

**EXPERT GROUP STUDY
ON
RECOMMENDED PRACTICES
FOR WIND TURBINE TESTING
AND EVALUATION**

**9. LIGHTNING PROTECTION FOR
WIND TURBINE INSTALLATIONS**

PREPARATORY INFORMATION

*Submitted to the Executive Committee
of the International Energy Agency Programme
for
Research and Development
on Wind Energy Conversion Systems*

**RECOMMENDED PRACTICES
FOR WIND TURBINE TESTING**

**9. LIGHTNING PROTECTION FOR
WIND TURBINE INSTALLATIONS**

PREPARATORY INFORMATION

1. EDITION 1997

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FOREWORD

The procedures needed for testing and evaluation of Wind Turbines (WT) or Wind Energy Conversion Systems (WECS) must encompass aspects ranging from: energy production, quality of power, reliability, durability and safety as well as cost effectiveness or economics, noise characteristics, impact on environment, electromagnetic interference, lightning protection and electromagnetic compatibility. The development of internationally agreed procedures for testing and evaluation for each of these areas is needed to aid the development of the industry while strengthening confidence in the technology and preventing chaos in the market.

It is the purpose of the proposed Recommended Practices for Wind Turbine Testing and Evaluation to contribute to the development of such internationally approved procedures. The Executive Committee of the IEA Wind Agreement, through Annex XI to this agreement, will pursue this effort by periodically holding meetings of experts, to define and refine consensus procedures in each of the following areas:

1. Power Performance
2. Cost of Energy from WECS
3. Fatigue loads
4. Acoustics
5. Electromagnetic Interference
6. Structural Safety
7. Quality of Power
8. Glossary of Terms
9. Lightning Protection

This document addresses item 9 and - similar to item 5 and 6 - it is presented as preparatory information on the subject of lightning protection. In spite of this limited scope it is felt that the information contained in this paper can be of great value to manufacturers and users of wind turbines and therefore justifies the presentation of the document in this series of Recommended Practices.

The Executive Committee will seek to gain approval of the procedures in each member country through the IEA agreement. The recommendations shall be regularly reviewed, and areas in need of further investigation shall be identified.

august 1997

B.Maribo Pedersen
Operating Agent, annex XI

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1 Introduction

In early wind turbine (windmill) installations lightning was often not considered as a threat, or the nature of the threat was not well understood; however over recent years there have been a large number of lightning strikes reported to wind turbines and in many of these there have been instances of severe damage [Ref 19].

In particular the blades are subject to catastrophic damage, and because of both material and installation costs, any damage to the blades is expensive. A significant other area of damage or disruptions is where lightning affects electrical systems and control circuitry. Statistics show that lightning damage is a major contributor to down-time in the operation of wind farms.

It has to be borne in mind that lightning is a statistical phenomenon, and that probabilities play a large part in lightning protection. The location of the wind plant, and factors such as the ground flash density in that locality, is one of the important parameters which should be taken into account when considering a level of protection.

Even so there is still today, centuries after lightning research began, a great amount still to be learnt about the phenomenon of lightning. With respect to wind turbines knowledge of lightning effects will grow with ongoing research as well as with increasing operator experience.

2 Objectives and Scope

It is the purpose of this document to draw the attention to the threat of lightning to wind turbines and to show how it can affect mechanical hardware (blades, bearings) and the electrical systems (in particular control and data acquisition circuits).

The scope of the documents can be divided into the following:

- The nature or phenomena of the lightning.
- The vulnerable hardware components (mechanical or electrical components).
- Alternative solutions to increase the immunity of the wind turbine components.

The document does not lay down mandatory requirements but tries to give a better understanding of the phenomenon, and help those involved in Wind Turbines define a lightning protection approach which best suits their own requirements. In many cases it would be advisable for professional advice to be taken on lightning protection.

The document references IEC international standards where appropriate, and uses the relevant data given in these documents. The relevant IEC documents are listed as the second part of the reference list [Reference 41-50].

Additional information in this document includes a discussion on lightning effects on relatively tall structures (>60m). This is not covered by current IEC documents, but the matter is under discussion and will be addressed by the IEC in the future.

3 Background on Lightning Attachment Process

The physics of lightning and thunderstorms involves many different mechanisms which are not fully understood.


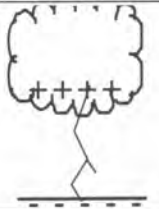
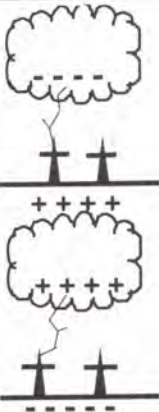
Whilst a detailed discussion of the physics of the generation of charges in clouds is not appropriate here a good description of such mechanisms is given in References (30) and (39). The processes by which lightning itself is formed in the presence of such charged clouds is important. In particular it influences the probabilities of lightning attaching to any particular part of the structure. A brief description is therefore given here.

3.1 STRIKE MECHANISMS

Once the charges have built up to the point at which local electric fields exceed the breakdown strength of the atmosphere then a lightning flash can develop, either between clouds or to a structure on the ground.

There is a sequence of very faint processes which occur in the formation of the lightning path; they determine where the lightning strikes, and also affect the current waveform of strike. These 'leader' processes create a conductive path in a series of jumps. When the path is complete it makes the connection between cloud and ground, then the main return stroke current flows along the channel which has been prepared.

