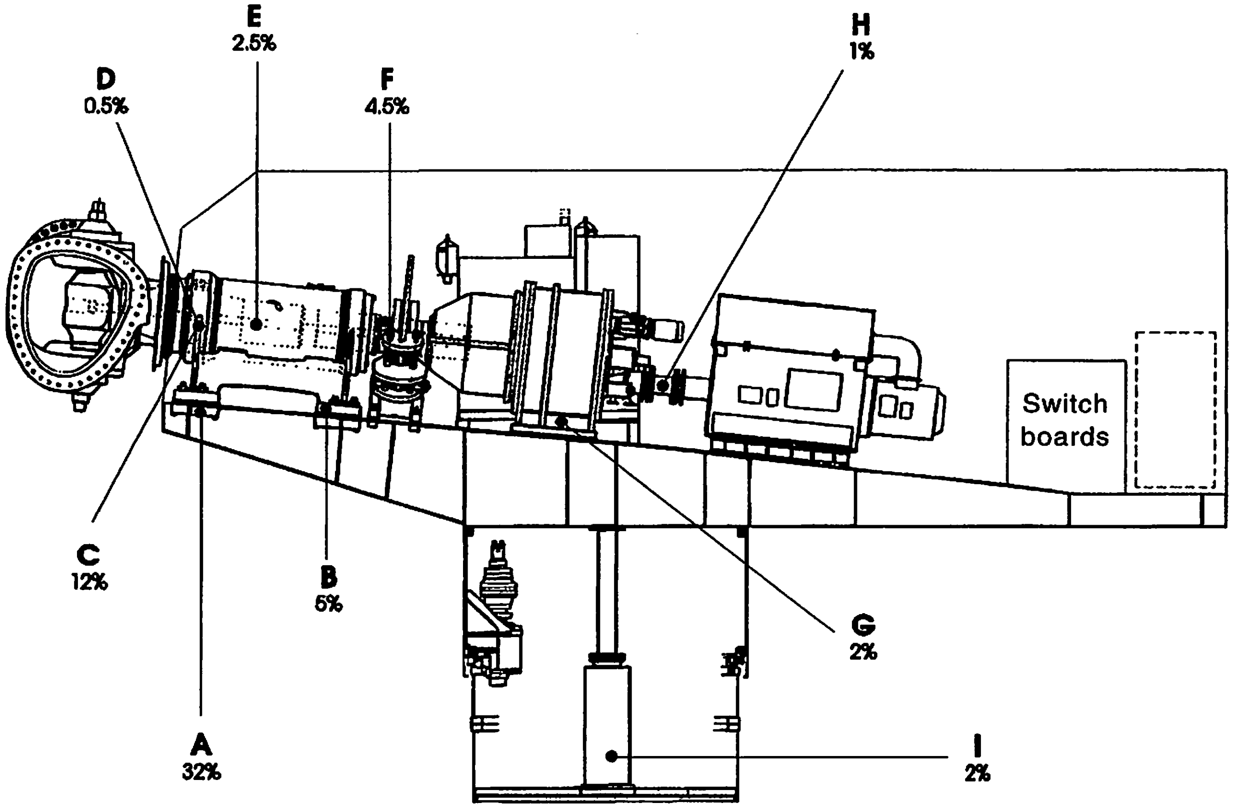


Fig. 3 - Current distribution (% of the injected current)

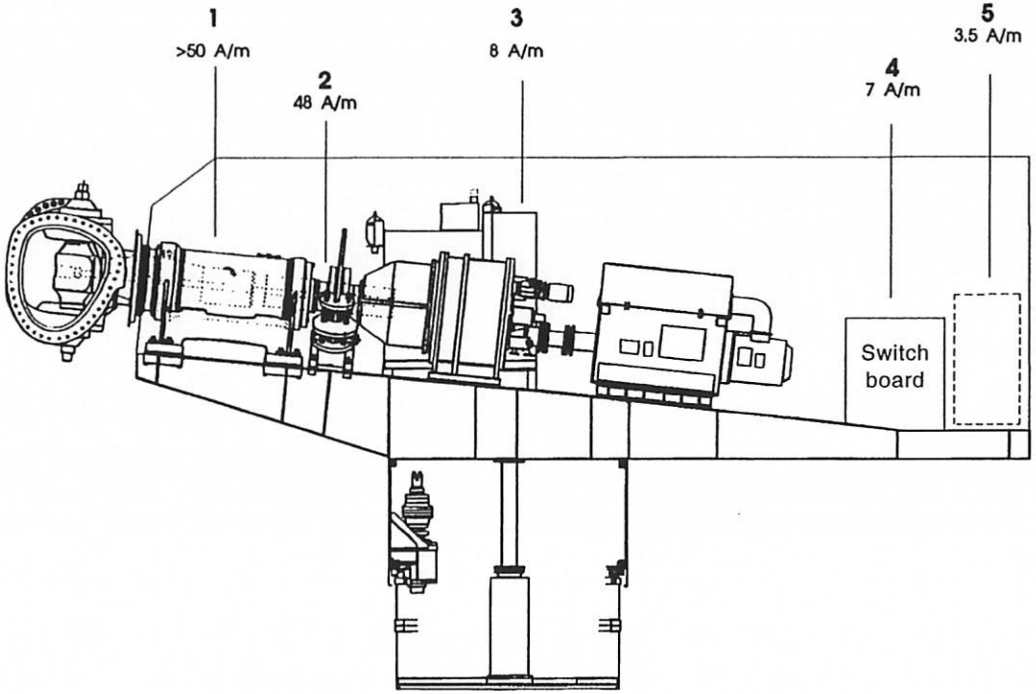
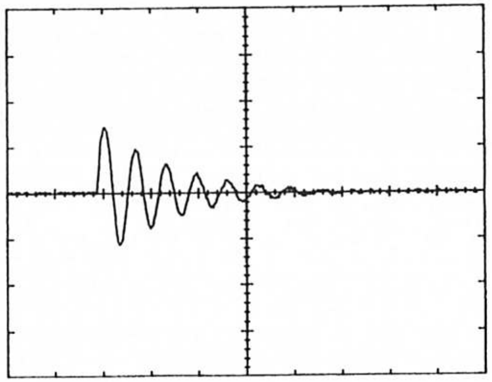


Fig. 4 - Magnetic field distribution

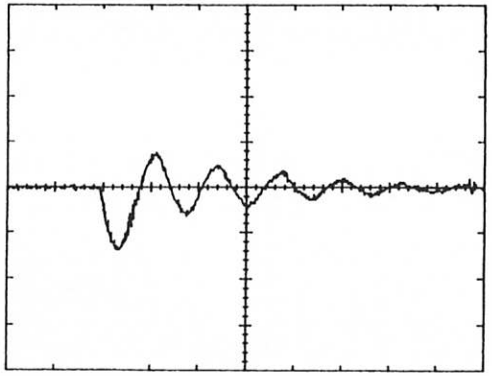


Osc. 3: 35 A/m/div - 100 µs/div

Fig. 5 - Exemple of magnetic field

CIRCUIT	INDUCED VOLTAGES (mV)	
	Zt = ∞	Zt = 150Ω
Tipical long path (screened cable)	130 (Osc. 4)	100
Tipical mean path (screened cable)	110	70
Tical short path (screened cable)	200	160
Tipical long path (conductor in unscreened cable)	1500	1400

Tab. 1 - Induced voltages on control circuits



Osc. 4: 100 mV/div - 50 µs/div

Fig. 6 - Exemple of induced voltage

EVALUATION OF THE DAMAGES CAUSED BY LIGHTNING CURRENT FLOWING THROUGH BEARINGS

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and

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ABSTRACT

A laboratory for lightning current tests has been set up at CESI allowing the generation of the lightning currents foreseen by the Standards. Lightning tests are carried out on different objects, aircraft materials and components, evaluating the direct and indirect effects of lightning. Recently a research has been carried out to evaluate the effects of the lightning current flow through bearings with special reference to wind power generator applications.
For this purpose, lightning currents of different amplitude have been applied to bearings in different test conditions and the damages caused by the lightning current flow have been analysed.
The influence of the load acting on the bearing, the presence of lubricant and the bearing rotation have been studied.

INTRODUCTION

The peculiar structure of the wind power generators and often the weather conditions typical of the areas where the eolic plants are installed, increase the probability for a generator to be struck by a lightning flash. If a lightning flash happens to hit a wind power generator, the lightning current path to earth can involve the shaft and the bearing (Fig.1). Similar problems may arise, for example, if a lightning flash hits the blades of an helicopter.
The flow of the lightning current can damage bearing rolling elements and raceways, with a possible consequent reduction of the reliability of the structure where the bearing is installed.

The evaluation of the effects produced by the lightning current flow through bearings is important both to evaluate the efficiency of the structure and to identify possible protection systems. For this purpose, lightning currents of different amplitude have been applied to bearings in different test conditions and the damages caused by the lightning current flow have been analysed.

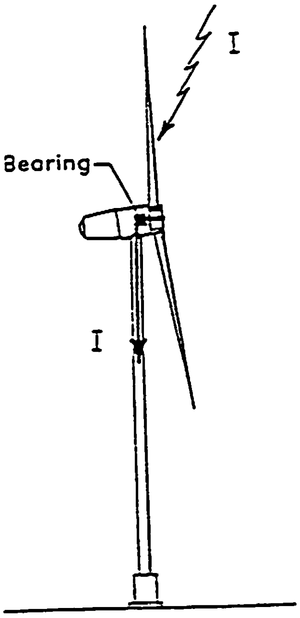

Fig. 1 - Schematic view of the lightning path in a wind power generator, with involvement of the generator bearings.

For the evaluation of the effects produced by the lightning current flow through bearings, the contact conditions among the rolling elements and the raceways are of special interest.
In the loaded zones of the bearings the rolling elements are in contact with the raceways, while in the unloaded zones the rolling elements are not in contact with the raceways and small gaps are formed.

The lightning current interests the contact areas between the rolling elements and the raceways.
The number of rolling elements in contact with the raceways is a function of the mechanical load (the number of rolling elements in contact increases when the mechanical load is increased); in the limit case only one rolling element can be in contact.
The extension of the contact area for each rolling element is also a function of the load.

The lightning current may interest the small gaps between the raceways and the rolling elements in the bearing zones not in contact. The electric strength of the gap depends on the kind and the characteristics of the insulating media.

The performance of the bearing under lightning can be finally influenced by its rotation.

It is evident that the phenomenon is very complex.
In order to try to understand the mechanism of damage, the tests were designed to analyse separately the influence of the parameters mentioned above.
In particular, the effect of the mechanical load and of the lightning current amplitude was analysed on a simplified configuration (single couple

of rollers), while the influence of rotation, lubrication and lightning current flow through the different rolling elements was analysed on complete bearings.

TEST OBJECT

The systematic research was performed on self-aligning roller bearings, with double order of rollers, having the following main characteristics: external diameter of 160 mm, internal diameter of 90 mm and dynamic load coefficient of 322 kN. The raceways and rollers of the bearings were made of high-chrome steel.
The following test configurations were examined, as shown in fig. 2:

a) <u>simplified configuration with single couple of rollers</u> (see fig. 2a) to analyse the effects of the lightning current flow through single rollers.
To this purpose all the rollers, except the two under investigation, were taken out from the bearing and substituted by an insulating ring having the function to maintain the bearing geometry. In this way the lightning current was forced to flow exclusively in the couple of rollers.
The bearing was tested in still condition, without lubricant.

b) <u>complete bearings</u> (see fig. 2b), to study their lightning performance in different conditions. Namely the bearings were tested without oil both in still and rotating conditions and finally in rotation with oil.
A rotation of 300 rpm was maintained through a motor mounted on the shaft. The lubricant was housed in a box under the bearing and transported through the rolling elements by the rotation itself.

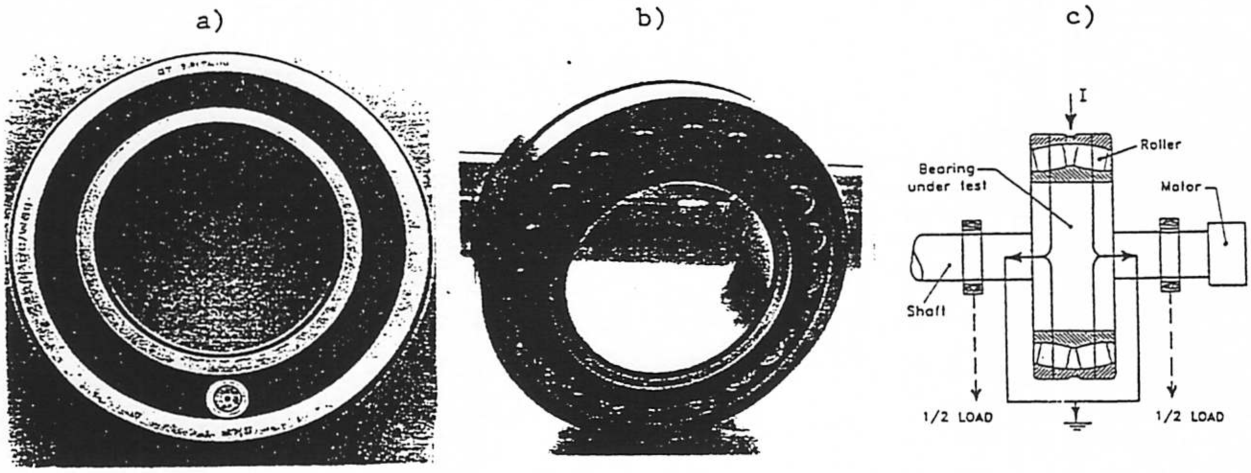

Fig. 2 - Test objects and test set up
a) picture of the simplified configuration (with single couple of roller)
b) picture of complete bearing
c) scheme of the test set up.

TEST CONDITIONS

MECHANICAL STRESSES

Radial mechanical loads were applied to the bearings under test; the load was applied symmetrically on the shaft (see fig. 2c).

The load was varied up to 10 kN in the tests on single couple of rollers to vary the contact area.
The relation between the contact areas on a single roller (S) (in the bearing under test, the contact areas are ellipses) and the load acting on the bearing is reported in Fig.3, where the curves relevant to inner and outer raceways are given [1].

A constant load of 5 kN was applied on the complete bearings. Mechanical calculations [1] indicate that in this case only 5 couples of rollers are in contact with the raceways. The calculation also permits to evaluate the load distribution among the different rollers and thus the contact areas. The extension of the single roller contact area results of 1.8 mm^2 for the most loaded rollers decreasing to 1.3 and 0.3 mm^2 for adiacent rollers (see fig. 8).

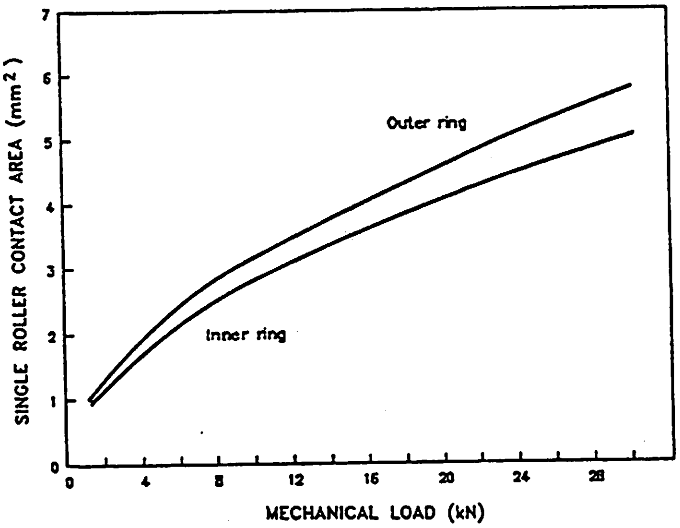

Fig. 3 - Mechanical calculations. Inner and outer ring contact areas of a single roller as a function of the mechanical load applied to the bearing simplified model, with only one couple of rollers.

CURRENT STRESSES

In all the above mentioned cases, the lightning current was injected in the outer ring of the bearing through an additional metallic ring externally clamped to the bearing itself.
The lightning current was flowing from the outer ring to the inner one through the rolling elements and then to earth through the shaft (see Fig.2 c).

The lightning current was generated by means of the test circuit shown in fig. 4; the circuit allows the generation of the current waveforms A,B,C and D foreseen by the Standards [2] both as single pulses and as a combined waveforms. It is composed by three current generators and a filter with blocking capacitors and inductances; the main characteristics of the current generators are described in the followings.

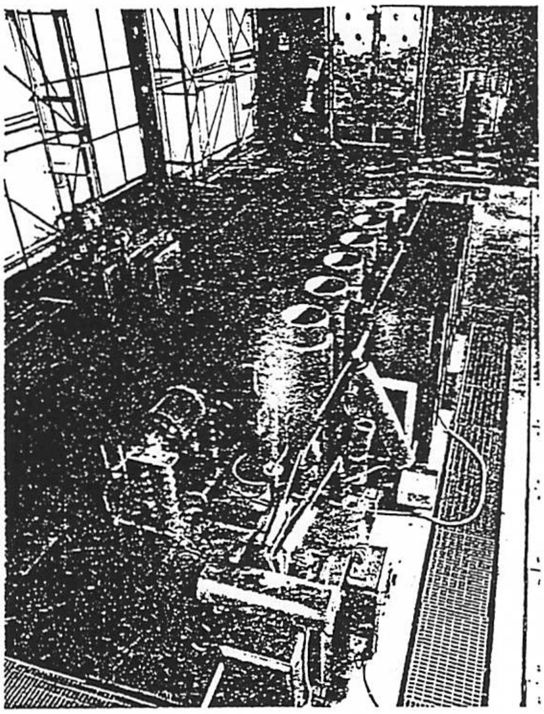

Fig. 4 - Test circuit to generate current components as in [2].

The A/D current generator consists of a 100 kV, 24 μF, 120 kJ capacitor bank; the capacitors can be charged in both positive and negative polarity. Damped oscillating waves with peak values up to 200 kA, action integral up to $2*10^6$ A^2*s and rise times between 8 μs and 20 μs can be achieved with load inductances up to some μH.
The B current generator is a 12 LC cell, 20 kV, 90 kJ generator. The cells can be charged both in positive and negative polarity. Currents with peak values up to 2.5 kA and duration of few ms can be generated.
The C current generator consists in a DC generator and a smoothing capacitor bank. Continuous currents up to 250 A with time durations up to 1 s can be generated.
Plasma gaps are used to switch the different lightning current components.

The systematic research was carried out injecting the A current component, while only few checks were made with B and C components.
The lower amplitude and rate of rise of the B & C lightning currents with respect to the A component, the longer time duration and the speed rotation of the bearing seem to be the most important parameters in determining the damage mechanism with this kind of current components. Further tests are foreseen in order to better analyse the influence of the different lightning components on the damage mechanism and extension.
In the following the results obtained with the A current component will be given.

Tests with current peak values in the range from 1 kA up to 100 kA and an action integral(1) in the range from 18 A^2*s up to $1.2*10^6$ A^2*s were applied to the simplified configuration with the single couple of rollers to determine the minimum current leading to damage (damage threshold) and study the relationship between current and damages.

A current impulse with a peak value of 100 kA and an action integral of $1.2*10^6$ A^2*s was applied to complete bearings under test.

TEST RESULTS

LIGHTNING TESTS ON SIMPLIFIED CONFIGURATIONS

Damages were observed both on the inner and the outer raceways and correspondingly on the rollers of the bearing.
The damage-threshold-peak-value of the injected current (Ipt) and the corresponding action integral (Et) are reported in fig. 5 as a function of the load acting on the couple of rollers: the threshold peak current increases when the load is increased.

By combining the data of fig. 3 and fig. 5, the threshold values of the current density Ipt/S and of the action integral density Et/S were determined. The damage-threshold peak current-density was found approximately constant (about 4 kA/mm^2) independently of the mechanical

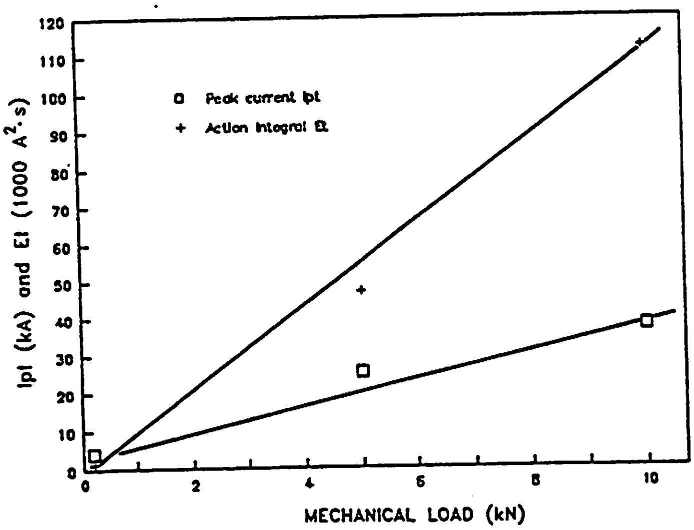

Fig. 5 - Tests on the simplified configuration with one single couple of rollers: damage- threshold current values as a function of the mechanical load applied to the bearing.
Ipt= peak current value
Et= action integral value

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(1) The Action Integral E represents the energy per unit resistance transferred by the lightning current and is defined as: $E = \int_T i^2 * dt$, where T is the duration of the current waveshape.

load. The damage threshold action integral density varied from 190 A^2*s/mm^2 to 6.000 A^2*s/mm^2 when varying the mechanical load in the examined range.

The type and size of damage varied with current and mechanical load value. At low current values, craters (see fig. 6a) were observed when very low mechanical loads were applied, while flutes (as shown in Fig. 6b) were observed for higher loads.
For higher current values the type of damage remained similar. However, bigger surfaces of the rollers and raceways were damaged and melted materials appeared at the flute extremities.

The damages caused by the flow of the lightning current to the bearing rollers and raceways were estimated, in a preliminary way, by evaluating the extension of the damaged surface, independently of the damage type. Other more precise evaluation of damages in terms of depth, volume, type and so on are undergoing. Metallographic exams will be also made in order to detect possible changes of the metal characteristics in the damaged areas.

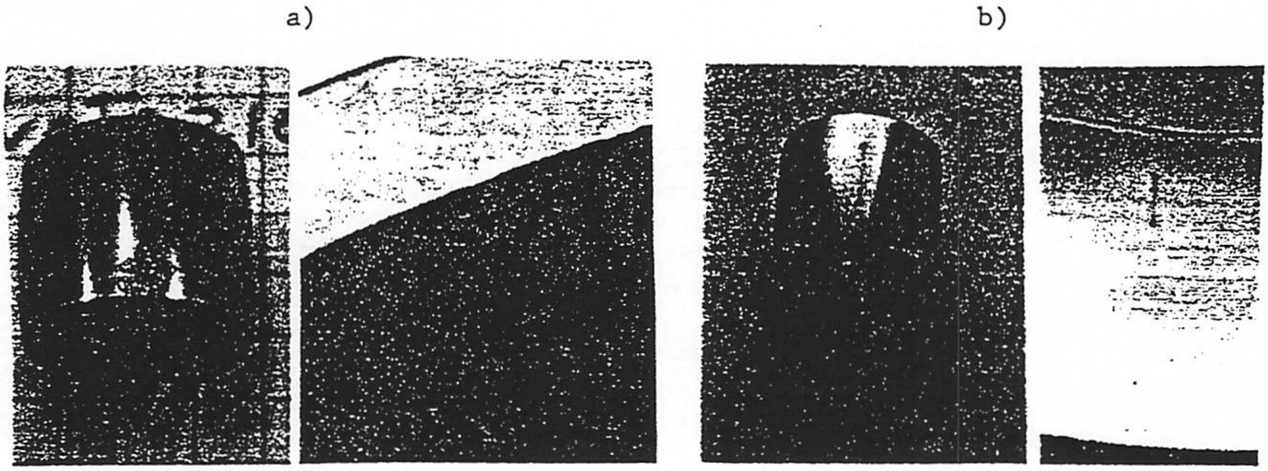

Fig. 6 - Tests on the simplified configuration with one single couple of rollers: damages observed:

a) craters
b) flutes

Fig. 7 reports the maximum values of the damaged area (independently of the type of damage), at one of the contact side of each roller, as a function of the peak value of the injected current for the three mechanical load conditions examined; the contact area of a single roller for the three different loads are also reported. The figure shows that the damage extension increases when the load is decreased and, for a given load, increases with the increase of the lightning current amplitude.
Comparing the damaged areas with the estimated contact areas, it appears clearly that while for low current values the damaged surface is close to the contact area size, for higher currents it is much larger.

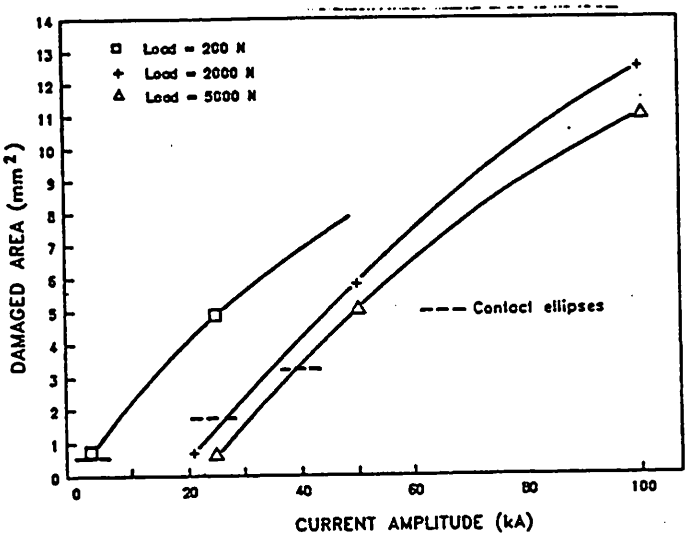

Fig. 7 - Tests on the simplified configuration with one single couple of rollers. Maximum values of the damaged surfaces as a function of the peak value of the lightning current for different load conditions.

TESTS ON COMPLETE BEARINGS

Also in the case of complete bearings, a rough estimation of the damages has been made. The damaged surfaces, independently of the damage type, are reported in Fig. 8 where the maximum values of the damaged areas are given in correspondence of each couple of rollers. For sake of simplicity only the cases of still bearing without lubricant and rotating bearing with lubricant are considered in the Figure.

A qualitative analysis of the damages observed on complete bearings was made.

In the case of bearings in still condition without oil, craters and burns were observed on the raceways and correspondingly on the rollers in the whole unloaded zone of the bearing, while very limited damages were observed in the loaded areas (small craters): a part of the lightning current had passed through the unloaded area, where air gaps were present.

For rotating bearings without lubricant, the damages were bigger than in the previous condition. Moreover abrasions were observed on the raceways. This may be explained considering that, owing to the rotations, the melted materials had been squashed around the damaged area and transported around the bearing causing abrasions on the bearing raceways.

In the case of rotating bearing with lubricant, craters were present in the unloaded zone only at the extremities of the loaded area, where the smallest gaps between rollers and raceways were present, while in the loaded zone, the size of the damages was higher than in the previous cases. Abrasions were more limited with respect to the case without lubricant. This can be explained considering that the presence of lubricant, acting as

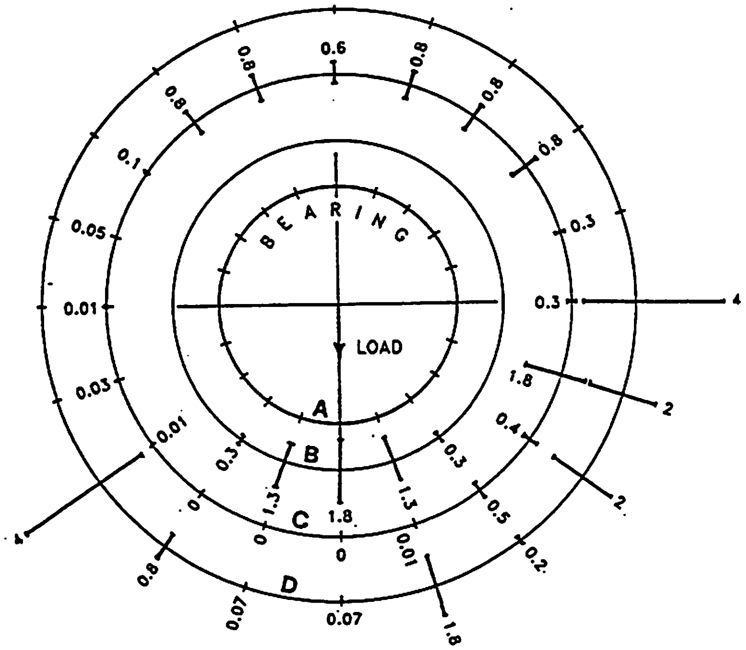

Fig. 8 - Tests on complete bearings. Contact areas and damage extension at each radial location (extension given in mm^2).

- A) Radial position of the rollers
- B) Contact areas
- C) Damages for bearing in still conditions without lubricant
- D) Damages for bearing in rotating condition with lubricant

a dielectric medium (with a higher dielectric strength than air), plays an important role in the prevention of the occurrence of localised discharge in the gaps and also in the reduction of the abrasions.

If the larger part of the lightning current would flow through the rollers in contact and it would distribute among them according to the contact areas, a theoretical peak current density of about 10 kA/mm^2 could be evaluated in the examined case of an injected peak current value of 100 kA. This value is more than twice the threshold value determined in the tests on the simplified configuration with one single couple of rollers and would imply damages of loaded zones. Actually the test results generally indicate a very limited damage in the loaded zone.

CONCLUSIONS

Lightning tests have been made on rolling bearings applying the A current component of the Standards and the damages caused by the lightning current flow have been analysed.
The damage mechanism and extension depend on current values and on the mechanical load condition, which determines the area of contact between roller and raceway.

When the lightning current flows through the contact areas, a consequent enhancement of the local temperature occurs. The high temperatures in the contact area can lead to local melting of the material, with a consequent formation of flutes.
The lightning current density (which is a function of the load and the current intensity) and the current energy content play an important role in this kind of damage mechanism.

Test in simplified conditions indicate that for areas in contact a peak current density of 4 kA/mm2 resulted sufficient to initiate the damage.

The lightning current may also interest the zone where rollers are not in contact with the raceways (unloaded zones). In fact, owing to the high di/dt associated with the A lightning current component, voltages are induced across the small gaps. These voltages can lead to the breakdown of the gaps; once the gap has been broken, the lightning current can flow through it and the resulting arc leads to the formation of craters and burns. The extension of the damages produced by the arc root can be bigger than that corresponding to the current conduction damages.

The research is going on and further tests will be made on bearings of different dimensions, with different lightning current components and in different test conditions, in order to better understand the ligthning performance of rolling bearings, obtain statistical data on the different kinds of damage and finally define an electrical-mechanical model able to describe the lightning behaviour of bearings in different operating conditions.

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A Methodology for the Evaluation of Lightning Protection Measures for Wind Turbine Generating Stations

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Abstract

A systematic approach to the economic evaluation of lightning protection measures for wind turbine generating stations has been developed and applied by a major wind turbine manufacturer and wind project developer. The methodology utilizes the application of basic and generally accepted lightning protection principles to allow for performance of payback analyses of lightning protection measures on a site specific basis. In this way, capital investment and maintenance resources may be directed to the measures with the greatest potential returns.

Background

KENETECH Windpower (formerly U.S. Windpower) is a wind turbine manufacturer and developer of utility-scale Windplants™, with over 400 MW of constant-speed and 25 MW of variable-speed wind energy capacity installed over the past 15 years. Despite the wealth of operating experience amassed in the design, operation and maintenance of wind turbines, the majority of development activity has been confined to three areas of California, U.S. with very low isokeraunic levels. As a result, the company's experience in lightning related damage consists of only three known direct strikes to turbines, and a few indirect strikes resulting in minor damage to communication and control circuitry. All known direct strikes have occurred on the 100 kW horizontal axis constant-speed technology machines.

The successful development in the early 1990's of a 400 kW horizontal axis variable speed machine with major economic and operational improvements over the constant-speed technology prompted world-wide interest in the turbine among utilities. Commericial development began in 1993, with Windplants™ constructed in areas of North America with substantially higher incidence of lightning than those previously encountered by the company. Suddenly, concern about the potential for lightning damage assumed great importance, and a systematic, consistent method for evaluating the level of protection that should be implemented at each new development became a necessity.

There were two primary obstacles to the development of such a methodology. First, while a vast amount of information is available on the protection of electric power systems and common structures (such as radio towers and buildings), there is almost no published research in the areas of particular concern to wind turbines, such as the blades and the mechanical bearings. The limited literature that does exist has very little basis in practical experience. Second, the potential lessons that could have been learned from the company's limited experience with lightning damage were not exploited. Lightning damage incidents were considered freak occurences, and little effort was made to document, test or otherwise examine the damage that did occur. Turbines were quickly repaired and returned to service, without regard to the value a post-mortem analysis could have on future designs. Hence, information regarding these incidents tends to be anecdotal, with heavy reliance on the memories of maintenance personnel who witnessed the strikes or repaired the damaged machines.

The purpose of the methodology presented here is not to devise a means of protecting all components of the wind turbine and balance of plant from lightning induced damage. Instead, a method is proposed for the selective implementation of the lightning protection methods that provide the greatest return on investment, and to allow a maintenance organization to estimate annual repair costs for those components for which protective measures do not have a sufficiently short payback period.

Evaluation Procedure

The proposed evalutation and design implementation process for a specific installation involves the following steps:

1. Determination of wind turbine direct strike frequency.

2. Estimation of annual damage to unprotected turbines.
3. Investigation of protective measures for each component of the wind turbine and balance of plant.
4. Determination of payback periods for proposed protective measures.
5. Examination of appropriate local and national building and lightning protection codes.
6. Incorporation of protective measures in design and maintenance planning model.

Direct Strike Frequency

Due to the frequent and damaging consequences of lightning on the operation of electric power systems, a great deal of empirical data is available to assist the lightning protection system designer in predicting strike frequency. While the validity of these methods must be examined in light of the number of simplifying assumptions that are required, they are acceptable when an order of magnitude calculation is needed to justify an implementation decision. In addition, the extreme variability of conditions which may affect the accuracy of such calculations is of lesser concern when a historical average over a number of years of wind turbine operation is desired. This step in the evaluation consists of two subtasks: 1) determination of ground flash density; and 2) determination of ground flashes to the wind turbine due to the ground shielding effect of the machine and its supporting structure.

As demonstrated in Table 1, a number of empirical relationships have been proposed which relate the ground flash density to the isokeraunic level of a site[1]. The most widely accepted of these relationships are of the form,

$$N = k\,T,$$

where N is the number of ground flashes per square kilometer per year, T is the isokeraunic level, or number of thunderstorm days per year, and k is a constant ranging from 0.1 to 0.2. These minima and maxima for k provide convenient points for most pessimistic and most optimistic scenarios which are common in ecomonic analyses, though the author's experience has shown the minimum value to produce results more in accord with field experience. T is determined through local weather services, or, less preferably, from an isokeraunic map if no local data is available.

Location	Ground flashes/ km² • year	Reference
India	0.1T	Aiya (1968)
Rhodesia	0.14T	Anderson and Jenner (1954)
South Africa	$0.04T^{1.25}$	Eriksson (1987)
Sweden	$0.004T^{2}$	Muller-Hillebrand (1964)
United Kingdom	aT^{b}	Stringfellow (1974) $[a=2.6\pm0.2\times10^{-3};\ b=1.9\pm0.1]$
United States (north)	0.11T	Horn and Ramsey (1951)
United States (south)	0.17T	Horn and Ramsey (1951)
United States	0.1T	Anderson and others (1968)
United States	0.15T	Brown and Whitehead (1969)
U.S.S.R.	$0.036T^{1.3}$	Kolokolov and Pavlova (1972)
World (temperate climate)	0.19T	Brooks (1950)
World (temperate climate)	0.15T	Golde (1966)
World (temperate climate)	0.13T	Brooks (1950)

Table 1. Lightning Ground-Flash Density vs. Isokeraunic Level (Reproduced from Ref. 1)

With a uniform ground flash density at the site assumed, the direct strike frequency to each wind turbine is estimated by calculating the ground area shielded by the turbine using the rolling-sphere method, and a strike distance, or sphere radius, based on the electrogeometric model. Use of the electrogeometric model, as opposed to a simple geometric shielding model, improves the accuracy of this calculation by recognizing the dependence of the striking distance on the magnitude of the first stroke current. Again, many empirically derived relationships for this strike distance have been proposed, a generally accepted one being[2],

$$S = 10\,I_S^{0.65}$$

where S is the strike distance in meters, and I_S is the first stroke current in kiloamperes. Since S is dependent on I_S, a value for I_S must be chosen. In the analysis of economic viability of protective measures, an average over the life of the plant is desired, so I_S is selected as the 50% probability stroke current on the statistical distribution of stroke currents. Many such distributions have been proposed by various investigators of field data collected throughout the world [3,4,5]. Unfortuntely, a wide range of values for this mean current is reported, but with most results in the 13 kA to 50 kA range. The lower end of this range has produced the results most closely correlating with the author's field data. The calculated strike distance is applied to the rolling-sphere shielding technique, as shown in Figure 1. The shielded area of each wind turbine multiplied by the annual ground flash density produces the estimated number of annual direct strikes to the turbine. While a derviation of this method is widely accepted in the calculation of strike frequency to power transmission lines, in the author's experience, this method tends to substantially overstate the lightning damage potential when compared to actual field data.

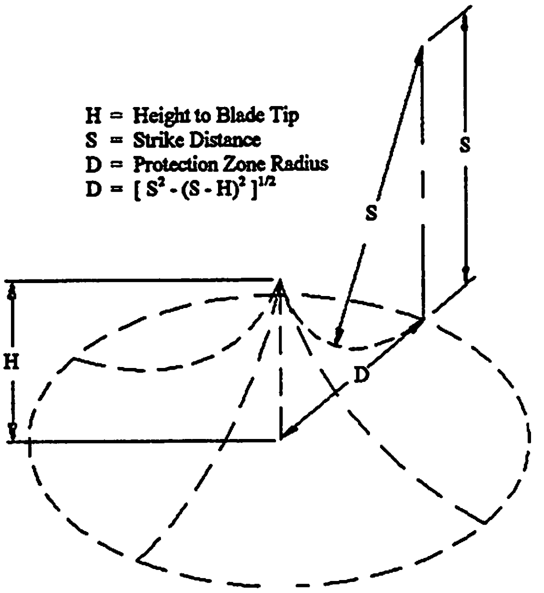

Figure 1. Rolling Sphere Zone of Protection

Annual Damage Estimation

With the strike frequency estimated, an annual damage estimate is prepared. This step is highly dependent on the design characteristics of the machine, and heavily influenced by field data and experience. Design characteristics which must be considered are blade material and configuration, bearing resistance and thermal inertia, and exposure of the balance of plant. Post-mortem analyses and documentation of lightning events are critical to accurately predict the course of future damage. It must also be recognized that the turbine electrical and electronic systems are vulnerable to induced voltages and currents that may result during strikes that do not terminate directly on the wind turbine.

Protective Measures

Lightning protective measures for any electrical or structural system fall into three categories: shielding (stroke interception), grounding and overvoltage protection.

A. Shielding

Shielding of any structure from lightning involves the installation of air terminals or lightning masts in a configuration such that the structure to be protected is within the zone of protection formed by the striking distance of the terminal or mast for the minimum stroke current for which one wishes to provide protection. The protection of non-conductive composite turbine blades is an example of such a structure, and offers perhaps the greatest challenge to the designer of the wind turbine lightning protection system, as the blades have the greatest exposure, and are often one of the machine's most costly components. Methods of effectively intercepting lightning strokes to the blades such as air terminals fastened to the gearbox or separate masts next to the machines may interfere with the operation of the turbine or be so costly as to make them impractical in all but the smallest machines or in areas of highest isokeraunic level. Alternatively, integration of the lightning receptor and down conductors in the blade construction has been proposed[6], but this has the potential to introduce the electromagnetic interference problems that were a concern with aluminum blades. Conductive composites (e.g., carbon/graphite fiber reinforced) may offer an acceptable tradeoff between lightning current conductivity and EMI acceptability, and have shown some promise in the aerospace industry as effective lightning shields.

For any turbine shielding method other than a separate mast, a path for stroke current through the turbine pitch bearing, mainshaft bearing, yaw bearing, or some combination of these bearings will be formed. The attendant damage will be dependent on bearing conductivity, mechanical strength and thermal inertia. It is generally recognized that the tens or hundreds of kiloamperes flowing at the peak of the stroke are of little consequence in this regard due to the short time period these currents are present. Instead, it is the several hundred amperes that continue to flow for a much longer period of time after the initial peak that represent the majority of the energy of the stroke, and, hence, has the greatest potential for thermal heating, pitting and deformation of the bearings. Slip-ring/brush arrangements which divert this current around the bearings have been proposed and implemented by others, but the high maintenance cost associated with keeping these systems functional must be included in the ecomonic evaluation process.

Shielding of the balance of plant may be accomplished by observing standard electric utility practice. Static wires strung between masts in the substation, with down conductors connected to the substation grounding mat, provide effective protection from direct strokes to substation equipment. Overhead medium voltage collection lines generally are not shielded in utility practice, as the insulation (air) is self-healing, and the consequence of an outage to these circuits is not as severe as for a high voltage transmission line, which generally will be shielded by static wires.

B. Grounding

Utilization of the turbine supporting structure as a lightning ground conductor requires a low-impedance grounding electrode to minimize local ground potential rise, with its attendant hazard to the network, and minimize step potentials for personnel near the tower during a ground stroke to the turbine. Maximum resistance to remote earth and/or configuration of the electrode is often specified by the local authority. In addition, multiple paths for stroke current may be required, but are prudent in any event to decrease the impedance of the down conductor and provide redundance for conductors that may have been thermally or mechanically damaged by previous lightning strokes.

Multigrounding of the ground conductors in the plant power collection system aids in attenuation of surge currents that may flow back to the network, and, likewise, limits the impact of strikes to the network transmission lines and structures to the wind turbines.

C. Overvoltage Protection

A wide variety of overvoltage protective devices are available to limit voltage transients on the wind turbine electrical and communications systems. Metal-oxide varistor type lightning arrestors at the main busbars of the turbine electrical systems will provide some protection from surges transmitted from the network. Gas-tube protectors, common to the telephone industry, and zener diodes with large surface areas to dissipate induced energy provide a degree of protection for communication terminal equipment at the wind turbine controller.

In the balance of plant, station class MOV arrestors can be applied at the high and low voltage bushings of substation step-up transformers. Cable insulation on underground lateral circuits may be protected by distribution class MOV arrestors at the riser poles. The voltage surges that propagate through the cable, while attenuated substantially by the presence of the riser pole arrestor, have the potential to double in magnitude at the open points on the laterals due to reflection at the high termination impedance. This situation may be averted by the application of additional surge arrestors located directly at the open points.

Payback Analysis

With estimated damage scenarios and protective measures proposed, a simple payback analysis is performed for each potential protective measure. Measures with a viable payback period are incorporated into the design of the turbine or the balance of plant, as applicable. Turbine and plant components which remain exposed to damage as a result of this analysis are factored into plant maintenance budgets.

Local and National Codes

An important part of the lightning protection design process is a thorough investigation of the applicable lightning protection and building codes enforced by the local authorities at the site. Since attainment of the required permits is normally contingent on demonstrated compliance with such codes, these requirements are investigated early in the design process to avoid redundance or omission of protection. In addition, specific local requirements often reflect field experience at the locality of which the designer may have no previous knowledge. Generally, through the course of the previous steps in the evaluation process, a design will be conceived which meets such requirements.

The most frequently applied North American and European standards [7,8] have much in common, and share the objective of minimizing the impact of a lightning strike to a turbine on the rest of the connected grid. Solid grounding of the wind turbine structure is heavily stressed, as is overvoltage protection at the interface of the wind turbine electrical system to the network. Protection of the turbine itself is generally not addressed in these standards.

Example Applications

The procedure described has been applied on a trial basis to wind power plants in North America with isokeraunic levels ranging from 2 to 30. The following implementations have resulted through this process:

In all cases, blades were given no intentional protection. Experience with the three direct strikes to the 100 kW constant-speed machines was consistent in that the blade tips were the point of attachment for the stroke current. The non-conductive composite material became sufficiently surface conductive due to moisture, atmospheric contaminants, and/or build up of static charge such that it was more attractive than the many grounded, conductive components in the nacelle below. Blades were burnt or punctured beyond repair in all three incidents. Attachment of an air terminal mast to the gearbox within the nacelle for blade protection was considered impractical due to the height of the mast that would be required for the desired zone of protection. Air terminals on separate masts were cost estimated, and found uneconomic given the strike probability, even in the area of 30 isokeraunic level. For the tower and blade dimensions considered, it is estimated that separate lightning masts will not be economically viable in areas with isokeraunic levels less that 60.

With an acceptance of sacrifice of the blades as air terminals, the path to ground from the blade root to the grounding electrode was examined for suitability as a down conductor. Of most concern were the pitch bearing, mainshaft bearing, and yaw bearing. Resistance measurements were made of these bearings in the laboratory, with results for each bearing a small fraction of one ohm. The shortcomings of such measurements are recognized. The readings were taken with the bearings stationary, and with fresh lubricant. The test produced 60 Hz resistances, not surge impedances. However, in these conditions, the path from the blade root to the tower through the mechanical bearings has a much lower impedance than the electrical bearings has a much lower impedance than the electrical grounding cable which connects the ground plane in the nacelle to the electrical grounding electrode at the tower base. Further, experience with the 100 kW machines showed bearing damage was not sufficient to affect the performance of the machine. The 400 kW machine's bearings are much more massive than the 100 kW machine's, so it is expected that their thermal and mechanical properties will provide for improved lightning withstand capability. Implementation and maintenance of a slip ring/brush arrangement that would maintain a sufficienty low impedance to divert stroke current around these bearings, was, therefore, deemed impractical.