There are various types of flash which can occur, and these are identified below:

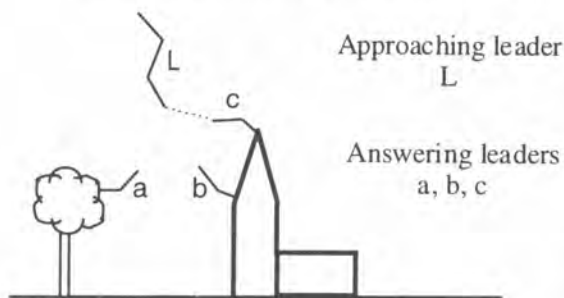
	Type	Note
	1. Negative flash in which leaders propagate from the cloud (Negative cloud to ground flash)	The most common cloud to ground flash representing around 90% of such strikes worldwide
	2. Positive flash in which leader propagates from the cloud (Positive cloud to ground flash)	Represents around 10% of cloud to ground strikes worldwide
	3. Ground to cloud flashes	Not enough data available to differentiate between characteristics of negative and positive flashes. Both types occur, always to tall structures

These flashes have different ways of attaching to structure, and also have different current waveforms, so that damage mechanisms can be a function of the type of flashes. (cf. 3.3)

3.2 CLOUD TO GROUND AND GROUND TO CLOUD FLASHES AND LIGHTNING ATTACHMENT MECHANISMS

3.2.1 Cloud to Ground Flashes

The commonest type of cloud to ground flash overall is the negative cloud to ground flash which forms an average 90% of all strikes. The leader travels from the cloud in quasi-random jumps or steps of 20-100m, and it is only when the leader becomes within this distance from the ground that it sees the influence of structure on the ground and the actual attachment point becomes determined. This is depicted in the figure below.



Cloud to Ground Negative Strike (1)

The answering leaders a, b or c which connects with leader L will become the final part of the path for the return stroke (L→c).

In general it is the conducting point on the ground or grounded structure which is closest to the tip of the approaching leader L, after its last jump, which is likely to become the initial attachment point.

Clearly such a strike does not necessarily take the highest point, although it is more likely to do so.

A similar process occurs for the positive cloud to ground strike, although data is more limited, and for this case the leader steps may be longer.

3.2.2 Ground to Cloud Flashes

The **upward propagating leader** which initiates ground to cloud flashes has a different influence on attachment point locations. The leader propagates upwards from a point on a tall grounded structure, and this point becomes the eventual lightning attachment point.

Because the initiation of such a leader begins where the local electric field is highest then attachment favours extremities of tall structures where the electric field is enhanced.

There is evidence to suggest that frontal storms with low cloud bases are more likely to initiate upward propagating flashes to structures such as wind turbines [Reference 30]. This tends to agree with reported operators experience. Time should provide more information, at present good data is limited.

A wind turbine in excess of 60m total height should therefore be assumed to be an attractive source of upward propagating lightning strikes. It is the uppermost extremities such as tops of towers, masts or blade tips which will take the ground to cloud lightning attachment.

3.3 POSITIVE AND NEGATIVE FLASHES – THEIR RELATIVE OCCURRENCE

Positive flashes have on average a higher peak current, charge and energy than negative flashes, and those flashes which are of very large energy are virtually all positive. Overall it is normally assumed that positive flashes make up 10% and negative 90% of all cloud to ground strikes and the IEC documents follow this assumption. However geographical variations, as well as seasonal and climatic factors, will influence the relative occurrences of positive and negative flashes. The maturity of a given storm is also a significant factor.

These variations show how difficult it is, at our present state of knowledge, to provide absolute protection levels for all types and locations of installation. This is particularly true as wind turbines are often installed on coastal areas, and areas susceptible to frontal storms, aspects which are not well covered by existing measurement data.

4 Lightning Strike Parameters

4.1 INTRODUCTION

The most important data on the currents involved in lightning strikes have been provided by measurements on instrumented ground structures.

These have been carried out in only a few locations; in Europe these have been mostly at or near the Alps [see for example references 2, 3, 5, 10, 12, 14, 25, 29, 38].

It is this type of ground measurement which is used as the basis of the IEC international standard strike levels [References 41-50].

There is now an increasing amount of data also available from lightning location systems. Although these can determine strike polarity and give a statistical analysis of strike severity, operators are still learning how to understand and interpret the data. Their ability to record all strikes, or to give accurate measurements of individual strike parameters is still an area of discussion, but in the future it is expected that they will be a good source of data.

It is difficult for lightning location systems to determine whether the strike is upward or downward propagating, and many ground measurements, particularly those made many years ago, do not provide this data either. This important data is lacking, but will grow with time.

The following sections discuss some of the characteristic parameters of different categories of lightning strikes. These parameters are then discussed further in Section 6.

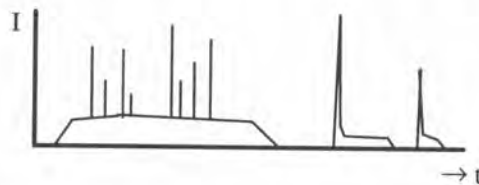
4.2 CHARACTERISTICS OF NEGATIVE CLOUD TO GROUND FLASHES

A typical negative cloud to ground flash, of which 90% of strikes overall consist, is shown in the figure below. The initial high current of the first return stroke is of only tens of μs duration and is sometimes followed by an intermediate current of up to a few kA flowing for some milliseconds (2). There may then be a continuing current of a few hundred amps which can last for as long as 1 second. Then can follow a number of restrikes (4).



4.3 CHARACTERISTICS OF NEGATIVE GROUND TO CLOUD FLASHES

Negative flashes which begin with upward propagating leaders are very common for tall towers, but are not recorded elsewhere. They are frequently recorded for example on the Peissenburg Tower in Bavaria, and here they typically take the form of the waveform shown below [Reference 40]. The typical waveform has a very long low level initial phase with high coulomb content, and superimposed with sharp spikes similar to the multiple burst effects seen during aircraft strike initiation. Following this may be a series of high current amplitude restrikes, the same type as the negative cloud to ground strike, and having similar ranges of parameters.



The parameters of these flashes will be similar to those from downward negative flashes, but the charge transfer levels may be much higher because of the critical continuing current. Such possible high charge transfer should be considered during design of tall structures. These interesting measurements from Peissenburg show the diversity of lightning currents, and continuing investigations on cloud to ground flashes in different locations will help increase understanding on what is clearly a very important effect for large wind turbines.

4.4 CHARACTERISTICS OF POSITIVE FLASHES

Discharges from positive clouds form on average around 10% of all flashes, but the actual figure varies widely and depends on the geographical location and may also depend on structure height.

Measurements show that a positive flash takes the form of one long continuous discharge, with a variety of possible waveforms. A typical waveform is shown below. Positive flashes tend to have a much higher energy content than negative flashes, and some have a very high charge transfer (coulombs). There is little data available on positive ground to cloud flashes.



Positive strikes have only a single strike without any subsequent strokes.

4.5 SUMMARY OF STRIKE PARAMETERS

The summary data below is taken from IEC 1024-1-1 which contains more detailed statistics on the positive and negative cloud to ground flashes. This is followed in Table 3 by a combined data set for both types of flash. Tables 1 and 2 are for information, Table 3 gives values which will be referred to for protection levels.

TABLE 1
Relationship between Parameters and Probability Levels
for Negative Cloud to Ground Flashes

Parameters		Probability Level		
		95%	50%	5%
Peak Current	kA	14	30	90
Long Duration Charge Transfer	C	1.5	7	40
Specific Energy	J/Ω	6×10^3	6×10^4	6×10^5
Maximum di/dt*	kA/μs	4	20	100

Note that ground to cloud negative flashes can have much higher charge transfers similar to the positive flashes below, but that otherwise parameters are similar to ground to cloud negative flashes.

TABLE 2
Relationship between Parameters and Probability Levels
for Positive Cloud to Ground Flashes

Parameters		Probability Level		
		95%	50%	5%
Peak Current	kA	5	35	250
Long Duration Charge Transfer	C	20	80	350
Specific Energy	J/Ω		8×10^5	13×10^6
Maximum di/dt	kA/μs		3	32

In the absence of adequate data, it is assumed that ground to cloud and cloud to ground flashes of the positive polarity have equivalent parameters.

TABLE 3
Relationship of Lightning Current Parameters to Protection Levels

Lightning Parameter		Protection Level		
		I (98%)	II (95%)	III-IV (90%)
Current Peak Value	kA	200	150	100
Total Charge	Q_{total} (C)	300	225	150
Impulse Charge	$Q_{impulse}$ (C)	100	75	50
Specific Energy	W/R(kJ/Ω)	10,000	5,600	2,500
Average Steepness	di/dt30/90% kA/μs	200	150	100

* Value given is for subsequent strokes which have a higher di/dt than the first return stroke.

5 Lightning Damage Mechanisms

5.1 INTRODUCTION

Each lightning flash has the several associated parameters whose magnitude probabilities were listed above. These parameters are important because they contribute to different damage effects. The important parameters are as follows:

	Effects
Peak Current	(Peak) Heating, Shock effects, peak forces
Specific Energy Joules/ Ω	(Total) Heating, Shock effects, forces
Rate of Current Rise $\frac{di}{dt}$	Induced voltages on wiring by magnetic flux coupling, flashovers, shock effects
Long Duration Charge Transfer Coulombs	Damage at arc attachment point or other arc sites in current path (e.g., bearing damage)

The way in which these parameters cause damage is described below.

5.2 PEAK CURRENT AND ACTION INTEGRAL

Where lightning currents are conducted there will be an associated heating effect, and usually a magnetic force on the conductor. These are both primarily dependent on the action integral of the lightning current waveform - its energy content.

The heating effect on a conductor is relatively easy to calculate.

Energy dissipated by the lightning pulse in a conductor of constant resistance R^1 is given by:

$$E = \int i^2 R dt = R \int i^2 dt$$

the parameter $\int i^2 dt$ is known as the specific energy (action integral); it is the parameter of a given strike which can be considered to define its "energy content". It has units of Amp². Second, which is equivalent to J/ Ω . Given that a severe negative strike has parameters of 2×10^6 J/ Ω it is clear that there is a great deal of energy available.