Protection of the fiberglass nacelle was deemed unnecessary, as the blades provide an effective zone of protection for the nacelle for greater than 99% of all probable stroke currents.

In all cases, the turbine towers were utilized as lightning down conductors. Lattice steel towers were found to be an acceptable galvanic connection from top to ground, without modification of the tower design or installation practice. Multi-section tubular towers did require modification to provide an electrically continuous path to ground, due to a non-conductive finish at the flange joints. Multiple copper cable jumpers were installed to effectively route the stroke current around these joints.

Tower grounding electrodes were site specific, ranging from a single ground rod to a complete ground ring with multiple ground rods and bonding to the tower foundation rebar. Tower grounding design was more heavily influenced by soil conditions and local practice and codes than isokeraunic level.

The control electronics of the wind turbine have been designed for high EMI immunity due to the fact that they must perform in the EMI-rich environment created by the high frequency, pulse-width-modulated switching transistors which comprise the turbine's power electronic frequency converter. A number of precautions taken for this reason, including electrostatic shielding of circuit boards and control cables, as well as fiber optic isolation between the uptower and downtower controllers, is expected to harden the control electronics from lightning induced transients as a side benefit. No additional measures were incorporated within the control circuitry for the express purpose of lightning protection.

In all cases, turbine electrical power distribution and communication systems were protected from overvoltage by metal-oxide varistors and a combination of gas tube protectors and zener diodes, respectively. Substation transformers and medium voltage cable and transformers were likewise protected by MOV surge arrestors. The use of overvoltage protectors appears to be the one lightning protective measure which offers such great potential benefit at such a low cost that it can be shown to be economic in all cases, and hence, be considered a standard part of the product configuration.

Lightning protection measures at each development were well below 1% of the installed cost of the Windplant™. In all cases, the proposed lightning protection met or exceeded the requirements of the local building authority and electric utility company.

Conclusion

A systematic approach to the ecomonic evaluation of lightning protective measures has been presented. The results of such an analysis are highly dependent on the design characteristics of the wind turbine and balance of plant. Economically justfiable protective measures are also site specific, with the isokeraunic level at the site the overriding consideration.

Operating experience in high isokeraunic levels is necessary to verify the many assumptions required to perform such analyses. Future activities will include:

- Correlation of field experience with calculated strike probabilites.
- Correlation of field experience with estimated damage scenarios.
- Investigation of the comparative lightning performance of glass and carbon-fiber reinforced composite blades.
- Improvement of event and post-mortem analysis documentation, recognizing that much of the data on component lightning performance cannot be obtained by test.
- Lightning monitoring with high speed recording equipment at a test site in New York, U.S.

The sensitivity of the analysis to predicted ground flash density based on isokeraunic level is a recognized weakness. The installation of lightning location systems, which is being pursued by electric utility organizations in North America, will provide more accurate data in this regard in the future.

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INTERNATIONAL ENERGY AGENCY

Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems

26th Meeting of Experts

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Experience gained in the lightning protection of aircraft and petro-chemical installations applicable to wind turbine generators

1 ABSTRACT

The nature of lightning was discussed and the method used in the aircraft industry to gain adequate protection.

Direct effects (damage) and some aircraft test specifications are presented in Appendix A.

Indirect effects (electrical interference) and methods of avoiding problems of induced voltages are presented in Appendix B for aircraft, and Appendix C for ground installations.

The main text deals with aspects of the protection of wind turbine generators using read across from aircraft and petro-chemical complex protection.

2 DIRECT EFFECTS

In any given strike the electrical current waveshape is pre determined by nature, but will vary widely from strike to strike. When the lightning channel (the visible flash) attaches to a structure of any sort the structure also carries the pre-determined lightning current.

In the protection of aircraft there is no method of avoiding a lightning strike, which will have both entry and exit points, and the design must allow for any damage to be of an acceptable degree.

Ground structures in general do not require such rigorous protection, there will be some degree of damage or marking local to the point of attachment, and if the remainder of the structure is unable to cope with the energy imparted to it an explosive failure may result.

This is most likely to occur at points where all the current is constrained to flow in a thin metallic wire. Also at points of poor contact between surfaces and at places where penetration into an otherwise non conducting material is possible such as elastomeric bearings or glass fibre reinforced plastic components. Current traversing large metallic bearings may cause minor damage which can shorten normal life.

2.1 Bearings

An attachment to any point on the rotor will result in current flowing through the main rotational bearing, probably some elastomeric bearings and the yaw bearing.

2.1.1 Main Rotor Bearings

These often consist of roller bearings either fixed or self aligning in a large metal housing. Due to geometrical considerations it will never be practical to reduce the lightning current flowing through the bearing to a few percent of the total. It is unlikely that any slip ring contacts could be devised to bypass the bearing because its construction would need to be of similar complexity and bulk to the bearing and housing itself.

However the ability of a roller bearing to carry lightning current depends on the pressure between the rollers and race tracks. If the pressure on all rollers at all times could be maintained above 586 Bar [8500lb/in^2] (Reference 1) by pre-loading, it is likely that lightning current could be carried without damage.

2.1.2 Elastomeric Bearings

Bearings or resilient mountings consisting of an elastomer bonded to metal end fittings are electrically non conducting. If there is no other electrical path between the parts supported by such a bearing lightning will easily develop enough voltage to flash across between the two end fittings. This is most likely to happen outside the elastomer in which case minimal damage may result. However the voltage needed to flashover may be injected into other systems. If the elastomer is hollow or faulty the flash may take place inside the material this could result in explosive failure of the bearing or mount.

The method of protection is to ensure that there is a much smaller deliberate gap which can cope with the energy, placed so as to prevent flashover in the bearing, or to bypass the bearing with a bonding conductor. The cross-sectional area of copper of such a conductor should be 20mm^2 or more and very well terminated at its ends.

2.1.3 Pitch Change Rods

Many helicopter rotors use pitch change rods which consist of an adjustable metal link with spherically seated bearings (ball joints) at each end. The ball is often mounted in a seating which is lined with PTFE or similar material of a fraction of a millimetre thickness. The effects of lightning can easily flashover the PTFE lining and the subsequent current flow can weld the bearing solid.

With such a thin layer and small gap between the metal parts a bonding conductor is the only method of reducing the problem. Even this may not totally eliminate all damage in certain cases.

2.1.4 Yaw Bearings

The nacelle and platform are often mounted on the tower by a simple sliding bearing using a PTFE or similar material.

Such a configuration will flashover at a point where the voltage required is lowest, such as where the gap is smallest, where there is a bolt head or nut, or some other close approach of the conducting parts. It is unlikely that solid PTFE will puncture, but flashover across its surface is possible. In any gap formed by two metal parts with air between them the flashover voltage will be lower when the gap is bridged by the surface of an insulation material than with air alone. The bearing construction of a yaw bearing is probably so massive that no significant damage will be caused at the point of flashover.

However the voltage required to breakdown the yaw bearing will be introduced into every power or control circuit which is connected to the platform equipment and to the tower base equipment. For this reason it is most important to bypass non conducting yaw bearings with six or more equally spaced sliding spring loaded conducting blocks, or a similar system which is equally effective.

2.1.5 Blades - Totally Non Conducting

Blades which have no conducting wires or other components are not considered by the aircraft industry to be free from lightning damage risk as there have been a few incidents. Glass reinforced plastic or epoxy impregnated timber blades when new and perfect are probably non conducting enough that lightning would flashover the outer surface probably doing little damage. However in service all such structures attain an equilibrium moisture take up as indicated by a slow increase in weight. Also cracks develop which fill with moisture and contaminants.

These factors make it possible for a conducting path to form within the structure. Lightning current can then dissipate massive energy within the structure causing possible explosive failure. For aircraft propellers the protection method is to provide an external conductor down the whole length of suitable cross sectional area and fixing to survive without melting. On aircraft radomes segmented diverter strips are used to avoid interference with transmissions; current types are disposable and would probably not be suitable for use on wind turbine blades, but a development may be useful. Temporary wiring installed on otherwise non conducting blades for instrumentation such as strain gauges is particularly vulnerable and difficult to protect.

2.1.6 Blades with Some Conductors

When blades made mostly of non conducting material have internal metal components such as tip control cables or other internal conducting parts a different problem exists.

The very high voltages available can puncture through the glass reinforced plastic in order to attach to the internal metal parts. This is equivalent to the radome puncture problem on aircraft and can result in severe damage. In wind turbine blades the severe damage would be fairly localised to the point of puncture. Having punctured however the internal metal parts will now carry the current and may explode if of inadequate cross sectional area. Where the only conductor is a thin control cable, a damaging explosion is possible and it could involve the whole length of the blade.

2.1.7 Blades Containing Carbon Fibre Composite

Carbon fibre composite has an electrical resistivity about 1000 times that of aluminium. This means that for a given strike intensity a carbon fibre composite blade will take up 1000 times more of the available energy than would an equivalent metal blade. Only sections which are very thick for structural reasons can cope unaided. Thin surface skins require some form of protection such as surface metal mesh. There is some similarity with helicopter blade design, but due to the much reduced rotor speed of a wind turbine advantage cannot be taken of damage reduction due to the sweeping effect.

3 INDIRECT EFFECTS

3.1 Ideal Current Shield Concept

If a very large, but short duration, impulse current flows in a thick wall metal tube with no holes in it, and with thick welded metal discs closing the ends, none of the current will appear inside. Impulse current tends to flow on the outer surfaces of structures and can only penetrate good electrical conductors slowly. It is therefore possible for the pulse to be over before any current has penetrated to the inner surface. Even if it is able to penetrate the voltage from one end to the other of the tube will be very small, being dependent only on the current multiplied by the resistance of the tube, probably only a few tens of volts.

This can be considered the ideal shield and personnel or equipment inside touching the tube would be perfectly safe.

Like aircraft, wind turbines can be thought of as a conducting tube with apertures at various places.

The larger the apertures and the more of them the more current will appear inside. Apertures are formed by doors etc., in steel towers, and by the spaces in the metal reinforcing bars in concrete towers. The apertures will allow the magnetic field associated with the current to penetrate instantly and link with wiring inside. The process is different to resistive voltages produced by penetration through good conductors in that it is proportional to the rate of change of the current. In exposed situations this voltage can be very large such as tens of kilovolts. In wind turbines the most likely area for this type of induced voltage is inside a nacelle which is made of non conducting material, or where the cover is conducting, but not well connected to the base frame. Well connected means reliable connection at a multiplicity of points around the base, not just at one or two places.

If lightning current is injected into the rotor or a conducting support member of such a nacelle cover, the wiring and equipment in the nacelle will be exposed to high level induced voltages since they have no effective shield and are essentially in the open.

The protection method here is to enclose all wiring and equipment in metal screens or conduit connected to both ends by 360° contact to metal equipment boxes. This could only be relaxed in cases where the nacelle cover was conducting, and was reliably connected to the base plate at many equally spaced points.

3.2 The Broken Ideal Shield

So far only apertures in the ideal shield have been considered. If the yaw bearing is formed with PTFE surfaces, the end of the ideal shield tube is in effect open. There may be power and control wires which connect to the equipment in the nacelle and at the other end to equipment or cubicles in the base of the tower. When lightning current begins to flow the ideal shield of the tower is completely negated by the annular gap at the yaw bearing. All the current will flow in the sheaths of these cables if they are connected at both ends and a voltage given by the resistance of all the sheaths in parallel times the current will appear common mode in all circuits. If the sheaths are connected at one end only, or if there are no sheaths, the common mode voltage injected into all circuits will increase to whatever level it takes to flashover the yaw bearing gap. The gap will flashover at one point only and after this has happened the common mode voltage will be the arc voltage plus that produced by the magnetic field penetration due to the otherwise open annular slot.

Such voltages will be large enough to flashover most electrical power equipment probably at the cable entry points. Also it will puncture any instrumentation transformers opto-isolators. The energy will be enough to destroy circuit boards and electronic components. The same argument applies to any poorly conducting joint between steel tower sections (but probably much less magnitude).

The only protection method for this severe condition is to render such gaps conducting by robust sliding contacts placed equidistantly around the gap. In the case of a yaw bearing at least six such contacts would be needed, thus returning the structure electrically to the ideal configuration, but with apertures.

Care should be taken that elastomeric non conducting bearings mounting the base plate or machinery do not again result in an electrically open top to the tower in a similar way in which the yaw bearing can.

3.3 Connection to the Tower Base

Recommendations for the protection of wiring and other services which interconnect structures are given in Appendix C, and also in Appendix C of British Standard 6651 of 1992.

4 REFERENCE

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LIGHTNING STROKE SIMULATION BY MEANS OF A LEADER PROGRESSION MODEL

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1. INTRODUCTION

The knowledge of the frequency of lighting strikes on a wind power generator is one of the most important parameters in judging its reliability.
To evaluate the probable number of direct strikes on the generator structure a model of the "lightning mechanism" is needed which allows the impact point to be defined by taking into account both the main lightning parameters and the effects related to the orography of the point of installation.
From among the algorithms available [1, 2, 3, 4], the model implemented by ENEL-CESI (4) is the only one that simulates the progression of lightning channels from the cloud to the earth, taking into account the orography.

2. MODEL OF PROGRESSION OF LIGHTNING CHANNELS

The model was formulated by basing on the supposition that there is a substantial similarity between the phenomena which cause the formation and progress in space of lightning channels and those which are at the origin of the disruptive discharges, up to 30 metres long and obtained during tests with impulse voltages characterised by peak time of the order of 300 - 1000 µs. In particular this model is able to simulate analytically the mechanism of discharge of the lightning in its most important aspects, namely:

- the propagation of the downward channel closest to the structure in question up to its impact on the structure or, possibly, to the ground;
- the formation of the counterdischarge which originates in the most critical element of the structure considered;
- the propagation of the counterdischarge up to possible interception of the downward channel.

Further on we list the main features of the model developed described fully in [4].

The simulation of the behaviour of the lightning channels is shown in diagram form in Fig. 1. The description of the phenomena in mathematical terms requires the evaluation of the intensity of the electric field [5] in the gap between the downward channel and the structure. This evaluation must be repeated at different times in order to represent correctly the variations of the electric field due to the different location of the charges as a result of the progression of the lightning channels.
The profile of the ground and of the ground structures is represented by means of an appropriate combination of charges.
The main elements involved in the definition of the path of the channels and hence of the point of impact of the lightning are the cloud, the downward channel and the

ascending one when present.

2.1 Downward channel

The parameters which determine the behaviour of a downward channel are indicated below, together with the methods adopted for defining relative values assumed in the model.

Charge in the channel

The experience gained through laboratory tests shows that the charge value per unit of length required for ensuring the progression of channels in areas of heavily ionized air is equal to circa 50 µC/m and 100 µC/m respectively for positive and negative channels. These values are in full agreement with the charge values which can be obtained from experimental observations relating to minimum negative lightning currents. By examining recordings of lightning currents [6,7] it is possible to deduce the relationship between the charge in the downward channel (Q) and the peak value of the lightning current (I):

$$Q = 76 \cdot 10^{-3} \cdot I^{0.68} \qquad (C;\ kA) \qquad (1)$$

The model does not represent all the branches of the channel, but instead considers the presence of a single downward channel: the effects due to the charge in the branches are taken into consideration attributing to the upper part of the channel a charge per unit of length which takes account of the total quantity of the charge involved.

The lower part of the channel, for a section of some tens of metres, is however represented with a charge per unit of length equal to the one determined in the laboratory. This assumption is justified by the fact that the more advanced part of the channel, being the most recently formed, must necessarily have similar charge values to the minimum ones required for the progression of the channel itself.

Velocity of the channel

The experience acquired in laboratory tests [8, 9, 10 e 11] on air gaps up to 14 m in length confirms field data relevant to lightning channels.

In particular the available data indicate a reduction in the velocity of the downward negative channels as they approach the ground (from 100 to 20 cm/µs approximately) and an increase in velocity of the upward positive ones (from 4 to 20-40 cm/µs circa).

It should nevertheless be emphasised how the structure of the model only requires definition of the ratio between the velocities of the two channels, contributing to limiting the effects linked to the uncertainties which still characterise this parameter.

In the case of negative lightning, a phenomenon which occurs much more frequently (90% of cases), an initial ratio of the two velocities has been calculated as 1:4, a ratio which achieves equity in the instant immediately prior to the joining of the two channels.

Extent of the ionized area

The extent of the ionized area, which is formed in front of the channel and which precedes the formation of the subsequent progression of the highly ionized channel, is determined on the basis of the criteria which are derived from laboratory experiments. Although the phenomenon is fairly complex, in the model it is assumed that this area extends as far as points in which the electric field has an intensity of 3 kV/cm.

Direction of propagation of the downward channel

The direction of progression of the downward channel is determined by the direction of the maximum gradient along the equipotential line which defines the limit of the extent of the ionized area formed at the lower end of the channel itself.

2.2 Ascending channel

The features of this channel are wholly similar to those examined in the laboratory. This similarity is the result of the fact that, in nature, during the propagation of a downward channel, the variations in time of the electric field at ground level are similar to those which affect the air gap near the electrode energised during tests with impulse voltages having fronts of the order of hundreds of microseconds.

Formation of the channel

The dielectric tests on rod-plane electrode configurations have shown how the behaviour is practically independent of the dimensions of the electrode being tested, reaching a maximum critical dimension referred to as "equivalent critical radius" [12]. In order to check the validity of this criterion tests were performed on the electrode configuration illustrated in Fig. 2, consisting of a spherical electrode suspended from a crane at a distance of approximately 7 metres from the top of a pulse generator set up to generate negative polarity voltages.

This test configuration, even if geometrically reversed in relation to the real situation, aims at reproducing the electric field conditions around a structure at the ground (sphere suspended from crane) when the negative channel of a downward lightning stroke (top of the generator) has reached the vicinity of the structure itself.
As confirmation of the implications of the criterion of the "equivalent critical radius", the recording (Fig. 3) indicates the formation and progression of a positive channel from the ground structure (sphere) without any corona phenomenon on the negative electrode (top of the generator).
The experimental research performed on air gaps up to 27 metres [13] indicates that the values of the "equivalent critical radius", although increasing when the discharge distance increases, have limit values equal to approximately 35 cm and 10 cm respectively for spherical and cylindrical electrodes. These values were assumed in the model to simulate the various points of the structure (or of its elements) from which upward positive channels may form.

Charge in the channel

The charge values per unit of length assumed in the model to simulate the ascending positive channels are equal to the minimum value defined in the laboratory (50 μC/m).

Extent of the ionized area

This is evaluated in accordance with the method proposed at [14], as the area which extends from the upper end of the ascending channel as far as the points in space in which there is an average gradient of at least 500 kV/m.

Direction of propagation

This is assessed by a similar technique to the one described for the determination of the direction of the downward channel.

2.3 Charge in the cloud

A simplified representation of the charges in the cloud was used: in particular the equivalent charge necessary for producing the formation of a upward channel on a structure characterised by an "equivalent radius" equal to the critical one was calculated. On the basis of the results obtained and of the probability with which lightning rising from the structure occurs [15-16], the statistical distribution of the negative unipolar charge was determined to allow the best representation of reality (Fig. 4). The hypothesis was also assumed that there is perfect correlation between charge in the cloud and intensity of current relating to the first downward lightning strokes.

2.4 Applications of the model

The model allows, when the distance between the downward channel and the structure considered has been predetermined, identification of the point of impact of the lightning (structure, possible protection element, ground). It is therefore extremely useful both in evaluating the number of strokes which in a set period of time may affect the structure in question, and in designing systems suitable for preventing the structure itself (or some of its elements) from being struck or, more generally, able to reduce considerably the probability of damage caused by lightning.

In order to assess the exposure to lightning of a structure it is necessary to determine the maximum horizontal distance between the structure itself and the downward channel (characterised by a defined charge per unit of length and hence by a corresponding current intensity) at which the lightning can still reach the structure. This distance is referred to as "lateral distance" (LD) and the methods for determining it are indicated in Fig. 5, which gives the paths of the negative channel of a downward lightning stroke, characterised by a current of I = 21 kA, positioned at an increasing distance from a tower 220 metres high and located on flat ground. A similar method enables calculation of the extent of the area of sky from which a stroke of lightning characterised by a predetermined current may reach an element of the structure in spite of the presence of elements set up to intercept lightning.
With reference to electrical overhead lines, the width of this area of sky is commonly indicated as - "shielding failure width - SFW". In order to underline the influence of orography, Fig. 6 gives examples of lightning paths for lines in different orographic conditions (flat - along the side - on the top of a hill).
From among the possible applications of the model a comparison was made (Fig. 7) with the field data relevant to the number of lightning strokes which have struck tall structures [17, 18, 19, 20 e 21]. The information in this respect contained in technical literature is sufficiently abundant and detailed both as regards the characteristics of the structure (function, height etc.) and as regard the intensity of the lightning activity in the area in which the structure is located.
The comparison shows how the calculated values can be considered a good interpolation of the data observed, at least as regards those obtained on structures placed on flat land. To show, albeit schematically, the effects due to the position in which the structure can be installed (with reference to the orography of the surrounding area), Fig. 8 also indicates the results relating to a slim structure 50 m

high, situated at the top of hills with a conical shape (height between 300 m and 1000 m), characterised by ratios between the base diameter and height (γ) ranging betwen 0.2 and 2.
The comparison between the experimental data and the results with the model of propagation of lightning channels therefore demonstrates the effectiveness of the model in determining the equivalent interception area which characterises a structure, also taking into account conditions of installation and the orography of the surrounding area.

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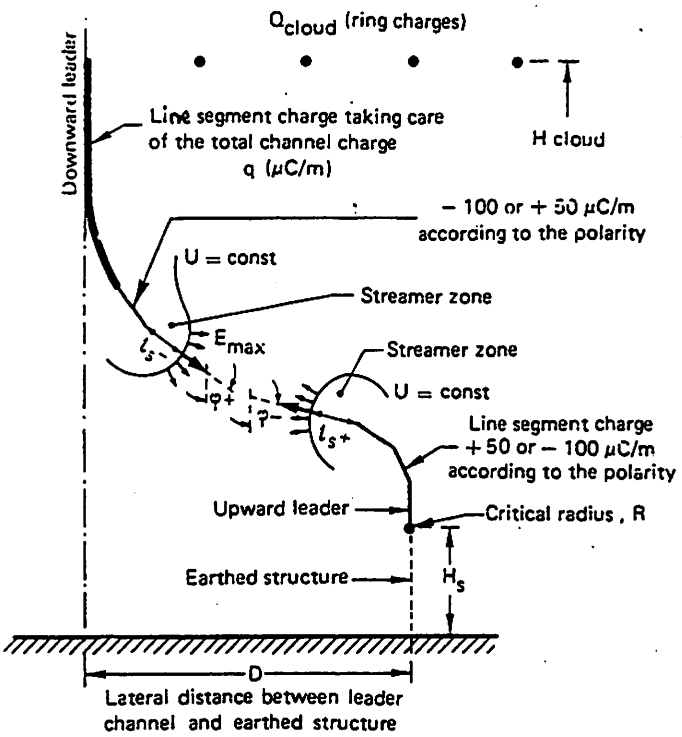

Fig. 1 - Sketch of the step-by-step progression of the lightning, as simulated in the calculation.

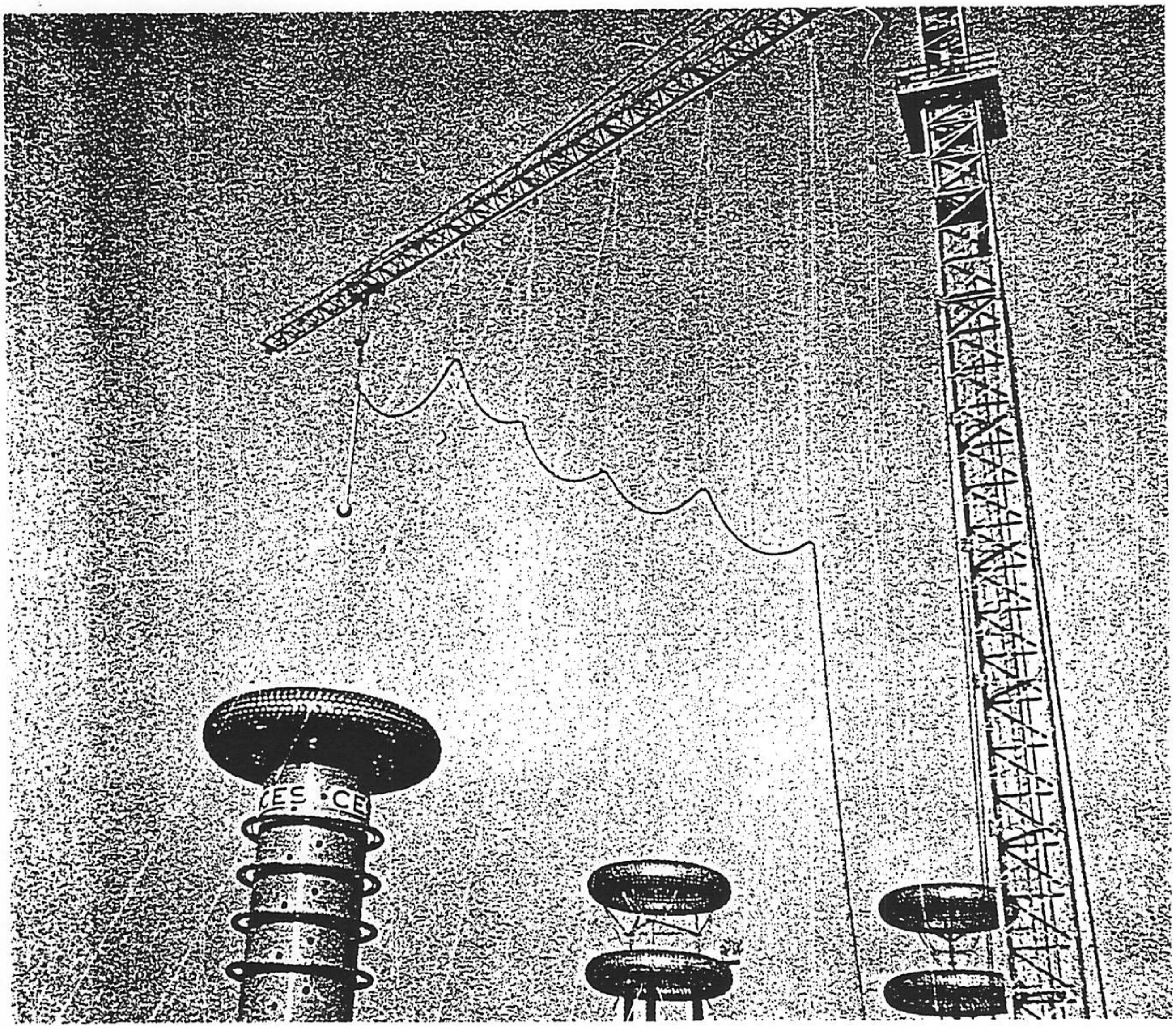

Fig. 2 - Test configuration for the study of the development of positive leaders from earthed structures in negative discharges.

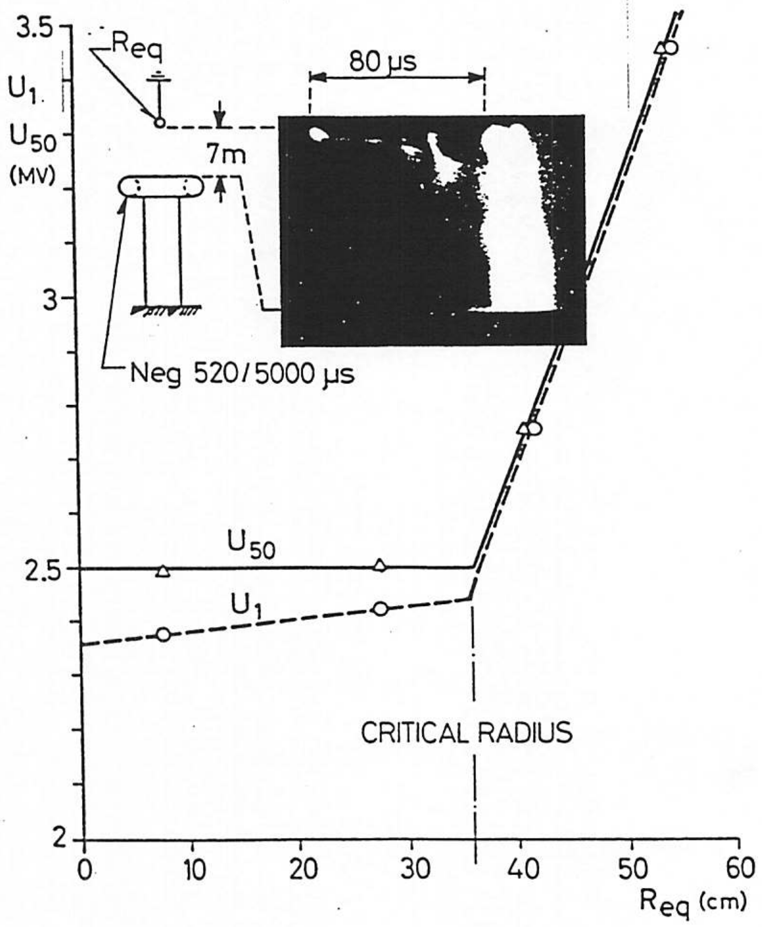

Fig. 3 - Image converter picture of the development of the discharge.

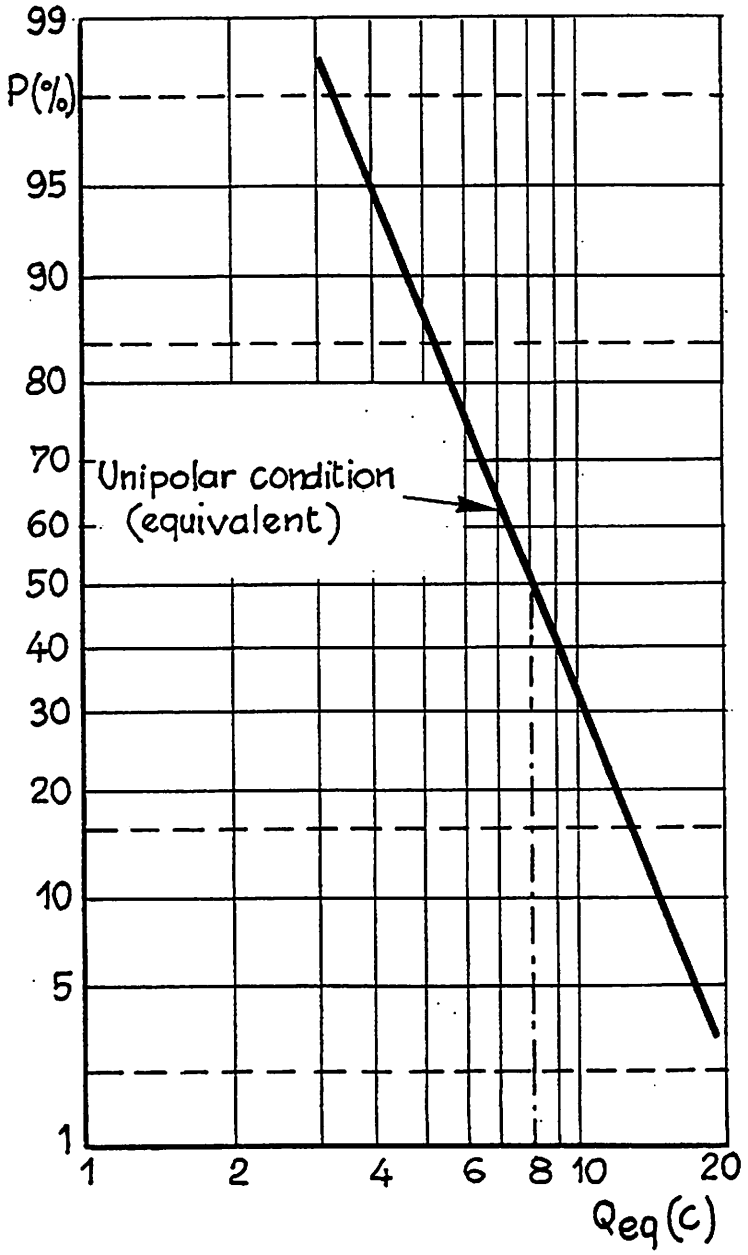

Fig. 4 - Computed cumulative statistical distribution of the equivalent unipolar charge in the clouds

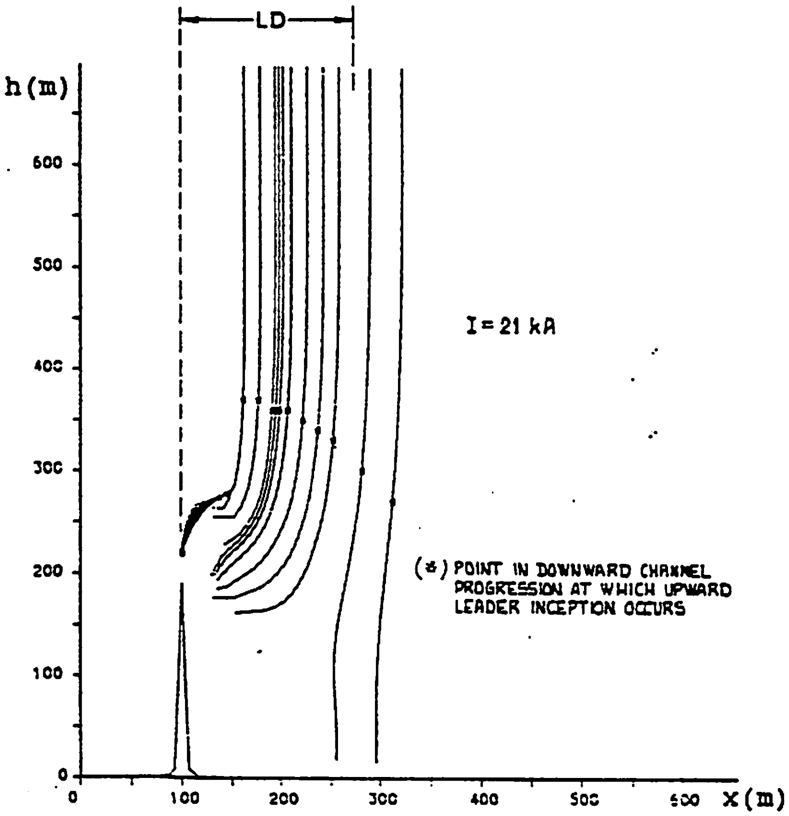

Fig. 5 - Example of application of the model to a free-standing structure 220 m height.

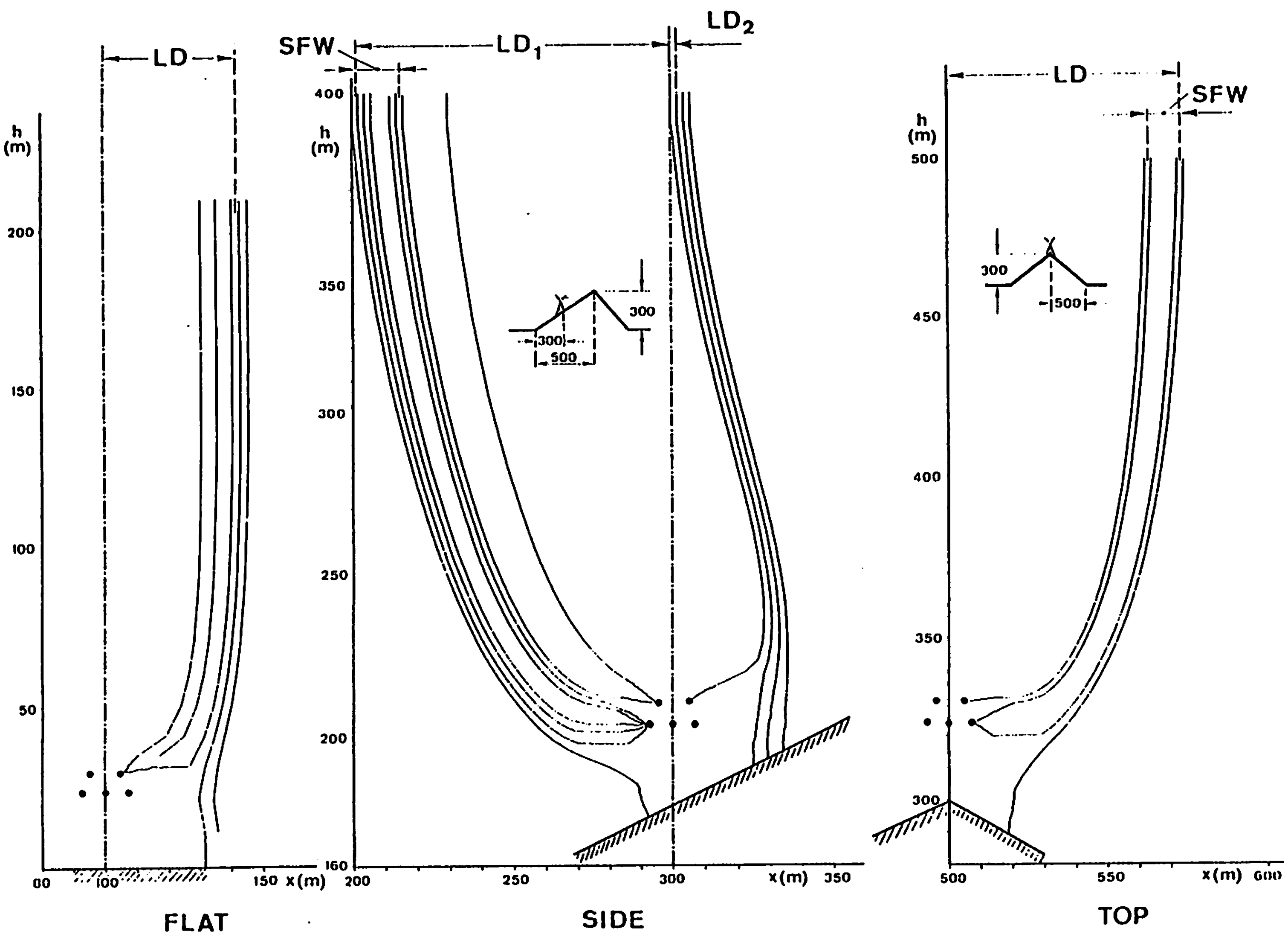

Fig. 6 - Example of the computed leader paths of a 420 kV line in different orographic conditions.

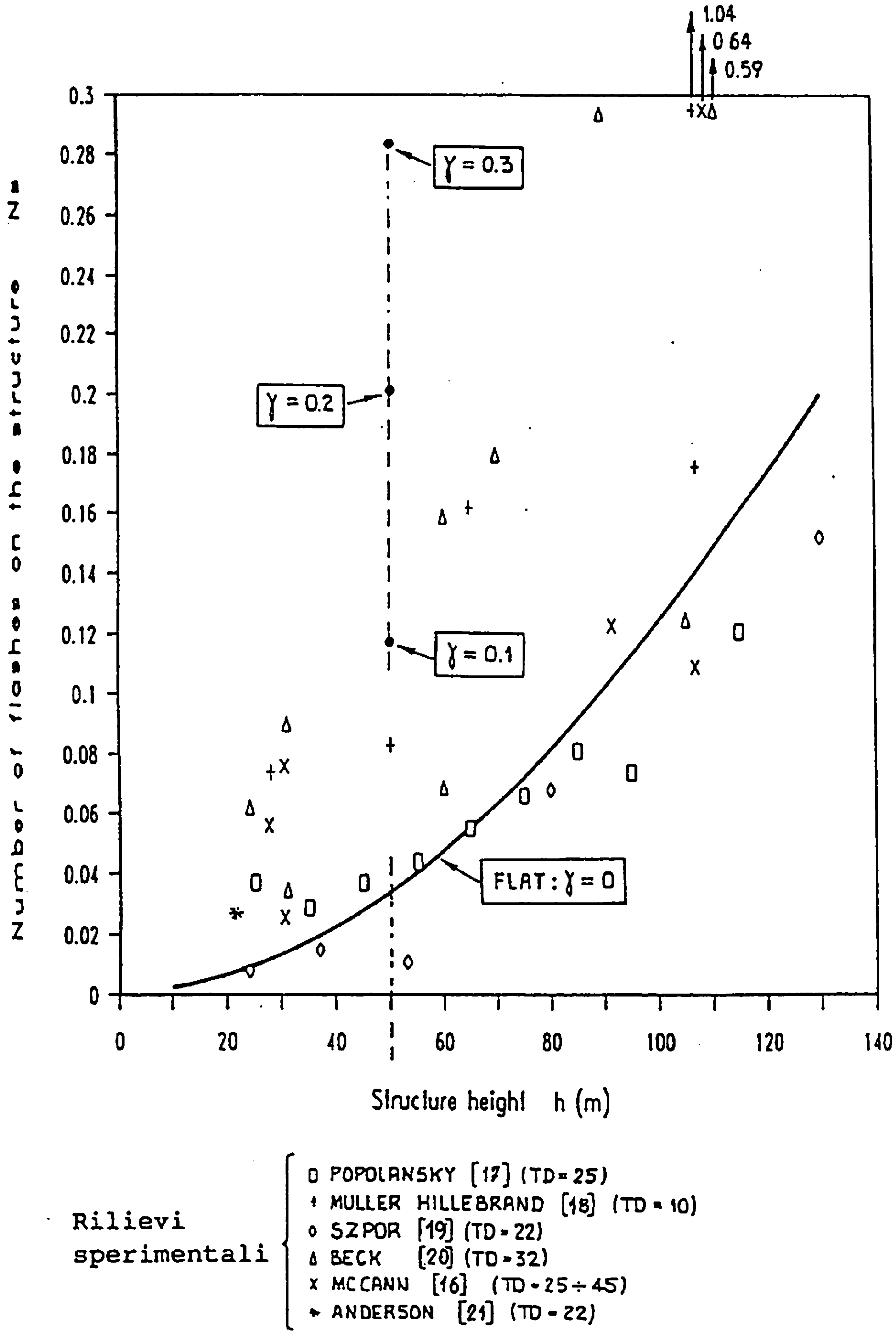

Fig. 7 - Number of flashes on thin structures in various orographic conditions.

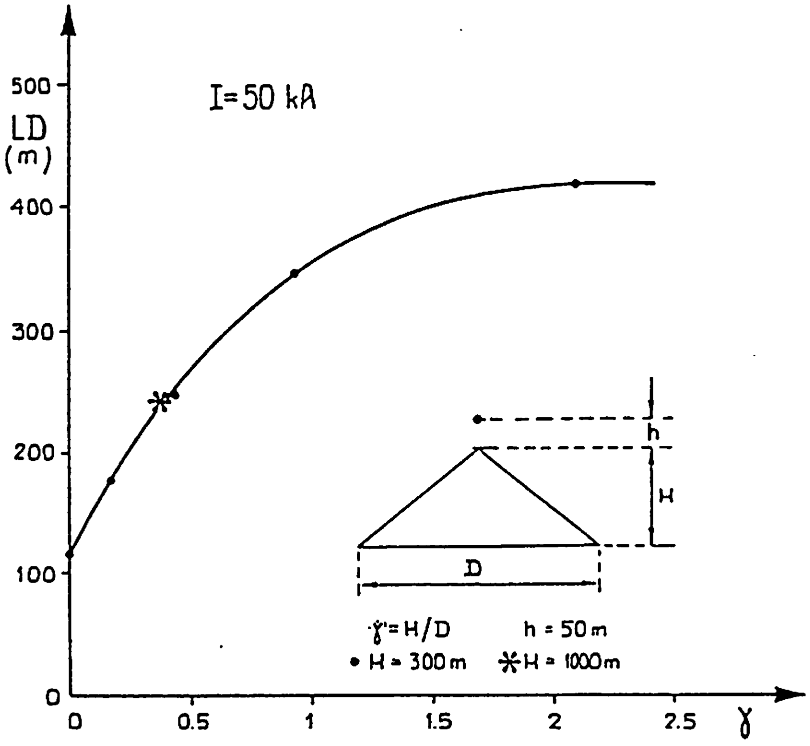

Fig. 8 - Lateral distance as function of ratio H/D for a 50 m height free-standing structure.

LIGHTNING TESTS ON WINDMILL BLADES

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A. Pigini, F. Ballarin- CESI

1 - INTRODUCTION

Testing activity was performed to determine the behavior of windmill blades following lightning strokes.
In fact, for windmill power stations, depending on the area where they are installed and the structure of the windmills, there is a good possibility that a windmill may be struck by lightning.
The parts with the highest risk of a lightning stroke are the blades. The impact of the lightning and the current flow over different parts may cause structural damage ("direct effects" of lightning) and thus prevent the windmill from operating at full capacity.

2 - TESTS PERFORMED

Tests were carried out on a 50 kW twin-blade windmill with blades built with insulating material (glass-fibre compound) and on a 5.2 kW single-blade windmill with blades built with partially conducting material (carbon fibre compound - CFC).
Tests were performed by simulating a real windmill generator installation configuration. For this purpose, the blades being tested were mounted on a mock-up installed on a metal structure that simulates the windmill support, as shown in Fig. 1 and 2.

Attachment tests and evaluation tests of the "direct effects" of the lightning were considered.

To verify lightning attachment a simplified condition was considered, simulating a lightning channel in close proximity of the wind mill. A rod was positioned at different locations along the blade with a constant distance from the blade, as shown in Fig. 3. Standard switching impulses of positive and negative polarity were applied to the rod. The distance from the rod to the blade was of 5 m for the positive polarity voltage and 3 m for the negative one.