From a combination of calculation and lightning simulation test the following data have been produced [Reference 8]. These data give cross-sectional areas of different materials to carry action integrals of 2.5×10^6 J/ Ω or 1×10^7 J/ Ω for a 200°C temperature rise. The values of action integral are severe values, appropriate approximately to 90% and 98% levels respectively.

¹ In practice materials which are heated by the lightning current have their resistance R increased so that energy dissipated can become even greater if the conductor is too close to the design limit.

TABLE 4

Material	Cross-sectional area in mm ² to carry $2,5 \times 10^6 \text{J}/\Omega$ (90%)	Cross-sectional area in mm ² to carry $1 \times 10^7 \text{J}/\Omega$ (98%)
Copper (HC)	12*	24
Aluminium 99,5% Pure	17*	34
Aluminium (clad) alloy 2014A-TB/L72	21	42
Stainless Steel (Typ)	63	125
Titanium Alloy 2TA10	110	223
Multi-directional PLY CFC*†	600	1185

* These data are based on tests carried out using simulated lightning waveforms. The remaining data are found by calculation from the physical properties of the material.

† These values can vary considerably for different material and construction. For carbon fibre composite particular care must be taken at current entry/exit points.

The cross-section of copper and aluminium required to carry severe levels of action integral is relatively small, and should be easily achieved. However a severe strike might produce damaging heating effects for example in a steel cable, which would be likely to have a cross section well below 100mm². The percentage figure at the top of each column of tables 1 to 3 represents the lightning protection level (i.e., percentage of cloud to ground strikes for which the specific energy is less than this value).

Magnetic Forces

If relatively small conductors are used (e.g., braided bonding straps) a good margin on thickness should be assumed, to provide protection from magnetic forces. These forces can buckle, or even break, conductors which are thick enough to withstand the heating effects.

Magnetic forces can also be formed if two conductors in parallel carry current. If the directions of current are the same, the force on each of the conductor will attract each other. On the other hand, if the direction of the current is the opposite, the force on each conductor will oppose each other. A tight bend especially one which is smaller than 90 degrees may create a similar effect (i.e., the flux induced by one current direction affects the current flowing in the other direction). Thus an impulse force is created on the bent conductor.

Such forces can be great enough to bend conductors, tear them from their fixings or end lugs, and can cause unfixed conductors to whiplash.

To reduce magnetic forces sharp bends in conductors should be avoided, and conductors firmly fixed down. To carry energy levels of $2.5 \times 10^6 \text{J}/\Omega$ (A²s) bonding braids of at least 30mm² cross-section should be used (i.e., >6mm diameter).

Explosive Effect of Enclosed Arcs

Enclosed arcs will generate very large overpressures, an effect which has been clearly responsible for damage to many turbine blades. This appears to occur when the arc develops along the inner surface of the blade, probably penetrating through a drain hole or flaw. The overpressure is related to the action integral of the waveform and possibly also on waveshape, and is sufficiently large to be destructive to a blade.

Resistive Voltages

Induced voltages on wires which are screened, and with the screens bonded at both ends are a function of the peak current of the flash. They are proportional to the current carried by the screen or overbraid during the flash, and are discussed further in Section 10.

5.3 CHARGE TRANSFER

The other significant component of the lightning strike for physical damage is the transferred charge (in coulombs, = $\int Idt$). Most of the charge transferred occurs in the long duration relatively low level lightning currents.

These long duration currents have a similar effect at the arc attachment point as would be expected from an arc welder; where the current from the lightning arc enters a conducting material the surface will melt away and erode. Metal tip components or surface metallisation would be eroded away by the charge transfer of a lightning attachment and in a severe flash several hundred cubic millimetres of metal could be lost at the point of attachment. This is not likely to be a failure mechanism for the blade, simply a cosmetic (or possibly an aerodynamic) problem where a part of the metal has been burned away at the lightning attachment point.

However similar erosion of metal will also take place at any other point in the lightning path where arcs are formed. At the arc sites pitting will occur and if a large proportion of the lightning current flows through these arcs then severe pitting or even welding may occur.

This is a potential problem with bearings, since arcs can occur between bearing surfaces and in the worst-case weld them together. Testing work reported on wind turbine bearings [Reference 9] suggests that although some pitting is to be expected, welding is unlikely, because of the relatively large contact areas in the bearings. Furthermore pre-loaded bearings improve electrical contact across the surfaces, and pitting damage is reduced. There is no reported evidence in service of a bearing seizing up due to lightning.

However any pitting created in the bearings will enhance the wear of the component and reduce service life.

5.4 RATE OF CHANGE OF CURRENT

During the return stroke, and even more so at the beginning of the subsequent strokes, there is a very rapid rate of rise of current. Any rapidly changing currents will induce voltages in nearby wiring, the induced voltage u being given by:

$$u = M_{TF} \frac{di}{dt} \quad (1)$$

where M_{TF} (the mutual transfer function) is a function of the structure, and $\frac{di}{dt}$ is the rate of change of current. (M_{TF} is sometimes considered as being the self inductance of the structure, minus its mutual inductance to the wire under consideration $M_{TF} = L_s - M$.)

This is a particularly important concept for considering induced voltages in wiring, but also determine whether flashover can occur.