To verify the effect of the lightning current flowing through the blades oscillating impulses with a frequency of about 18 kHz, amplitude of 100 kA and action integral of 1.2 10^6 A^2*s.
The current was injected through a 2 cm air gap as shown in Fig. 4.

The tests on the partially conducting material were carried out simulating various possible conditions for the blade (dry condition, presence of rain, pollution). Furthermore the effects of the presence of conductive strips along the blade were considered.

3 - TEST RESULTS

3.1 Attachment tests

With the rod positioned just above the nacelle all the discharges intercepted the nacelle itself (Fig. 5 a).
With the rod positioned above the end of the blade all the discharges intercepted the blade (Fig. 5 b). This fact occurred both for blades of partial conductive material and for blades made of insulating material.
The tests have shown that the blade, even if of insulating material and in dry condition, can act as an intersection element and the presence of the supporting structure and nacelle does not constitute a preferential attachment point.

Tests with the insulating blades and protective strips all along the blade itself showed that the strips were effective in intercepting the discharges.

3.2 Direct effect tests

The following main results were obtained:

a) Fiber glass blades

Flowing of the current along the surface of the blades did not cause major damages. Big damages were observed only in the presence of metallic inserts inside the blades. In this case puncture of the insulating materials occurred, as shown in Fig. 6.

b) CFC blade

In all the cases considered the current flow through the material resulted in major damages to the blade itself, as shown in Fig. 7.

4 - CONCLUSIONS AND FUTURE WORK

The research carried out have indicated that important damages can occur to wind mill following lightning stroke. These effect depend on wind mill design and blade material. To complete the picture further research could be useful, considering different design solutions.
Furthermore future research may also consider more representative simulation of the lightning, especially with reference to attachment phenomena and to peculiar aspects, such as the formation and propagation of upward channels. A possible arrangement to study this last aspect is shown in Fig. 8.

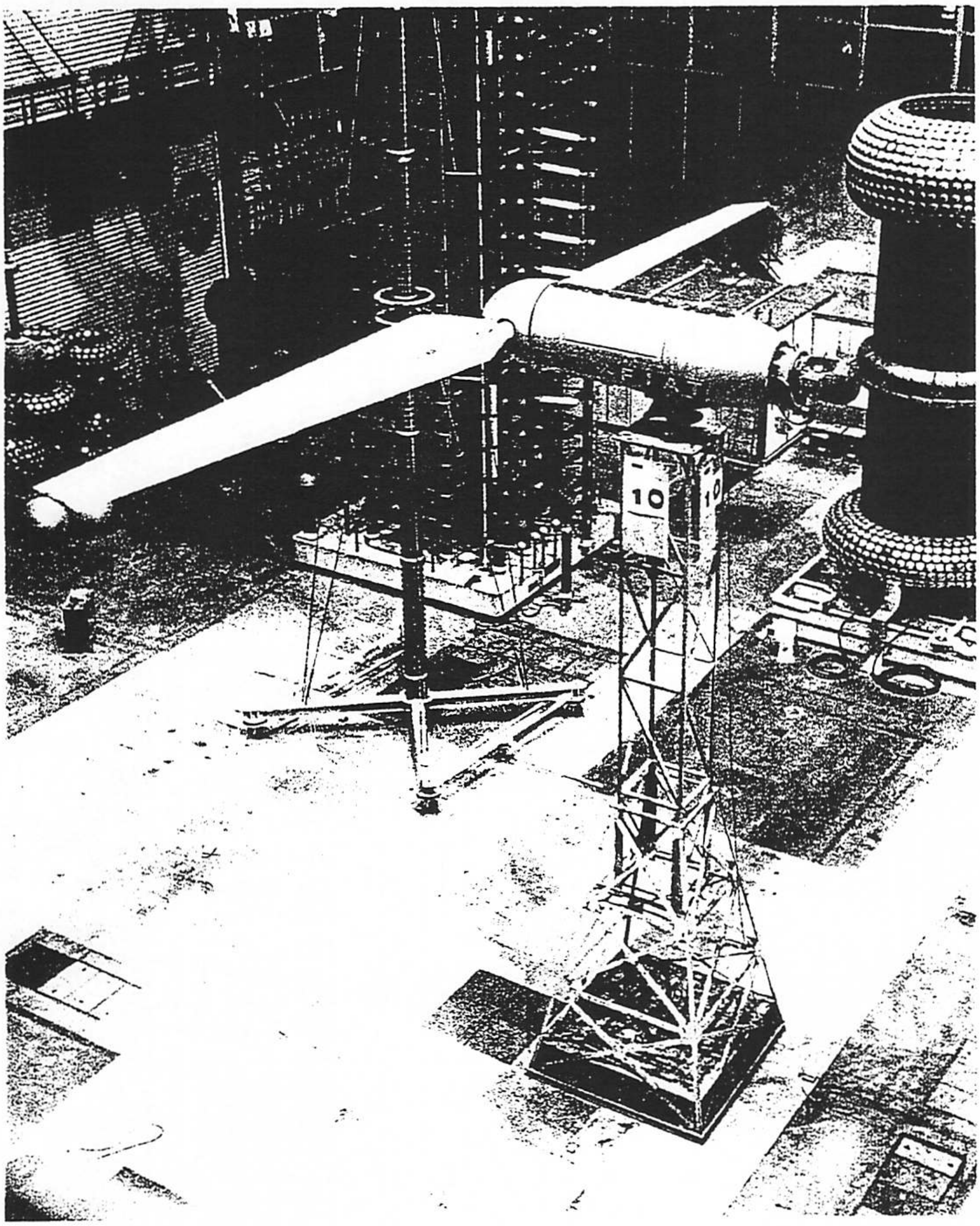

Fig. 1 50 kW twin-blade windmill with blades built with insulating material (glass-fibre compound)

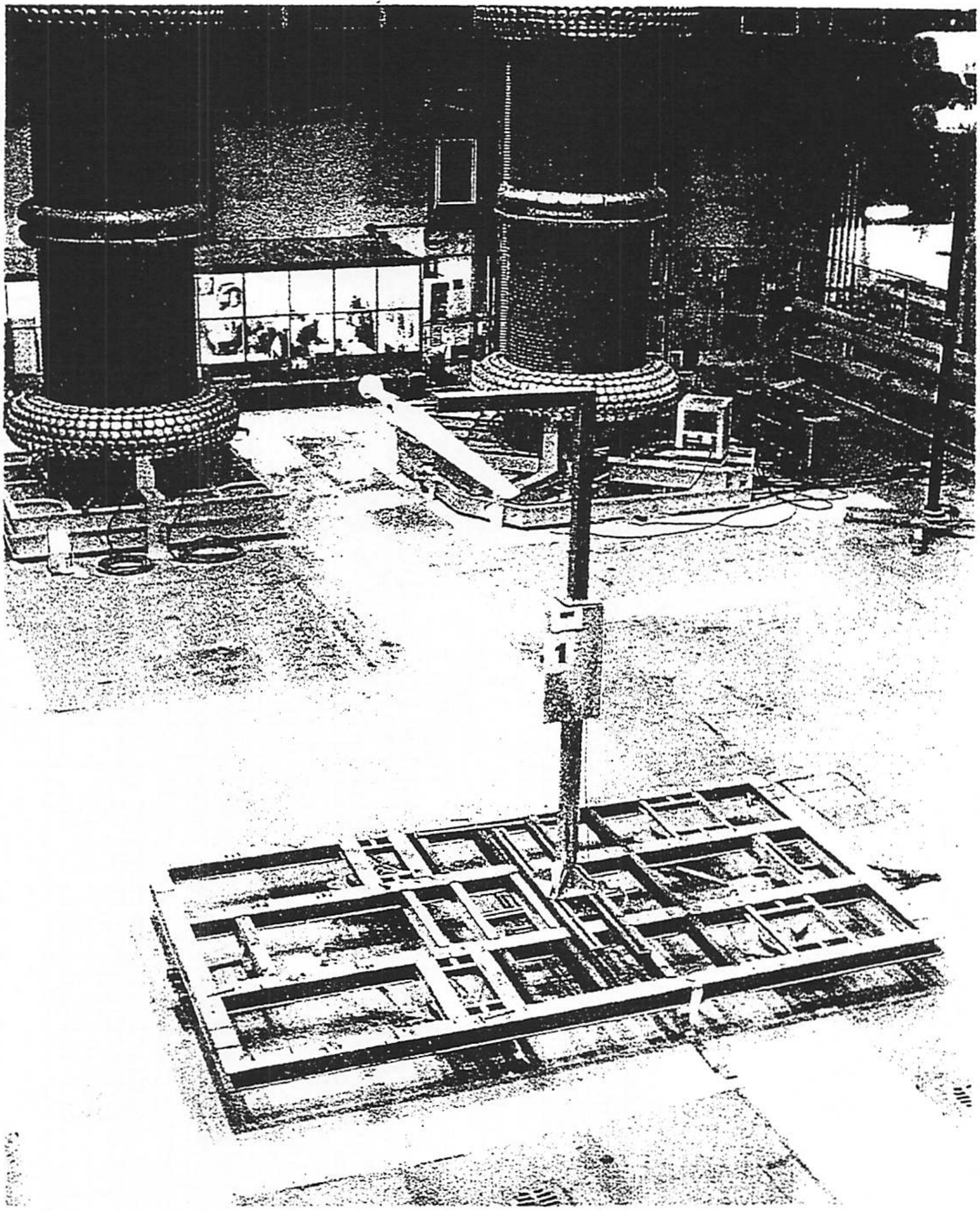

Fig. 2 5.2 kW single-blade windmill with blades built with partially conducting material (carbon fibre compound - CFC)

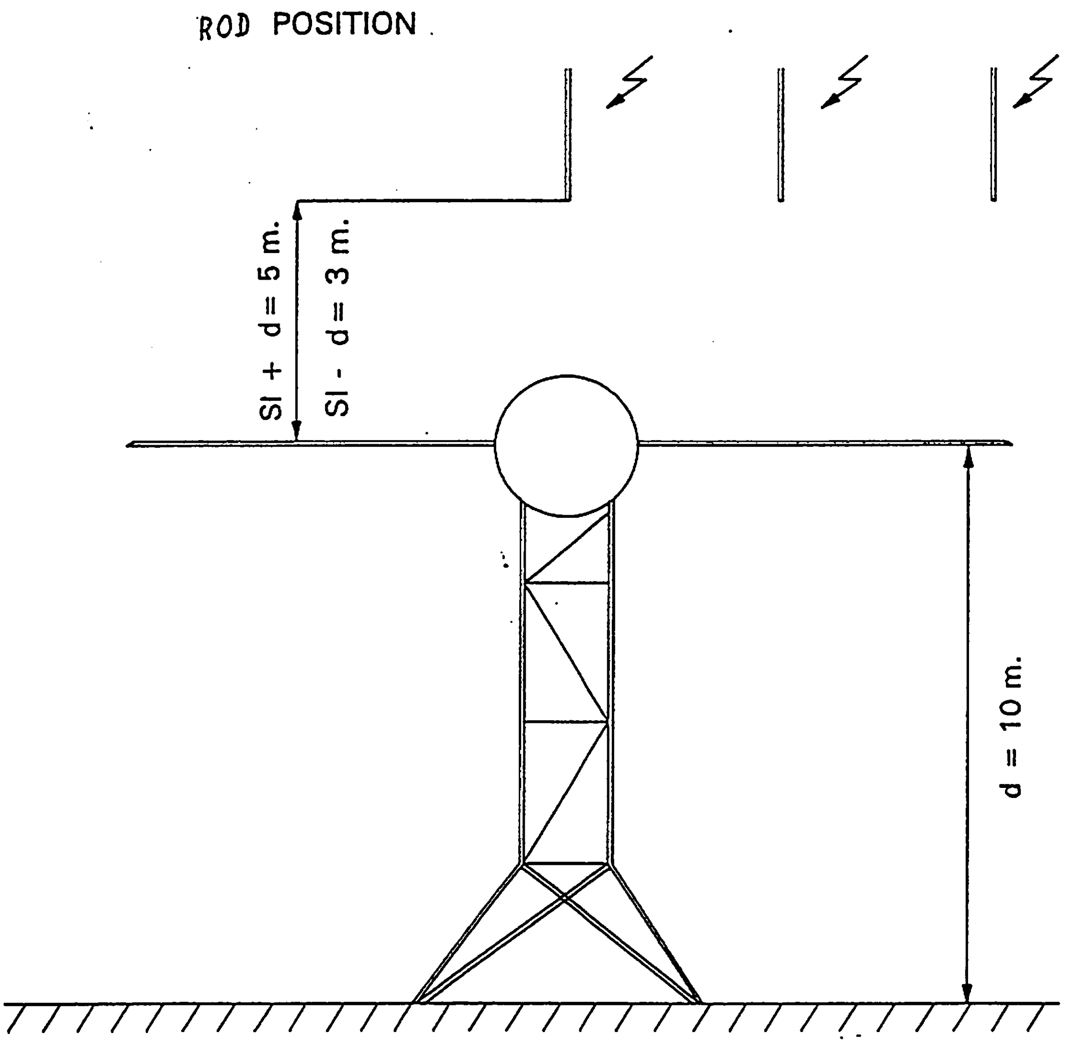

Fig. 3 Test arrangement for attachment tests (voltage test)

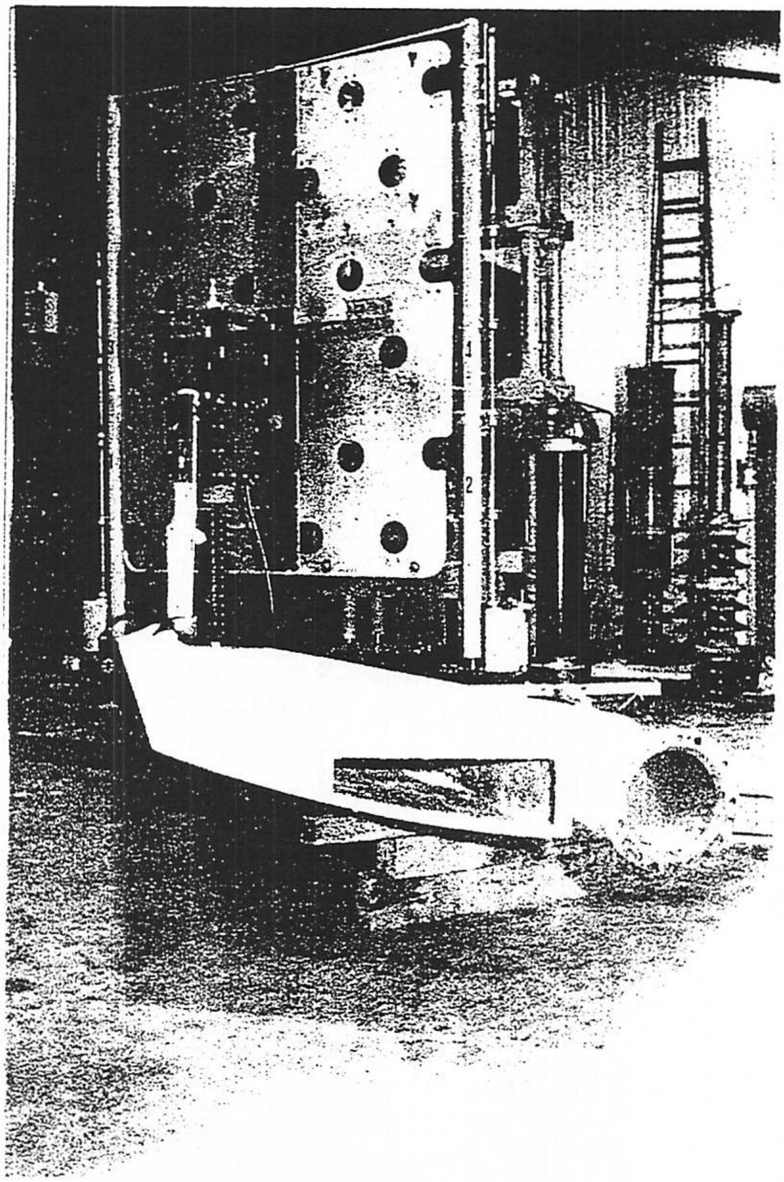

Fig. 4 Test arrangement for direct effect tests (current tests)

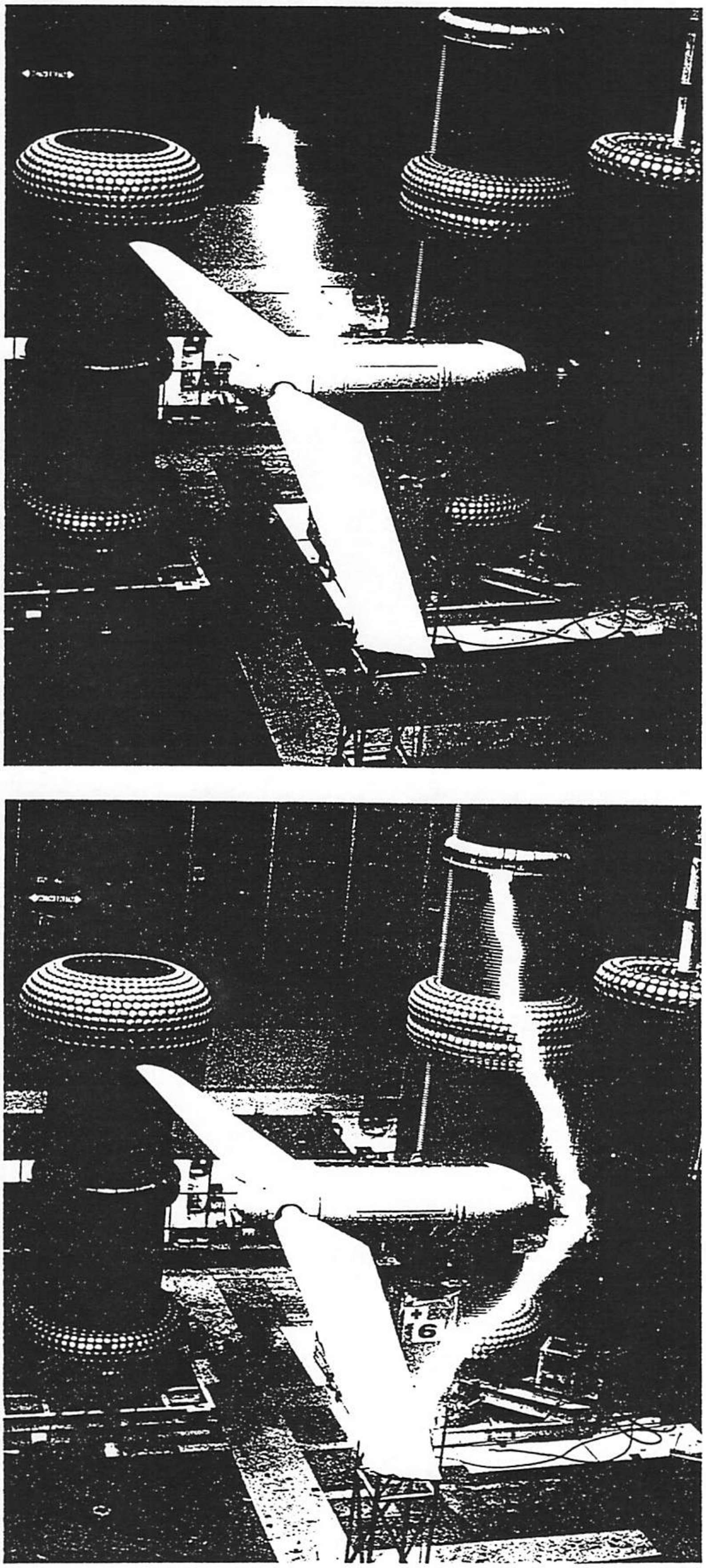

Fig. 5 Examples of discharge paths for the 50 kW twin-blade windmill, with blades of glass fibre compound.

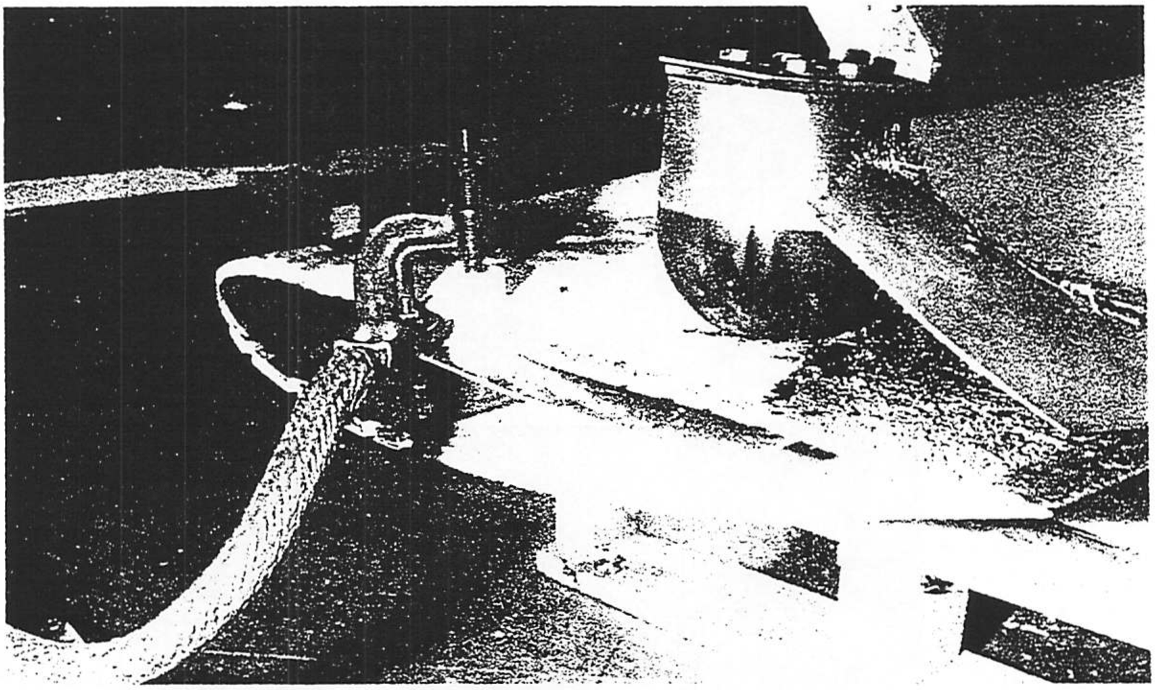

Fig. 6 Example of direct effect on the glass fiber blade,with injection of the current in the vicinity of the metallic insert.

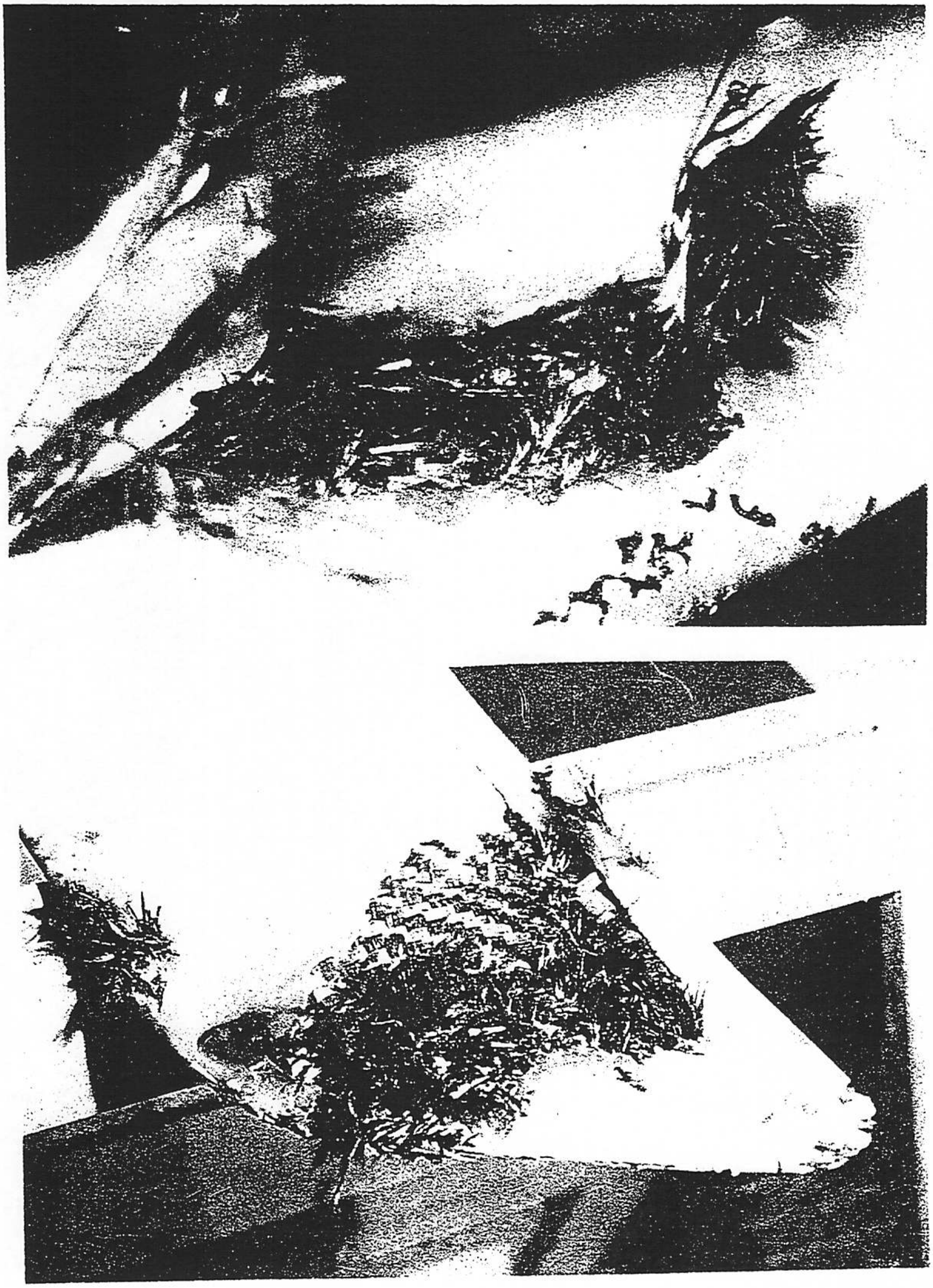

Fig. 7 Example of direct effect on the CFC blade.

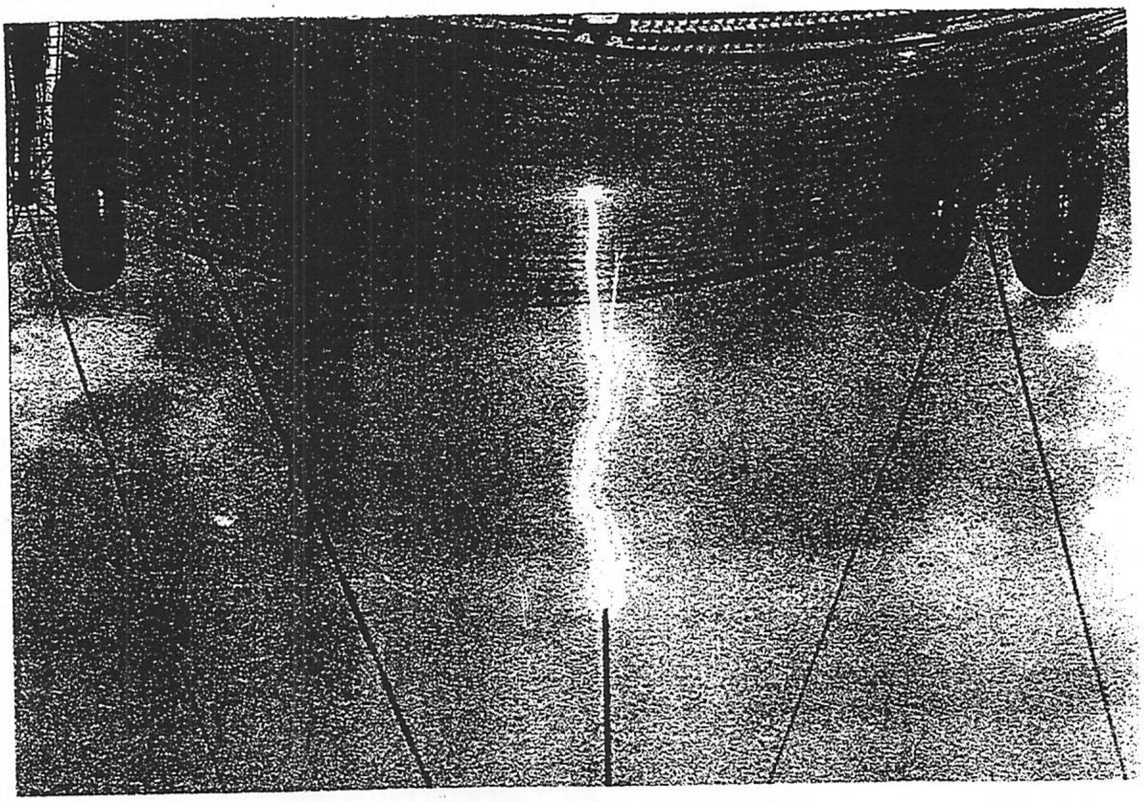

Fig. 8 Possible alternative arrangement for the study of lightning attachment.

FIFTH INTERNATIONAL SYMPOSIUM
ON HIGH VOLTAGE ENGINEERING

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TESTS ON COMPOSITE MATERIALS AND AIRCRAFT COMPONENTS TO ASSESS LIGHTNING PERFORMANCE

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Abstract

Lightning protection design and certification require particular attention especially for aircrafts which make a wide use of composite materials.
The test activity to prove the adequacy of the components and protection systems is presented in this paper, making reference to some examples of tests recently carried out on behalf of Aeritalia.
The significance of the various tests are also discussed.

Keywords

-Aircrafts-Composite materials-Lightning protection-Test techniques

1-Introduction

Ligthning to aircrafts is a relatively frequent phenomenon: available statistics /1/ indicate that, in average, aircrafts are struck by one lightning every about 3000 flying hours.

The problem of lightning to aircrafts has become of particular concern due to the introduction of composite (Kevlar, fiberglass) and advanced composite (CFC:carbon fiber composite) materials.
These materials are infact either insulating or poorly conductive (such as CFC), thus can be punctured by the lightning or highly stressed by resistive heating due to lightning current.
Furthermore they present no shielding effectiveness or low shielding effectiveness, causing larger EMC problems than those expected in metal alloy aircrafts.
Direct effects of lightning, such as heating, puncture, delamination etc., and indirect effects, such as voltages and current induced by lightning must be controlled and minimized in design by means of suitable protection devices.
The typical requirements of such protection systems are the capability to catch lightning and to carry the relevant current, thus to prevent puncture of non-metallic skins and attachment to underneath metallic hardware.
Indirect effects can be minimized either by using suitable screening systems or by installing on the wiring suitable arresters.
The effectiveness of the adopted protection systems has to be verified through laboratory tests.
In the following examples of recent tests to prove the adequacy of protection design are reported and discussed.

2-Tests to verify the lightning protection design

A simplified schematization of the development of lightning to aircrafts is shown in Fig. 1.
When a leader approaches an airplane, (Fig. 1a) the high electric field may cause starting of streames and leaders from the aircraft. When the streamers from the aircraft reach the streamers of the main channel, a sort of final jump is launched and the discharge channel attaches to the airplane, charges it and, due to the large amount of charge transferred to the aircraft, causes a new leader to propagate from the aircraft itself. Since this moment the discharge grows in the normal way. When the ground or another charge pocket in the cloud is reached, the return stroke is generated and the relevant current flows through the airplane, which is stressed by two arcs and by the current conducted between the "entry" and "exit" points.

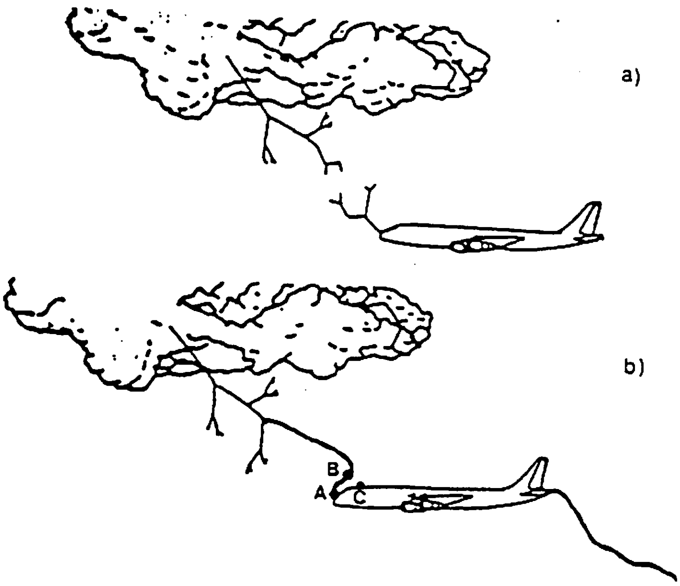


Fig.1-Schematization of lightning phenomena with special reference to aircrafts.
a) Lightning approach to the aircraft
b) Return stroke and swept stroke phases

Due to the movement of the airplane during the leader propagation and flash duration the arc is stretched as shown in fig. 1b. When the voltage across points B and C of fig. 1b exceeds the strengh of air the lightning arc reattaches to point C. This phenomenon, known as "swept stroke", causes the presence of a set of attachment points along the flight direction.

Unfortunately full duplication of lightning in laboratory is not possible. The design development and certification is therefore to be made trying to duplicate separately the various lightning aspects and effects. In particular, as required by Standards /2/,/3/, the following tests are required:

-Tests to verify the ability of protection systems to catch the lightning, avoiding damages to the protected structures and components (Lightning attachment tests)

-Tests to verify the ability of the protection systems, or of other parts of the aircraft stressed by lightning current, to carry the current without damages (Physical damage tests).

-Tests to check the impact of electro-magnetic fields generated by lightnings on electrical and electronic aircraft components (Indirect effect tests).

2.1-Lightning attachment tests

These tests have to be performed for aircraft components especially exposed to lightning and made of insulating materials to assure radio frequency transparency (like antenna housing and radome).
In this case the protection system is generally made by applying continuous metallic or special segmented strips on the external skin of the protected object. The aim of these tests is to verify that the protection systems prevent lightning from striking the protected components (absence of shielding failures).

According to the Standards, certification tests are to be made applying high voltage impulses (linearly increasing with a rate of rise of 1000 kV/us up to breakdown) to a rod located at a distance of 2 m from the object under test. Fig. 2 shows an example of tests performed according to this procedure on a radome. As also evident from the picture, the design of the protection system, consisting of strips, resulted adequate from the point of view of shielding failure. It is to be underlined the importance of the above tests also in a design phase. In the examined case preliminary design tests (lightning attachment tests and physical damage tests) allowed to optimise number and location of the strips.

Fig.2-Lightning attachment tests on a radome, made of composite materials, with special strip protections. Voltage rate of rise:1000 kV/us.Voltage polarity: negative. Distance between rod and radome skin: 2 m.

Furthermore they allowed to fix the minimum clearance necessary between the strips and the radar antenna.

The above tests aim to simulate only the last phase of the lightning channel attachment: the rod aims to simulate the leader from which only streamers propagate toward the protection system.
The simulation of lightning phenomena is in this case limited: as an example much longer streamers are to be espected for actual lightnings /4/,/5/. On the other hand the test has the advantage to be carried out also with generators available in small laboratories.

A closer simulation of lightning phenomena is achieved by using slow front voltage impulses (Switching Impulses, SI) and much larger clearances between the high voltage electrode and the test object. In particular they could allow:

-to simulate the propagation of a downward leader with the relevant streamer zone
-to simulate field conditions on the surface of the test object closer to the actual ones, before the arrival of the streamers from the downward leader. This could permit the formation and propagation of upward predischarge phenomena, reproducing, at least qualitatively, actual field conditions.

An example of tests performed on an aircraft finn with SI is reported in Fig.3. The finn was in the examined case grounded and the clearance to the HV rod was mantained of about 7 m.

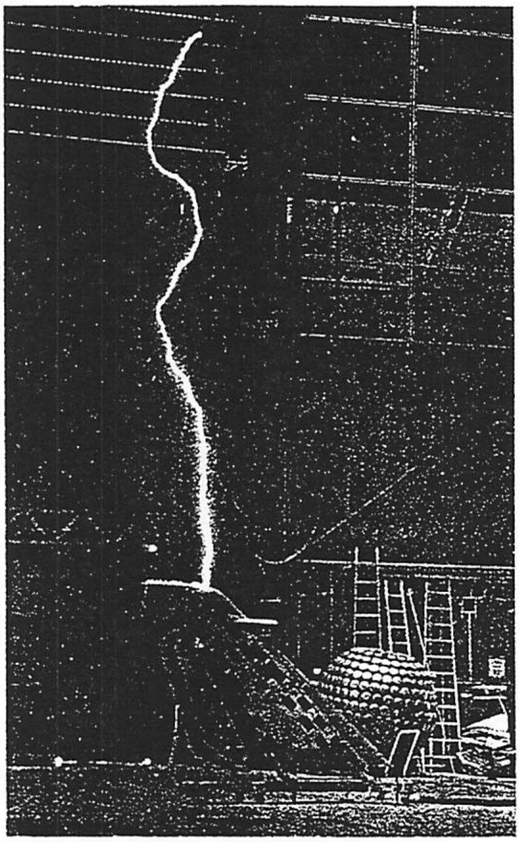


Fig.3-Lightning attachment tests on a finn, made of composite materials with strip protection. Applied voltage: SI of positive polarity. Distance between rod and finn top: 7 m.

The problem of the best simulation of the lightning from the point of view of attachment is still open. A research in this field could be therefore very valuable. Among the aspects to be investigated it can be quoted:

-The influence of the test object condition (grounded or at floating potential) on the test results. In principle floating condition should allow to better represent actual charging conditions of the tests objects.

-The influence of the clearance between HV electrode on the test results. Tests in outdoor laboratories /6/, could allow to reach easily clearances up to 30 m.

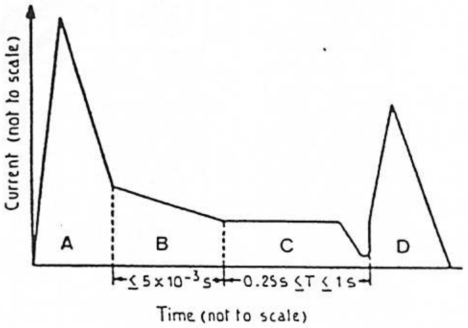
The recording of the dynamic development of the discharge through image converter could be very useful to study the similarity between laboratory tests and actual phenomena /3/,/6/.

2.2-Physical damage tests

These tests have to be performed on all the components which can be interested by high density current.
The aim of these tests is to verify the ability of the aircraft structure and of the protection system to carry the lightning current avoiding damages to the underneath structure, and avoiding the build up of a voltage drop sufficient to cause backflashover.
The parameters that play the major role in determining lightning effects on structures have been proved /1/ to be the followings:

- peak current: I_p
- current front steepness: di/dt
- action integral: $\int i^2 dt$
- tranferred charge $\int idt$

Because some of the above parameters are more critical for the first return stroke and other for intermediate lightning phase, standards /2,3/ require to simulate , for certification purpose, the lightning current with the waveshape shown in fig. 4. which is made of four components, each one representing a phase of the lightning current. In the figure also the values of the parameters to be considered are listed.



CURRENT COMPONENT A
(Initial Stroke)
Peak Amplitude = 200 kA+10%
Action Integral = $2\times10^6 A^2$ s $\pm$ 20%
Time Duration $\leq$ 500 s

CURRENT COMPONENT B
(Intermediate Current)
Maximum Charge Transfer = 10 Coulombs
Average Amplitude = 2 kA $\pm$ 10%

CURRENT COMPONENT C
(Continuing Current)
Charge Transfer = 200 Coulombs$\pm$20%
Amplitude = 200 ÷ 800 A

CURRENT COMPONENT D
(Restrike)
Peak Amplitude = 100 kA+10%
Action Integral = $0.25\times10^6 A^2$ s $\pm$ 20%
Time Duration $\leq$ 500 s

Fig.4-Physical damage tests. Current waveshape recommended by Standards for the tests.

Depending on the location of the part to be tested on the airplane, namely direct impact zone or swept stroke zone, all the current components or only part of them have to be applied. The current must be applied as a continuous discharge except when all the components are simulated; in this case the last component is applied alone after extinction of the preceeding discharge.
The generation of the above waveform requires to set together and synchronize different generators, as shown in Fig.5. The current is injected creating an arc having a length of at least 1 cm.

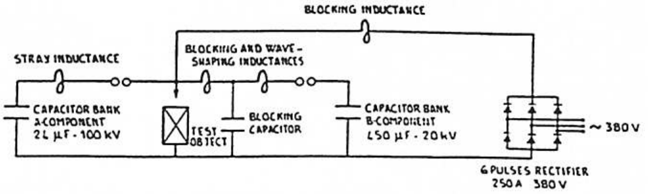


Fig.5-Physical damage tests. Scheme of the circuit adopted by CESI for the generation of waveshapes as in Fig.4.

Also these tests are especially useful in the design phase, and when developing new materials. In case of development tests the components can be applied separately to verify the behaviour of the protection system adopted when subjected to each component.
As an example Table I reports some results of tests obtained on CFC panels protected with various conductive layers, under impulse A only. An example of the damages obtained during the above mentioned tests is reported in Fig.6. In particular the tests has allowed to prove the inadequacy of some protective solutions.
In particular these tests could be very useful to solve problems still open, like that of the choice of structural joints suitable from the point of view of lightning.

Table I- Physical damage tests on CFC panels. Results of some of the tests performed.

Specimen	Peak value of A component [kA]	Tests results
Sandwich panel: CFC/honeycomb/ CFC not protected	141	Delamination of 3 layers
Sandwich panel CFC/honeycomb/ CFC protected with aluminized fabric	143	Debonding of protective layer, light damage to first CFC layer
CFC fabric panel protected with Ni coated fabric	170	Damages to protection layer only
CFC fabric panel protected with aluminized fabric	139	Damages to protection layer only
CFC panel Tape 90° not protected	73	Panel broken

Fig.6-Physical damage tests on CFC panels. Example of damages observed.

2.3-Indirect effect tests

These tests are to be performed on complete vehicles or on significant and representative parts. The aim of these tests is to measure induced voltages and currents in electrical wiring to identify circuits which may be susceptible to lightning induced effects.
According to the Standards the lightning may be simulated through current impulses of defined shapes.

The Standards pay major attention to the coupling mechanism associated with high current.
It is still open the aspect of the simulation of the capacitive coupling between electronic components and lightning channel during leader approach when non metallic structures are concerned. An example of the noise induced during lightning attachment tests in the wiring inside the finn of Fig. 3, is shown in Fig.7.
The shielding effectiveness of various screening solutions may be also determined by field immersion testing. As an example Fig. 8 shows the finn under test inside an anechoic chamber at CESI laboratories.

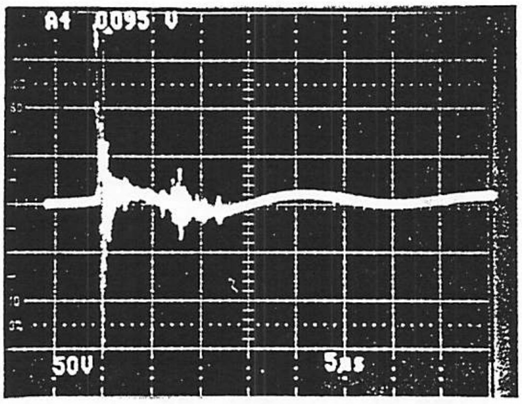


Fig.7-Indirect effect tests on finn.
Example of induced voltage on cables.

3-Conclusions

-The study of the lightning performance of aircrafts is of fundamental importance, especially when solutions with composite materials are considered.

-The tests are very helpful in the development phase, since the mathematical modelling of the lightning phenomena is not easy.

-Unfortunately lightning can not be fully represented in laboratory and therefore various tests are necessary to represent the various lightning effects.

-The Standards are very exhaustive and prescribe a complete test program to certificate the lightning performance of aircrafts and aircraft components. The tests proposed take care of representativeness and feasibility. In particular the tests are designed in order to be carried out also in relatively small laboratories.

-Research tests with more sophisticated procedures could be very useful to confirm the soundness of existing Standards and to assure a high reliability of aircrafts from the lightning point of view.

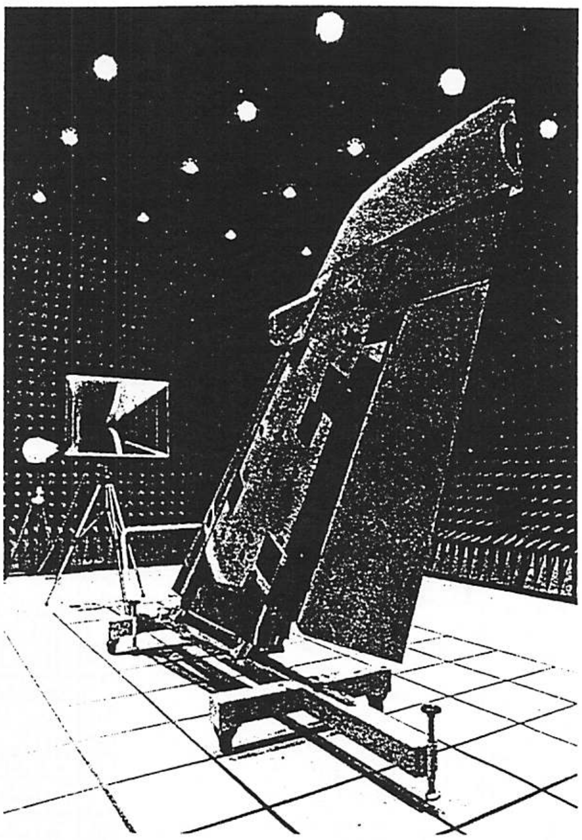


Fig.8-Indirect effect testing.
Finn mounted in the anechoic chamber.
Dimension of the chamber in meters
13 X 9 X 4.5 (high).