Flashover Voltages. When the rapidly lightning changing current flows down part of a structure, the self inductance of the path along which the current flows may be such that the voltage drop down the structure, $u = L_s \frac{di}{dt}$, may be sufficient to cause a flashover to an adjacent path.

Within a blade it is good practise to bond all possible parallel current paths together, and allow them all to carry current. This prevents the possibility of flashover internal to the blade which could be damaging.

6 Determination of Likely Attachment Points to Wind Turbines

The positions of likely lightning attachment points from cloud to ground flashes can be estimated by simplified methods such as the rolling sphere.

The Rolling Sphere as a Predictor of Negative Downward Propagating Strike Attachment Points

As a means of determining possible lightning attachment points for negative downward strikes a methodology known as the "rolling sphere" approach has been developed, and is widely used for ground structure [References 11, 23]. The approach is only valid for structures <60m tall, but its application for higher structures is under consideration, for inclusion in a future IEC document.

The rolling sphere approach is derived from the way in which a stepping lightning leader channel approaches the ground.

If an imaginary sphere of a defined radius is rolled over the structure, then those points which can be touched by the sphere are possible attachment points.

The answering leader distance used as the effective radius of the sphere is related to the protection level, since lower severity strikes tend to have a lower leader step distance. IEC [Reference 42] gives the sphere radius which should be applied for a given protection level. Application of such a rolling sphere to a wind turbine would indicate that most of the blade, the hub, rear of the nacelle, and parts of the tower are possible attachment points.

It is not obvious how to apply the rolling sphere method for glass blades or even tip-protected glass blades. To be on the safe side the whole structure, including glass blades should be included in the model to determine attachments. It is clear though that any external metal work on a blade would be a much more likely attachment point than nearby internal structure which could be reached only by puncture of the GRP.

However if a GRP blade has no local external metallisation, then puncture of the insulating blade skin can occur especially if there is conducting structure internal to the blade which is indicated by the rolling sphere as a likely attachment point. This means that puncture of the protected blade could still occur, but the installation of a tip protection would protect against a large proportion of possible attachments. It is not clear at the moment how the rotation of the blades is likely to influence possible attachment points, therefore it would be advisable to assume a higher risk.

Experience shows that even insulating blade tips are likely attachment points, although whether they are susceptible more to one particular type of strike is not known.

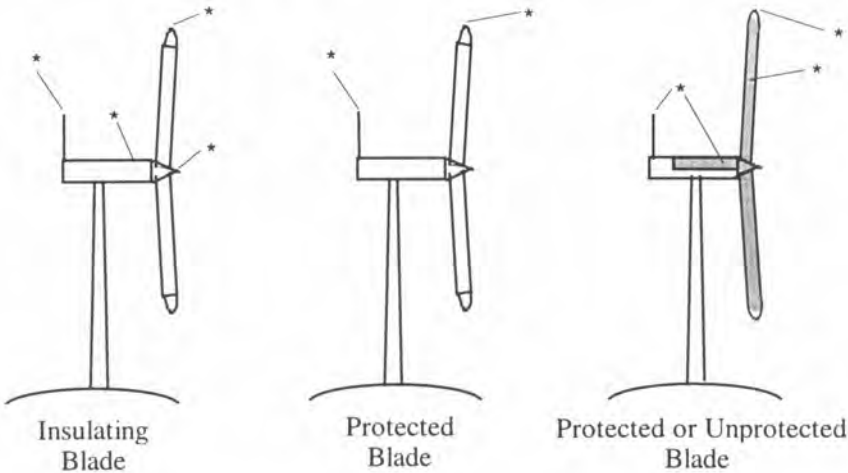
Cloud to ground flashes, typically the relatively common negative cloud to ground strike, are most likely to attach to the tip of the blade. However because of the random downward path of the negative leader there is a reasonable probability of an attachment taking place to the side of the blade, and possibly even puncturing to reach internal conducting structure.

Ground to cloud flashes are formed from extremities, and very strongly favour blade tips and other external points such as nacelle masts. If the blade has lightning protection, even if it is only exposed at the tips, then upward propagating lightning flashes will strongly favour attachment to the tip protection.

There is a good argument therefore for considering the lightning protection methodology of the wind turbine structure as follows.

- (1) The tip should incorporate exposed metal at or near to the tip, which is adequately bonded back to ground. This part of the structure should be protected to at least IEC Level II. Exposed conducting structure on the rest of the blade should be protected against at least IEC Level III. However often Level I protection can be achieved without significant further effort, and if there are safety implications for nearby personnel this may be necessary anyway.
- (2) As well as the blade, the nacelle, hub and tower are also susceptible to initial attachment. These do not present many extra problems since attachments to the blades themselves will drive current through these areas. However the nacelle may need to be protected in order to provide protection to any personnel inside. It may also be an advantage to protect the nacelle to help to keep induced voltages inside to an acceptable level, although there are other ways in which induced voltages can be reduced. If the blades are protected then they will be more attractive lightning attachment points and will provide protection for the nacelle. Even so a rear mounted mast should also be used to protect the nacelle from lightning attachments, and for nacelles of insulating material it is recommended that a catenary is installed for the protection of personnel working inside (i.e., a mast forward and aft with a wire hanging between). Each end of the catenary should be well bonded back to structure.

The diagram below shows the most likely attachment points for ground to cloud flashes (Sketches 1, 2). The rolling sphere approach for cloud to ground flashes would indicate additional possible attachment points on the faces of the blades (third sketch).



Ground to Cloud Flashes (1 and 2)

Cloud to Ground Flashes (3)

Possible attachment areas are shaded or marked -*.

7 Expected Frequency of Direct Lightning Flashes to a Structure

IEC 1024-1-1 discusses how the average annual frequency of cloud to ground flashes striking structures can be estimated. At the present time this approach is only to be considered valid for structures up to 60m tall, although considerations for taller structures are being discussed. For structures <60m tall the following formula gives the annual strike rate as:

$$N_d = N_g \cdot A_e \cdot 10^{-6} \text{ per year (for } h < 60\text{m)}$$

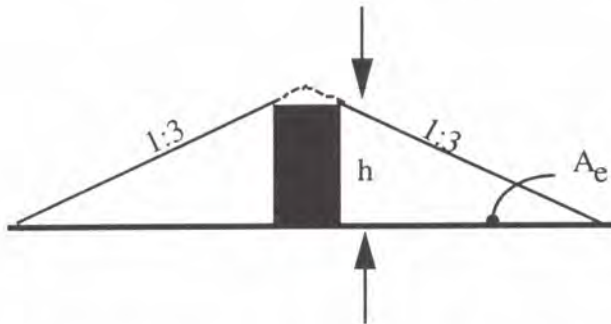
in which,

N_g is the average annual ground flash density, in lightning flashes per square kilometre per year, concerning the region where the structure is located. (The approximate figure for specific locations should be available from local standards, or from lightning mapping organisations.)

A_e is the equivalent collection area of a structure (m^2).

The equivalent collection area of a structure is defined as an area of ground surface which has the same annual frequency of direct lightning flashes as the structure.

For isolated structures the equivalent collection area A_e is the area enclosed within the border line obtained from the intersection between the ground surface and a straight line with 1:3 slope which passes from the upper parts of the structure (touching it there) and rotating around it.



Assuming a 50m tall structure which is isolated on relatively flat ground this yields an effective collection area of $A_e = \pi r^2 = \pi (50 \times 3)^2 \cong 0.07\text{km}^2$.

For complex topography or overlapping collection areas refer to IEC 1024-1-1.

For a protected blade the height which should be assumed in the calculation is the maximum tip to ground distance; for unprotected blades the effective height is somewhere between this value and the nacelle to ground distance.

Limitation of Calculation

The calculation is specifically aimed at structures less than 60m tall. It is believed that in some locations strike rates are significantly higher than those calculated in this way because the turbine may itself trigger a lightning attachment.

For structures greater than 60m high these strike rate figures should therefore be considered too low at this time.

There are also more sophisticated methods available for calculating lightning strike frequency, but with the limitations of available data on structures such as wind turbines they should all be used with caution.

8 Appropriate Protection Levels for Wind Turbine Structures

The manufacturer of wind turbine blades and wind turbine installation will ask, "against what level of the above lightning parameters must components be designed". The strike rate expected may be a factor in this.

The answer often lies with the manufacturers, as the level of lightning protection installed can be a selling advantage. However once the effort has been made to give the blades some lightning protection, it is often not at all difficult to ensure protection against severe lightning parameters.

The level of protection would normally be identified on a cost-benefit basis, but it would be wise, where protection is cheaply and easily provided, to protect to the highest level (for example in including in the blade sufficient cross-section of conducting materials to carry high levels of current) This is important for components such as blades where repair or replacement is expensive and a long lifetime is expected.

In some locations, safety to nearby personnel or livestock will need to be taken into account, especially with regard to the possibility of debris being ejected from a damaged blade..

It is recommended therefore that for structures such as blades which are critical to the operation of the turbine and expensive to repair, or in areas where there are safety implications, then design and testing should be carried out to at least level III and preferably level II. Otherwise the manufacturer should be free to choose his own protection levels, and may well wish to protect to level I if this can be easily achieved, or if there are special safety considerations..

TABLE 5
Relationship of Lightning Current Parameters to Protection Levels

Lightning Parameter		Protection Level		
		I	II	III-IV
Current Peak Value	$I/(kA)$	200	150	100
Total Charge	$Q_{total} (C)$	300	225	150
Impulse Charge	$Q_{impulse} (C)$	100	75	50
Specific Energy	$W/R(kJ/\Omega)$	10,000	5,600	2,500
Average Steepness	$di/dt_{30/90\%} kA/\mu s$	200	150	100

Because of the nature of ground to cloud strikes, a long duration charge transfer at up to 500C should be considered for extremities of the installation.

9 How to Achieve Protection against Physical Damage

The structure has to be protected from:

- Arc damage or high current density damage at the attachment point.
- Damage from current flowing through the structure either conducted, or as an enclosed arc.

In principle protection can be achieved in three ways, if there is a structure which is potentially vulnerable.

- (1) Provide another larger conducting structure which itself attracts the lightning strikes and provides an area of protection for the vulnerable component. In practice this protection approach can help the nacelle for example, if the blades are protected. To protect the blades themselves would normally require an adjacent structure which is so high as to be impracticable.
- (2) Ensure that materials which are likely to be lightning attachment points will not be damaged by such attachments at the site of the arc root.
- (3) Provide a conducting path to carry all of the current safely to ground; or if there is resistive structure such as carbon-fibre in the blade which could be damaged, to provide a parallel conducting path. If the vulnerable component has an alternative conductive path provided in this way then energy dissipated in it will be much reduced. More specific requirements are made below.