4-References

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LIGHTNING PROTECTION OF THE FOKKER 100 CFRP RUDDER.

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ABSTRACT

This paper describes the construction of the structural parts of the Fokker 100 CFRP rudder with respect to the requirements for electrical bonding and lightning protection. Furthermore the philosophy for the selection of a consumable trailing edge is given. A description of possible alternative designs for trailing edges and their advantages and disadvantages with respect to damage after lightning impact will also be reviewed.

An overview of the tests performed on test samples and the rudder construction will be presented and discussed. The effectiveness of both the selected structural provisions and trailing edge will be described (and proven) by reporting the results of the simulated lightning tests performed at the High Voltage Laboratory of the N.V. KEMA, Arnhem, Holland. Proof will be presented that the trailing edge construction and its bonding through the structural parts of the rudder to the main aircraft structure is a solution which results in minor damage to the rudder after lightning impact. Furthermore it will be shown that the selected trailing edge construction is less favoured by the structural designers due to the weight penalty.

INTRODUCTION

Since the Fokker 100 empennage has a top mounted horizontal stabiliser which acts as a shield, the change of swept strokes or a direct lightning strike on the rudder's surface seems to be very small, but can not however be entirely excluded. In this case the rudder might become a part of the current path and would have to conduct a substantial current. The point of exit on the rudder of the lightning strike may either be at one of the bonding jumpers over the hinges at the trailing edge or at the static discharger.

Previous simulated lightning tests were based on direct impact damage in order to investigate the effectiveness of the protective layer on glass, aramid or carbon fibre reinforced test panels. The sample panels were positioned under a rod. The rod was positioned at a distance of about 1 cm above the test panel's surface. Furthermore, in these tests the effectiveness of several edge constructions was also tested. The latter was established by grounding the test panels at the aluminum supports at the edges (representing the aircraft's structure). The degree of damage to unprotected test panels was also established.

1. DESIGN CONSIDERATIONS

Due to the geometric shape and location of flight control surfaces like flaps, ailerons and rudders etc., the attachment or exit points of the lightning strikes will be localised at the trailing edge. The use of CFRP shall result in damage of the trailing edge after lightning impact. The degree of damage will strongly depend on the construction of the trailing edge used. After impact the current will be divided over the upper and lower skin panels of the affected flight control surface. This action will result in two effects:

- electromagnetic forces (causing delamination),
- resistive heating (causing vaporisation of the adhesive and/or resin, resulting in delamination).

Both effects will occur in cases where the upper and lower skins are terminated at the trailing edge and are connected by means of an adhesive layer (figure 1). In the case of a construction as shown in figure 2, the electromagnetic forces will dominate.

The degree of damage will be minimized by using a construction in which the trailing edge consists of a massive material (without resistivity change at the attachment point). Furthermore, this trailing edge must be connected to the upper and lower skins by means of rivets at a certain distance away from its extremity. In order to obtain the same degree of resistivity as the upper and lower skin panels the trailing edge has to be made from the same material (figure 3). Due to the absence of an adhesive layer the occurrance of an explosive expansion of this layer as a result of resistive heating is prevented. In addition, the degree of electromagnetic forces will be less at the connecting rivets of the skins to the trailing edge. This is because of the greater distance between the (skin) rivets and the lower current density in both skins (i.e. not concentrated at the trailing edge) compared to figures 1 and 2. The result will be that the actual electromagnetic force in the trailing edge will be les severe. So the degree of damage will only be dominated by the resistive heat build-up at the attachment point of the trailing edge.

Based on the above mentioned considerations it was decided to evaluate a trailing edge construction as shown in figure 3.

2. PURPOSE

Simulated lightning tests were carried out to investigate and verify the adequacy of the selected trailing edge and its fastening method. During the same tests the interfaces at the bonding jumper connection were subjected to the same test currents. For other reasons, it was decided at a later stage to mount a static discharger on the rudder. The method of fastening the static discharger base was also subjected to simulated lightning tests. The simulated lightning tests were performed at the High Voltage Laboratory of the N.V. KEMA, Arnhem, Holland and were in accordance with "Aerospace recommended practice: Lightning effect tests for aerospace vehicles and hardware" [1]. The test currents were based on zone 2 requirements [1]. Furthermore, the tests were mainly performed to determine the effects on the electrical bonding methods after being submitted to simulated lightning tests; this in accordance with MIL-STD-1757A [2].

3. TEST SET UP

During the tests the lightning current generator was connected either to one of the bonding jumpers and the trailing edge or between two bonding jumpers. This in order to simulate a possible current path through the rudder. After the aircraft has been hit by a lightning flash the lightning currents may flow through one bonding jumper (or enter at the trailing edge). These currents may enter the rudder either at the rudder construction at one of the bonding jumpers or at the trailing edge. Conductive tests were carried out in order to determine the capability of the structure to conduct the currents to which it will be subjected. For these tests the high current source was solidly connected to the test sample at one of the bonding jumpers or at the (for this reason extended) trailing edge. A rod was only necessary in order to create an attachment at the trailing edge. However the applied test current wave forms were the same.

All test specimens were subjected to a current impulse consisting of two components in accordance with reference 1 for zone 2. The first component was a current wave with a maximum amplitude of 100 kA and a duration of 25 µs. After 100 µs from the start of the first component a second component consisting of a current wave with an amplitude of 1,8 kA and a virtual duration (the time during which the amplitude of the impulse is greater than 10% of its peak value) of 3,5 ms was applied [1].

4. TEST SPECIMEN DESCRIPTION

4.1. Test specimen 1.

Test specimen 1 consisted of two CFRP sandwich skin panels connected at the trailing edge by means of a CFRP trailing edge member (figure 3). The specimen dimensions are representive for the Fokker 100 CFRP rudder at the location between the middle and upper hinge (figure 4). Due to the weight penalty caused by rivetting, the design office preferred to adhesively bond the trailing edge to both skin panels. In order to compare the effects of adhesive bonding and rivetting, the trailing edge of the test specimen was split into two sections. The upper section was adhesively bonded while the other section was rivetted (figure 5). The trailing edge was also extended for some distance in order to be able to make a connnection to the lightning current generator. Furthermore the sandwich skin panels were fixed in the correct position by means of two dummy (PU) ribs.

4.2. Test specimen 2 and 3.

4.2.1. First test series configuration.

Both test specimens consisted of CFRP sandwich panels representing a skin of the Fokker 100 rudder. Both test specimen cross sections were the same as for test specimen 1, but one of the corners was made representative for the spigot area. So both panels were equipped with two bonding jumpers: one for the middle hinge and one for the spigot area. Compared with test specimen 1 the construction was modified as follows:

1. bonding jumpers (greater cross section for the previous selected one had failed),
2. electrical bonding provisions at the bonding jumpers (e.g. a CFRP insert at the attachement area),
3. totally rivetted trailing edge,
4. additional CFRP layer at the outer surface of the outer skin, orientated perpendicular to the trailing edge (mainly for strength reasons, but the fibre direction will be beneficial by influencing the desired direction of current flow in the surface layer of the outer skin).

Furthermore the test specimens were equipped with dummy front-spar flanges and rib-flanges (spigot area). See figure 6.

4.2.2. Second test series configuration.

The (delaminated) front-spar flanges of both test specimens were replaced by a representative part of a production spar (complete). The (delaminated) dummy-rib flanges of both test specimens were replaced by another dummy. At test specimen 2 two monel rivets were mounted at the "ends" of the spar-rib flanges and at the "end" of the dummy rib (at the trailing edge location). Furthermore the number of rivets at the bonding strip of the middle hinge area was doubled.

4.2.3. Third tests series.

The delaminated production front spar of test specimen 2 was removed and replaced by another one. Furthermore the delaminated dummy-rib flange was also replaced. At the ends of the front spar flange and of the dummy-rib flanges metal strips were rivetted (figure 7). This is in order to simulate the (heavy) metal parts at the hinges and in the spigot area.

5. TEST RESULTS

5.1 Test specimen 1.

5.1.1. Test performed over the bonded trailing edge.

Before testing it was decided to add four rivets to one side of the adhesively bonded trailing edge (lower part of figure 8A). This was done at the request of the design office. They estimated that four rivets at the adhesively bonded trailing edge would be sufficient to conduct the simulated lightning currents. This in order to obtain a configuration with the lowest possible weight penalty. After being submitted to the simulated lightning current wave form, the adhesively bonded trailing edge was delaminated. In-house investigations revealed later that the trailing edge was delaminated over more than 75% of the cross section of its connection to the skin panel (upper part of figure 8A).

The trailing edge connection provided by four rivets was also delaminated, although to a much lesser extent. Furthermore, the outer skin plies of the trailing edge at all rivets was also heavily delaminated.

5.1.2. Tests performed over the rivetted trailing edge.

The rivetted trailing edge showed minor damage after the simulated lightning test. The damage was limited to small delaminations of the outer plies at some rivets. After this test the simulated lightning tests were repeated a further three times.

The damage to the trailing edge after the simulation of an attachment was limited to local burning of the resin (see figure 9A and 9B). The damage shown is the result after two subsequent tests.

After completion of these two tests a dummy static discharger base was mounted on the rivetted trailing edge. The subsequent simulated lightning tests showed that the fastening of the base by means of three rivets is sufficient to preclude structural damage after lightning attachment.

5.1.3. General.

At the bonding jumper area (representing the middle hinge) the CFRP skins of both skin panels were delaminated. Furthermore one of the bonding jumpers was broken during the simulated lightning tests.

5.2. Test specimen 2 and 3.

5.2.1. First test series.

5.2.1.1. Bonding jumper area.

At the bonding jumper connection of the middle hinge for both test specimens some arching and delamination of the outer CFRP plies (at the inner side of the rudder) occurred after the tests. This was considered to be unacceptable for the following reasons. In the event that the aircraft is struck in actual service it is difficult to establish damage inside the rudder. Furthermore, this was not acceptable in view of maintenance considerations.

No damage was detected on either of the two test specimens at the bonding jumper connection at the spigot area and at the trailing edge.

5.2.1.2. Flanges.

The dummy front-spar flanges of both test specimens were delaminated at both ends after the tests (figure 10A and 10B). The dummy rib flange of both test specimens was also delaminated at the end situated at the trailing edge area. The ends of the dummy rib flanges of both test specimens at the bonding jumper connection of the spigot area did not suffer any damage.

5.2.2. Second test series.

5.2.2.1. Test specimen 2.

Two simulated lightning tests were performed between the bonding jumper of the middle hinge and the trailing edge. Despite the two rivets installed at the ends of the front spar flanges, both areas suffered from delamination of the outer CFRP plies at the rivets.

5.2.2.2. Test specimen 3.

After the simulated lightning tests between the bonding jumpers of the middle hinge and the spigot area the end of the front-spar flange was heavily delaminated (figure 12A). At the end of the flange the resin in its "neck" had been vaporized blowing away carbon fibres (figure 11A and 11B). Furthermore, the inner and outer skin of the test specimen was delaminated at the honeycomb connection. This occurred in the region from the inner skin via the CFRP insert at the middle hinge area to the outer skin (figure 12B).

5.2.3. Third test series.

After two simulated lightning tests minor delamination occurred at the middle hinge bonding jumper attachment area of the inner skin (figure 13). This delamination occurred after the seventh simulated lightning test applied to this test specimen. The test specimen was subjected to a further three simulated lightning tests. No sign had been found to indicate that the delamination had grown after each single test. Furthermore no delamination occurred at the ends of the front-spar flange and at the end of the dummy rib flange (in the trailing edge area).

6. DISCUSSIONS.

For the actual Fokker 100 rudder design a rivetted trailing edge had been selected. This despite the weight penalty. Furthermore, the bonding jumper areas of the middle and upper hinge were designed simular to the configuration tested as described in chapter 5.2.3. Furthermore the ends of the front spar flanges of the rudder are well protected against damage by the heavy metal parts at the upper hinge and the spigot area. No metal parts at the ends of the top and bottom ribs have been applied. This decision is justified by the number of rivets and fasteners installed over the length of both ribs.
This had been a requirement from the Dutch Airworthiness Authorities. For strength reasons the design could not be permitted to rely solely on the quality of the adhesively bonded ribs. The same observation had been made for all the other ribs and the front spar. On the other hand this requirement was favourable for the electrical bonding of the structural parts of the rudder. Furthermore it would be very difficult, if not impossible, to apply a metal strip at the ends of both the top and bottom rib in the trailing edge area.

7. CONCLUSION.

Although the tests were not performed on a full scale rudder, the simulated lightning current was not reduced. So the skin current density and the current through the rivets and the bonding jumpers had a magnitude which is above the design requirements, resulting in worst case conditions.

The simulated lightning tests have resulted in a rudder design which is capable of conducting lightning currents. The result will be minor damage at the trailing edge.

Furthermore it is believed that:

1. the damage after (a possible) attachment to the trailing edge can be temporarily repaired, if necessary, by means of a so called high speed tape. The required cosmic repair can be performed later at the home base of the airliner.
2. No inspection of the (inner) rudder construction is necessary after the aircraft has been struck by a lightning flash.

8. REFERENCES

1. SAE Committee AE4L, Special Task F: Aerospace recommended practice "Lightning effects tests on Aerospace vehicles and hardware.
2. MIL-STD-1757A: Lightning Qualification Test Techniques For Aerospace Vehicles and Hardware.

9. ACKNOWLEDGEMENT

The author wishes to thank Fokker Aircraft Corporation for allowing him to present this paper. Furthermore the author wishes to thank Mr. W. Scholten of Fokker Aircraft Corporation for his cooperation during the tests and for his comments on this paper.

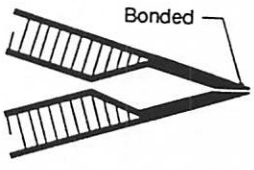
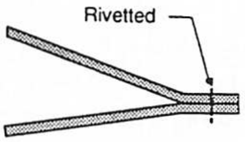


Figure 1.



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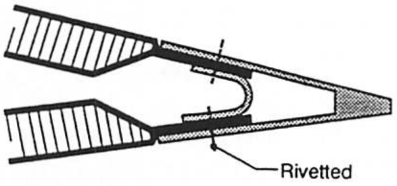
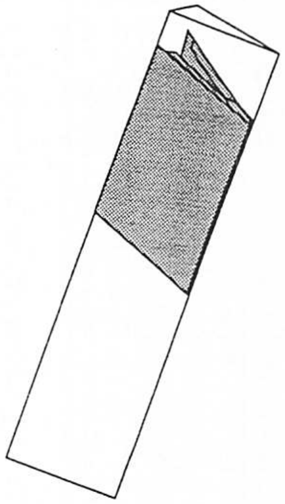


Figure 3.



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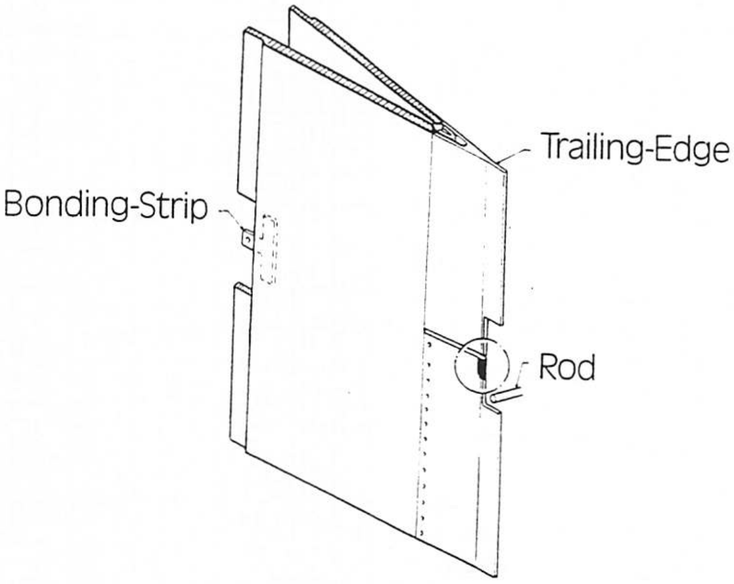

Figure 5.

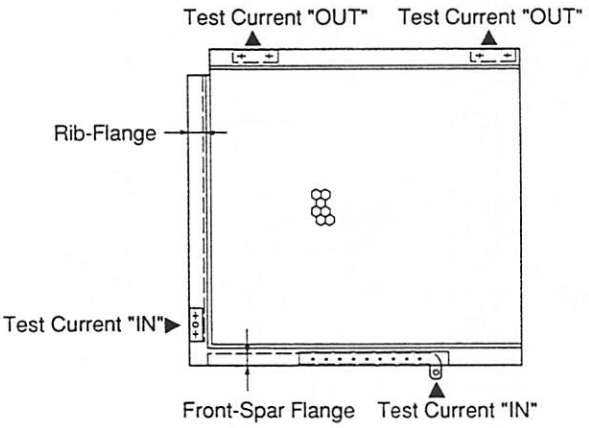

Figure 6.

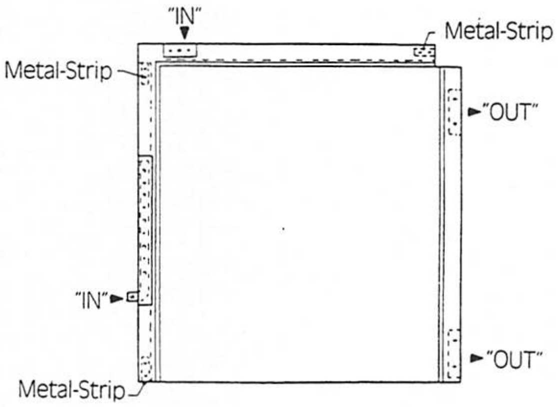

Figure 7.

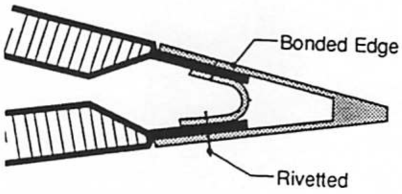

Figure 8A.

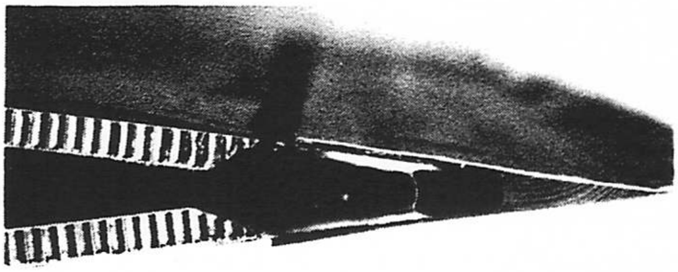

Figure 8B.

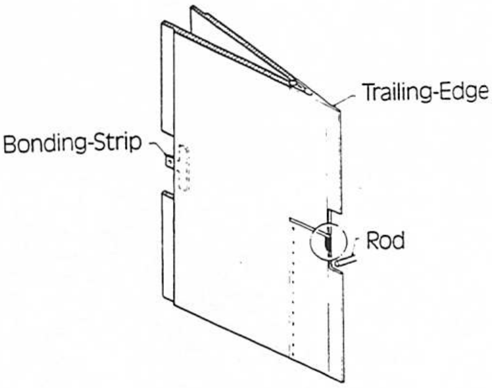

Figure 9A.

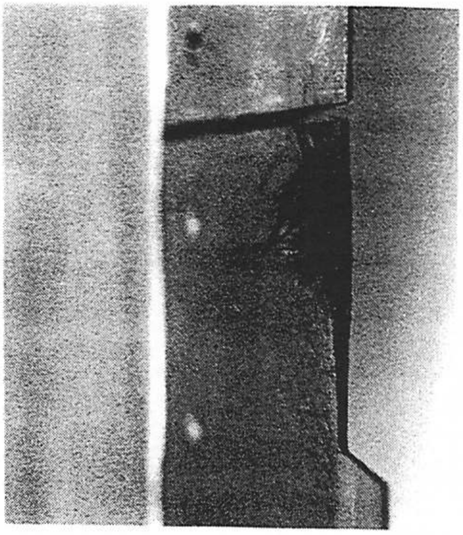

Figure 9B.

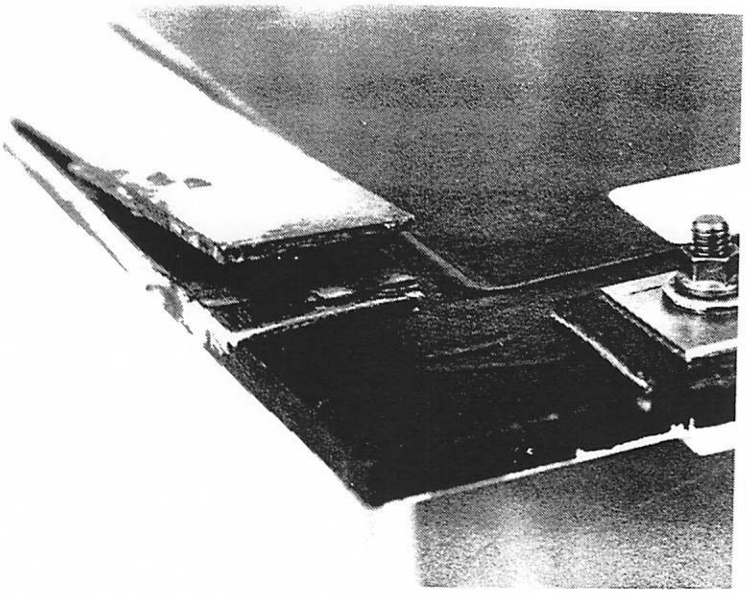

Figure 10A.

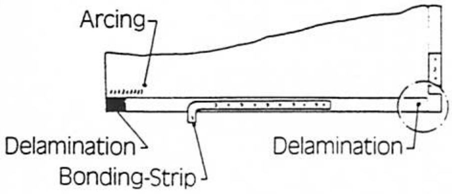

Figure 10B.

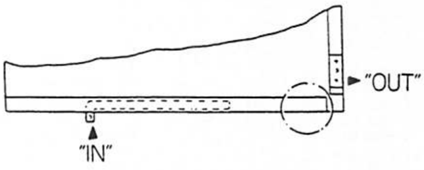

Figure 11A.

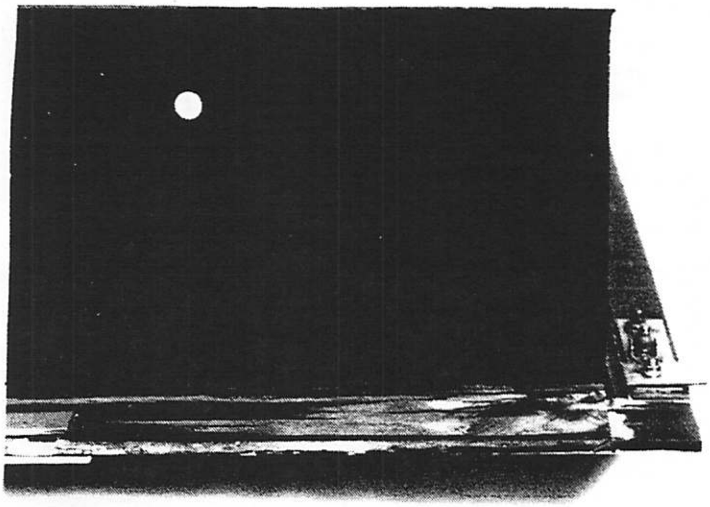

Figure 11B.