9.1 BLADES

9.1.1 Attachment Points in Relation to Type of Structure

Factors of blade construction which influence the location of a lightning attachment point and the consequent damage are:

- all GRP
- GRP with external lightning protection such as mesh
- GRP with blade tip/internal metalwork
- GRP with internal carbon spars
- wood epoxy
- presence of moisture

9.1.2 All GRP Blades and Wood/GRP Blades

Many blades currently in use have no internal conducting structure, but are exclusively GRP (fibreglass) or GRP-wood. Experience with unprotected GRP blades in service is that they do suffer lightning strikes at a disturbing rate, and that such strikes are generally catastrophic, causing blade destruction. In these instances the arc is generated on the inside of the blade, and the shock/explosive overpressures associated with the high energy components of the lightning strike result in the damage. The lightning arc is often found to puncture through to the centre of the blade by formation of an arc channel through drain holes at or near to the blade tip, or through cavities, flaws etc. It is probable that the presence of moisture and dirt in the blades or in cavities can assist the formation of a current path. The explosive vaporisation of moisture will contribute to the pressure increase and damage to the blade.

It is probable that many unobserved strikes flashover on the outside of the blade (rather than inside) and result in no significant damage.

9.1.3 Hybrid Blades GRP (Wood) with some Conductive Material

Composite blades often incorporate conducting materials, typically for example:

- (1) Control wires for tip-stall mechanisms.
- (2) Carbon stiffeners and spars.
- (3) Lightning protection installations.

Note that lightning is attracted to carbon as much as to metal [Reference 8] even though it is much more electrically resistive. This can lead to severe problems with glass blades which have internal carbon spars, as puncture of the blade glass skin is then likely to occur.

The presence of any electrically conducting structure changes the way in which lightning affects the blade, particularly if the conducting material is grounded to the hub of the blade (which is the preferred situation).

Firstly the lightning strike rate to such blades would be expected to be higher than to an insulating blade described above. However that should present no problems so long as:

- (1) No significant damage is created by local arc heating at the attachment point (arc entry).
- (2) The current can be safely conducted to ground through the conducting structure. The conducting structure should have adequate strength and cross-sectional area, and this can be determined from the data in Section 4.2.

9.1.4 Carbon Skinned Blades

Carbon skinned blades will be as attractive to lightning as metallic blades, and will sustain delamination and erosion of the material within several centimetres of the lightning attachment. Protection in the form of metallic mesh will reduce the damage considerably, but would need to cover the whole of the carbon skin.

Blades of any construction are known now to be likely attachment points. They can be protected by installing external surface metallisation, an external conductor, or an internal conductor, so long as the cross-section of metal is sufficient to carry the current. External surface metallisation can be in the form of a mesh or expanded foil. Some local damage to this surface would be caused by a lightning strike, but would not be likely to affect the strength or structure of the blade.

Conductors or surface metallisation are best terminated in a substantial metallic tip-cap.

This area is a subject of commercial interest. Careful design is needed to produce a lightning protection that is good enough, but does not pose aerodynamic and noise requirements (or in some installations RF interference).

9.2 BEARINGS

Most of the current flowing from a strike to the blades will normally be conducted into the tower through the slow-speed shaft bearing. This is preferable to being conducted along the shaft towards the generator part of the wind turbine.

Lightning currents conducted through bearings generally cause some pitting damage. However because of the size of the bearings the current density is low and lightning damage is not sufficient to cause immediate operating problems. Lightning damage could result in noise and vibration and an increase in mechanical friction loss, and the wear life of the bearings would be reduced.

It has been found in testing that damage is less if the bearings have an applied pre-load, since this improves electrical contact [Reference 9].

Normal practise is therefore to use preloaded bearings and accept that there will be some level of lightning damage, but at a low level.

It is very difficult to overcome the potential problem of bearing damage since:

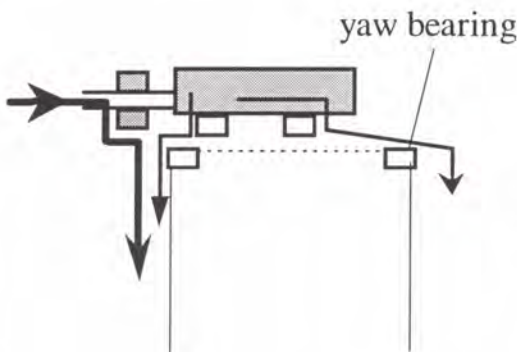
- (1) bonding straps in parallel with the bearing are usually not effective, nor are sliding contacts (slip rings). They would take only a proportion of the lightning current, the bearing would still carry most of it.
- (2) Often the bearing is to be encouraged as a current path as it effectively transfers current off the drive shaft and into the tower, so helping to protect the generator and its control systems.

Some bearings have insulating layers which prevent current from easily conducting through the bearing. However a flashover across this insulation is likely to occur anyway during a lightning strike, unless a parallel low inductance path across the bearing is provided such as via sliding contacts.