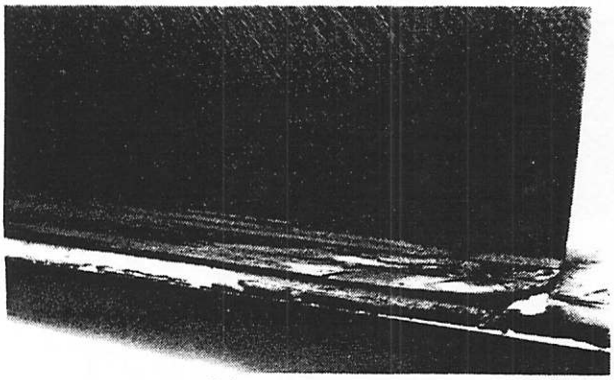

Figure 12A.

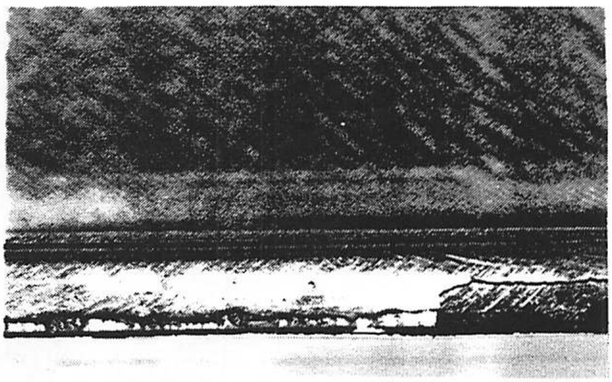

Figure 12B.

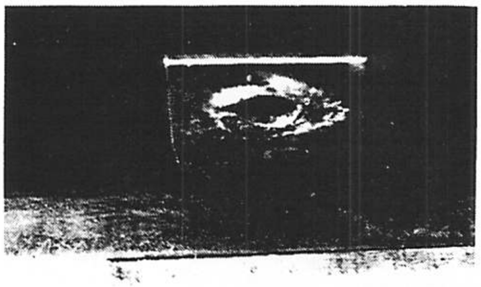

Figure 13.

IEA R&D WIND ANNEX XI: 26th Topical Experts' Meeting

Milan 8th-9th March 1994

Earthing of wind farms - a report of work in progress

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Introduction

There is now some 140 MW of installed wind turbine capacity in the UK, concentrated in the high wind speed areas of Wales and the western parts of England. The latest round of the Non Fossil Fuel Obligation, which provides the premium price for wind power, is likely to see at least a doubling of this capacity as well as installations in Scotland and Northern Ireland.

A typical wind farm consists of some 15-30 medium size (300-400 kW) wind turbines spread out over a wide area. The ground of the upland areas of the west of England and Wales is usually rocky with only a shallow layer of topsoil or peat. Therefore earthing (or grounding in US terminology) of extensive wind farms on high resistivity rocky soil has presented a considerable challenge to wind farm designers. In the rocky ground of wind farm sites it is not practical to use driven rod electrodes. Therefore, long horizontal strip conductors are laid in the trenches of the power collection cable network. On some sites these electrodes may be up to 5 km in length. The electrical layout of one wind farm is shown in Figure 1.

The UK standards give little guidance on how a suitable earthing system using these very long electrodes might be designed, installed or tested and so a research project was undertaken by UMIST and National Wind Power with support from the UK Department of Trade and Industry.

Model of earth electrode

After an initial literature review it was recognised that, in order to deal with both the very long electrodes and the changes in ground conditions over the site, a model of the earthing system would be required. An early version is described in reference [1]. A lumped parameter model was used to represent both the shunt resistances of the earthing system and the series impedances of the earth conductors. The model is shown in Figure 2 for two wind turbines (WTG_n & WTG_{n+1}). Zs is the series impedance of the earth electrode calculated using Carsons equations which are conveniently restated in [2]. Rp is the shunt resistance of the strip electrode while Rf is the resistance to ground of the wind turbine foundation and local electrode. The advantage of this approach was that Zs, Rp and Rf could be determined in one of two ways. Values could be calculated by using the usual equations which are suitable for small earth electrodes using measured soil resistivity values; these could have different values for changing soil conditions throughout the site. Alternatively small sections of the earth electrode could be tested using the usual testing techniques which are adequate for small electrodes but very difficult to apply to extended systems. Once a suitable model had been determined the rise in voltage due to fault currents was calculated using standard network analysis techniques.

Although it is convenient to be able to calculate, or test, the resistance of each part of the earth system separately it is obvious that mutual effects are important. Therefore, more recently the model has been extended to include the mutual inductive coupling between the power cables and the earth electrode as well as mutual resistive effects of different parts of the electrode system.

Test results

Over the summer of 1993 a series of site tests was carried out on three wind farms. Both soil resistivity and earth electrode resistance to earth were measured using standard techniques. As expected, some difficulty was experienced in the testing of these very extensive electrodes. A typical test result of a complete wind farm when tested using a "slope" test [3] is shown in Figure 3. A further complication was that subsequent investigation of the method of measurement indicated that the earth resistance meter used does not respond correctly under certain conditions with very inductive electrodes. However, reasonable agreement was obtained between the predicted and measured values for earth resistance for most of the sites considered and results from the substations locations and two wind turbine sites are shown in Table 1. It has to be stated that at some sites it was not possible to achieve such good agreement, mainly due to practical difficulties with testing.

Planned activities

More work is planned for the summer of 1994, concentrating on field experiments. It is proposed to carry out a current injection test on a wind farm site in mid-Wales and also to experiment with an instrument to measure both the resistance and self-inductance of the earth path. So far attention has been focused on the response of the earthing system to 50 Hz fault current but it is anticipated that the investigation will be extended to consider the response to fast transients.

References

1) Jenkins N & Vaudin A, "Earthing of wind farms", IEE International Conference on Renewable Energy Clean Power 2001, November 1993, IEE Publication 385, pp 190-195.

2) Engineering Recommendation S34, 1986, "A guide for assessing the rise of earth potential at substations sites", Electricity Council, UK.

3) Tagg G F, "Measurement of the resistance of physically large earth-electrode systems", Proceedings IEE, Volume 117, No 11, November 1970.

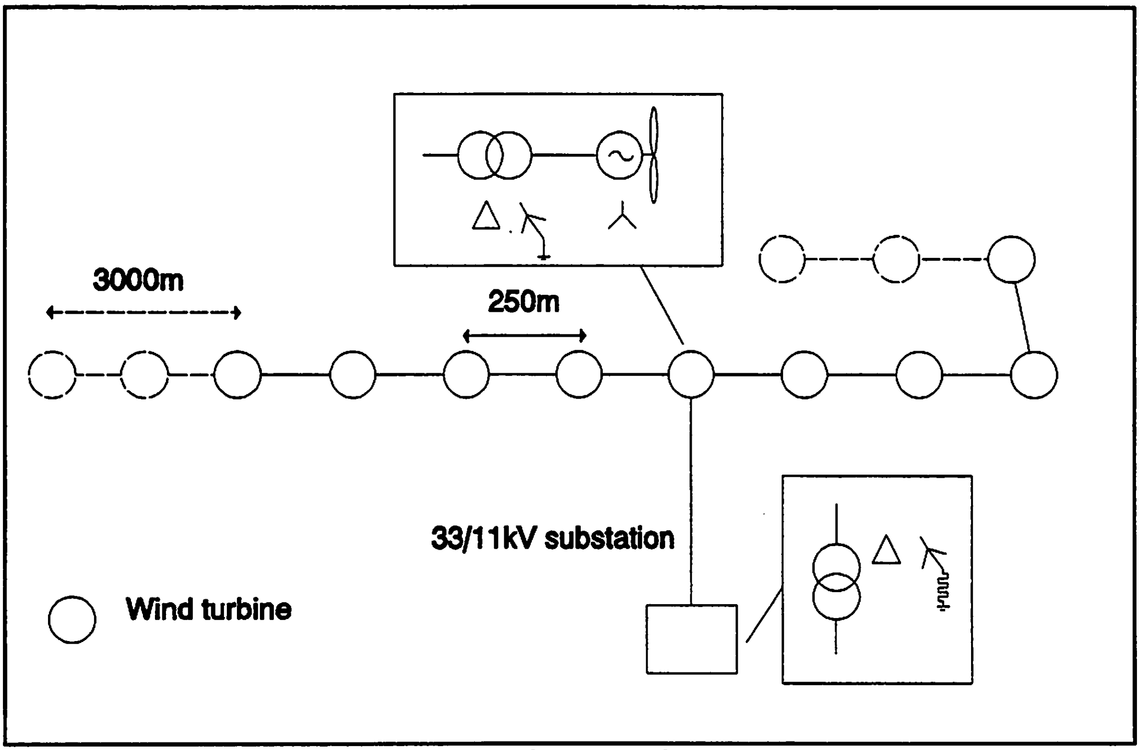


Figure 1 Electrical schematic of wind farm

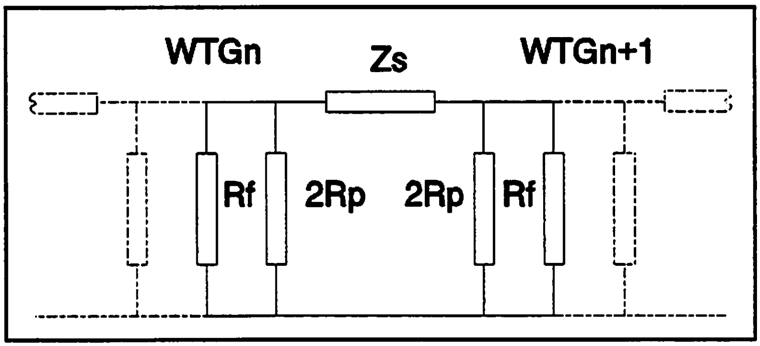
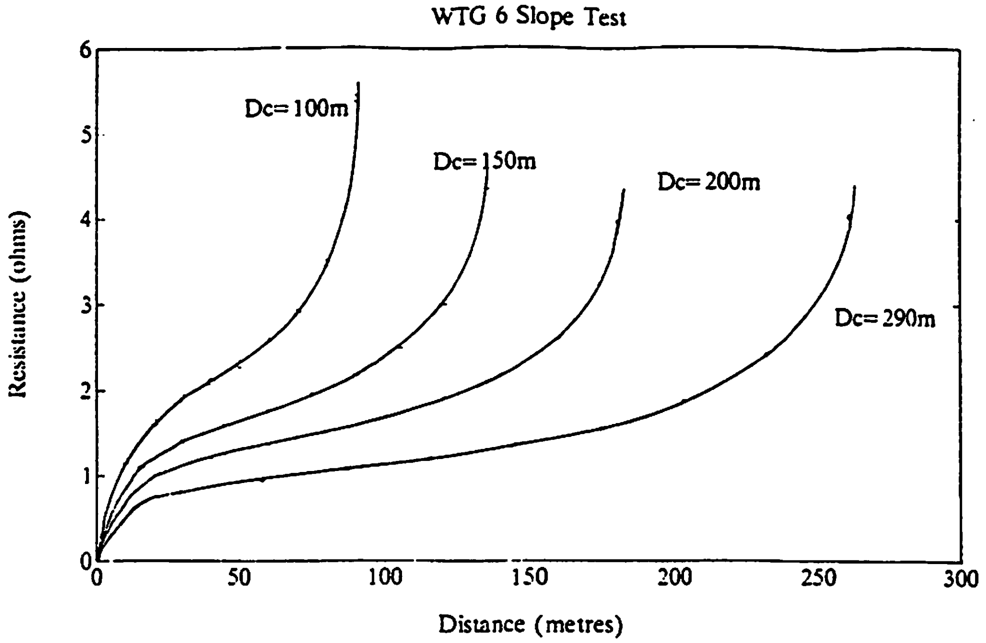


Figure 2 Lumped parameter model



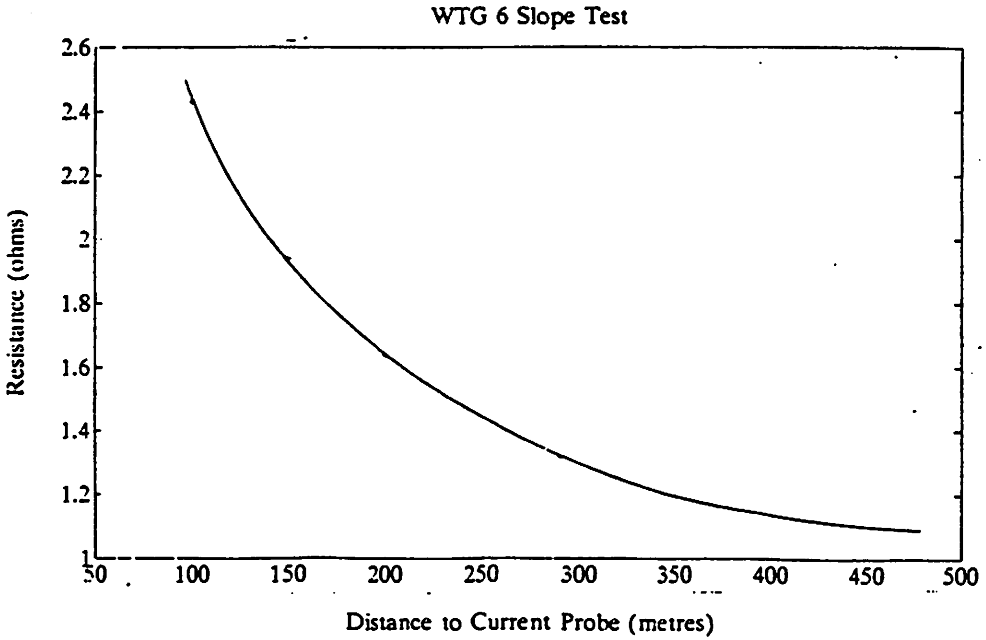


Figure 3 Typical results of "slope" tests

TABLE 1

WIND FARM 1

Site	Substation	WTG A	WTG B
Calculation	0.53	0.50	0.54
Test	0.69	0.50	0.56

WIND FARM 2

Site	Substation	WTG A	WTG B
Calculation	0.39	0.61	0.77
Test	0.3-0.5	0.66	0.82

All values are resistive part of 50 Hz impedance to earth.

SUMMARY.

IEA R&D WIND - ANNEX XI

26th Meeting of Experts
Lightning Protection of Wind Turbines Generator Systems and EMC Problems in the Associated Control Systems

INTRODUCTION

On 8th and 9th of March 1994, an invited group assembled at the Centro Ricerca Elettrica of ENEL in Milan to discuss this topic. The twenty one contributors were drawn from a variety of backgrounds and included those with experience in the study of: lightning protection of power systems, lightning protection of aircraft, wind turbine design and EMC of control systems. This mix led to a most stimulating discussion and a number of useful insights were gained into how the design of wind turbines might be improved. However, it has to be said that no clear consensus emerged on several points and more work is needed and experience obtained before this is likely to be the case.

PRESENTATIONS

The meeting commenced with a welcome by Claudio Casale on behalf of ENEL. Asle Schei opened the technical discussion with an account of the very high frequency of lightning damage which occurs to wind turbines located in the north of Norway. His remark that "most turbines are damaged each year" caused considerable interest. There then followed a lively discussion on both the cause of this frequency of incidents and the measures which might be taken to limit damage.

The next paper, by Eduard Muljadi and Sandy Butterfied of NREL, was a most comprehensive review of the subject area. The early work carried out on lightning protection of large wind turbines in the USA was discussed and brought up to date by a valuable survey of six case studies of operating wind farms. US experience would appear to indicate a much lower frequency of lightning strikes to wind turbines with an associated reduction in the level of protection which is considered to be appropriate.

Goran Dalen of Vattenfall then addressed the problem of the protection of very large wind turbines particularly those which are fitted with instrumentation on the blades for test purposes. It appeared to be the Swedish experience that it was preferable not to fit lightning protection to blades fabricated from non-conducting material although there is still the possibility of strikes to the blades and particular care is required with the use of carbon fibre.

Aage Pederson's paper included a description of damage to a 200 kW wind turbine and came to the conclusion that blades of non-conductive material are exposed to lightning flashes and hence need some form of protection. A Danish research project has commenced to determine how this protection might be provided.

Luigi Pandini of ENEL then described a study to investigate how the electrical and control systems of a wind turbine might be affected by lighting. Practical tests had been carried out on the Gamma 60 nacelle and both the path of the current and the associated magnetic field measured. Emilio Garbagnati presented the first of several papers. This reported tests on the transmission of lightning current through bearings. This paper generated considerable interest and it would appear from the discussion that there was general agreement that lightning will flow through the wind turbine bearings and devices such as brushes and external air-gaps are of very limited value. However damage may be limited if the bearings are adequately preloaded.

Michael Behnke discussed the approach adopted by KENETECH Windpower to evaluate the lightning protection measures appropriate to wind turbines at different sites. It was of interest that, to date, no intentional protection has been fitted to the blades of their wind turbines. An alternative view was then put forward by Roger Baldwin who described the precautions taken in the protection of aircraft against lightning. Aircraft practice is to protect non-conductive surfaces, eg wings, with conducting strip or mesh so that strikes may be conducted without excessive damage. If adequate conductive elements are not introduced on to the surface of wind turbine blades then, in the event of a direct strike, serious damage is likely to occur. However, it remains unclear how the introduction of conducting elements will effect the frequency of direct strikes to the blades.

Emilio Garbagnati then presented a paper dealing with a model to predict the behaviour of lightning strokes. Alberto Pigini presented the results of full scale tests carried out at CESI on a number of wind turbine blades. The particular precautions necessary with the use of carbon fibre were again discussed.

This was followed by a number of informal presentations.
Mr Ruiter recommended that tests were necessary to establish the performance of wind turbines with respect to lightning. Servaas Radamakers described the requirements presently laid down by ECN for the protection of wind turbines against lightning. These are limited to overvoltage protection at the point where the turbine is connected to the electrical network. Poul Thomsen of Vestkraft discussed his experience of operating wind turbines in Denmark. Once the overvoltage protection of the wind farm communication system had been improved there have been no serious incidents although the soil resistivity is low. Aloys Wobben then described how, as the size of the rotors and towers increased, it has become appropriate to fit metallic strips to the blades of the larger wind turbines manufactured by Enercon. This stimulated discussion of the effect of protected blades on television reception but it appears that interference can be reduced to the level of unprotected blades by connecting the blade protection in a loop.

Finally Nicholas Jenkins reported work in progress to establish ways to predict and measure the performance of large wind farm earthing systems on high resistivity ground.

FINAL DISCUSSION

The final discussion followed those of the other sessions in that no clear consensus emerged as to how wind turbines should be protected against the effects of lightning. It would appear that:

- All blades of whatever material will conduct lightning
- Opinions differed as to whether additional conducting paths should be introduced into the blades to conduct the lightning current

- The use of Carbon Fibre Composite materials requires particular care and additional lightning protection
- Lightning current will flow through bearings but damage may be limited by adequate pre-loading.

There was general agreement that, although the fundamental behaviour of lightning was now reasonably well understood, more R&D was required before this knowledge could be applied to protect wind turbines in a cost-effective manner. One project has been initiated in Denmark and it was generally agreed that a further experts meeting in, say, 2 years would be appropriate to review experience gained in that time.

The question of the preparation of standards for the protection of wind turbines against lightning was then raised. Opinion was divided with a significant minority of the meeting considering that the time was right to start work on preparing a standard but with the majority of the view that this was premature as there was no consensus on best practice. A proposal to prepare a document reviewing the present understanding of how lightning effects wind turbines and the options available for their protection received very wide support. Prof Pederson was asked to enquire whether this was an appropriate activity for the IEA to consider.

Finally the meeting thanked ENEL and its staff for their generous hospitality.

N Jenkins
UMIST, Manchester
April 1994

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

Cologno Monzese, 8th-9th March 1994

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IEA R&D WIND - ANNEX XI
TOPICAL EXPERT MEETINGS

1. Seminar on Structural Dynamics, Munich, October 12, 1978
2. Control of LS-WECS and Adaptation of Wind Electricity to the Network, Copenhagen, April 4, 1979
3. Data acquisition and Analysis for LS-WECS, Blowing Rock, North Carolina, September 26 - 27, 1979
4. Rotor Blade Technology with Special Respect to Fatigue Design Problems, Stockholm, April 21 -22, 1980
5. Environmental and Safety Aspects of the Present LS WECS, Munich, September 25 - 26, 1980
6. Reliability and Maintenance Problems of LS WECS, Aalborg, April 29 - 30, 1981
7. Costings for Wind Turbines, Copenhagen, November 18 - 19, 1981
8. Safety Assurance and Quality Control of LS WECS during Assembly, Erection and Acceptance Testing , Stockholm, May 26 - 27, 1982
9. Structural Design Criteria for LS WECS, Greenford, March 7 - 8, 1983
10. Utility and Operational Experiences and Issues from Major Wind Installations, Palo Alto, October 12 - 14, 1983
11. General Environmental Aspects, Munich, May 7 - 9, 1984
12. Aerodynamic Calculational Methods for WECS, Copenhagen, October 29 - 30, 1984
13. Economic Aspects of Wind Turbines, Petten, May 30 - 31, 1985
14. Modelling of Atmospheric Turbulence for Use in WECS Rotor Loading Calculations, Stockholm, December 4 - 5, 1985
15. General Planning and Environmental Issues of LS WECS Installations, Hamburg, December 2, 1987
16. Requirements for Safety Systems for LS WECS, Rome, October 17 - 18, 1988
17. Integrating Wind Turbines into Utility Power Systems, Virginia, April 11 - 12, 1989

18. Noise Generating Mechanisms for Wind Turbines, Petten, November 27 - 28, 1989
19. Wind Turbine Control Systems, Strategy and Problems, London, May 3 - 4, 1990
20. Wind Characteristics of Relevance for Wind Turbine Design, Stockholm, March 7 - 8, 1991
21. Electrical Systems for Wind Turbines with Constant or Variable Speed, Göteborg, October 7 - 8, 1991
22. Effects of Environment on Wind Turbine Safety and Performance, Wilhelmshaven, June 16, 1992
23. Fatigue of Wind Turbines, Golden Co., October 15 - 16, 1992
24. Wind Conditions for Wind Turbine Design, Risø, April 29 - 30, 1993
25. Increased Loads in Wind Power Stations, "Wind Farms", Göteborg, May 3 - 4, 1993
26. Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems, Milan, March 8 - 9, 1994