It is possible to use a scheme to allow current to bypass the bearing, by incorporating insulating layers in the bearing, and making current conduction off the shaft via sliding contacts or via narrow gaps (spark gaps). However these plans should be made with thoughts as to the overall lightning protection, since the bearing does provide a good grounding route for current off the blade, as in (2) above.

Similar considerations should be made to yaw bearing; generally the yaw bearing will provide a good conducting path across its full circumference. If it does not conduct for some reason of design, then a path must be provided.

It is recommended that bearings are inspected for damage following a known strike to the wind turbine.



Normal current flow through bonded bearings. Wire routing and shielding need to be thought of carefully.

9.3 NACELLE

The nacelle has importance in more than one way.

- (1) It should provide physical protection for personnel and equipment in the nacelle region from a direct lightning attachment.
- (2) It can provide protection to electrical circuits within the nacelle from induced voltage transients during a lightning strike.

To provide (2) the electrical shielding, the nacelle would be constructed of an electrically conducting material, and well bonded to adjacent structure. Necessary properties for the nacelle are described below.

9.3.1 Nacelle of Insulating Material

Some protection from a direct attachment is provided by the blades themselves if they have lightning protection. Even so a further lightning rod extending at least 2m above the rear of the nacelle should be fitted, and carefully bonded to the bed plate. If blades are unprotected then such a rod should be fitted at the forward and rear end of the nacelle with a catenary wire between.

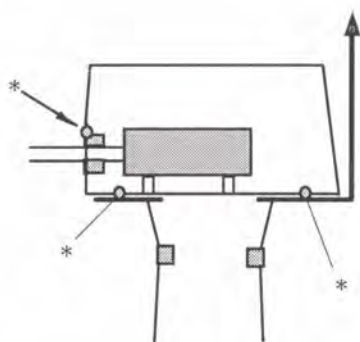
Wiring within a nacelle constructed of non-conducting material is exposed in such a case and care should be made in wire routing and in shielding to provide adequate protection from induced voltages. Control circuits and sensitive wiring should preferably be run in shields with the shields well bonded back to equipment boxes at each end. Wiring should be run as close to metal structure as possible, avoiding loops, which can be the source of induced voltages/currents as described in Section 10.

In particular wiring from the anemometer, if fixed to the mast (lightning rod) should be shielded or in a pipe, and run close to the lightning tape from the rod right up to the bed plate.

Additional personnel protection and some degree of electrical shielding can be provided by routing metallic strip(s) over the surface of the nacelle and connecting to structure around the nacelle base. This is a cheap and effective means of protection. This strip protection, or additional protection such as second lightning rod near the forward end of the nacelle, would be necessary if insulating blades are installed, as such blades could not be guaranteed to capture strikes themselves.

9.3.2 Nacelle of Conducting Material

By bonding a metallic nacelle to the slow speed bearing and to the generator base plate then excellent shielding of the electronics can be provided as well as protection for personnel inside. The fixings which provide the electrical bonding should be as short as possible and at least at four points around the base of the nacelle as well as at the slow speed bearing.



Metallic Nacelle

* = typical fixing points acting as electrical bonds between the nacelle and other structure.

Nacelles of non-conducting structure can be made virtually as effective as metallic ones by incorporating a woven or expanded mesh into the surface. However the bonding of such mesh to adjacent metallic structure such as the bearing is not so easy to achieve as it would be for an all-metal nacelle.

9.4 RETROFIT PROTECTION

9.4.1 Blades

Presently it is difficult to provide retrofit lightning protection to wind turbine blades with the blades remaining installed. A means of protecting a blade would usually involve installing a metallic conductor of adequate cross-section, as external mesh or strip (ribbon) or internal structure. Such installations would be likely to need the blade to be removed. Alternatively an external thin conductive strip may well be a cost effective limiter of damage, with a one strike capability. Unfortunately wind/rain erosion is likely to be a source of damage to such strips.

9.4.2 Other Components on the Turbine

If a particular type of installation is shown to be susceptible to other lightning induced problems, such as control failures, then retrofit changes may be made to improve lightning protection. These could be relatively simple, such as changes to bonding or wire routing, addition of shielding or use of carefully selected protection devices.

10 Protection against Induced Voltage Effects and Damage to Electronics

History of lightning strikes to wind turbines has indicated that control disruption or damage to electronics does occur frequently. Although the component damage may not be as expensive as when a blade is destroyed, cost of downtime can be significant, particularly as several turbines can be affected by a single strike.

Guidelines for protecting structures against lightning induced effects are given in many EMC handbooks. Installation guidelines are also given in the IEC documents [References 41-50], and some of the additional references (e.g., 16, 18, 20, 37).

However wind turbines have features common to all installations so the general guidelines in such documents can be focused to help the wind turbine manufacturer directly.

10.1 SOURCES OF VOLTAGES WHICH CAN DAMAGE WIND TURBINE CONTROL SYSTEMS

Voltage surges can be caused by direct strikes (to the wind turbine) or indirect strikes (to external power systems, to a nearby turbine, or to nearby ground).

The second two points are covered briefly here; most of the following discussion in 10.2 onwards refers to direct strikes.

A nearby strike will produce transients on incoming signal, telephone and power lines. The magnitude of the transients can be several tens of kV. If it was another turbine on the site which was struck then incoming transients can be at least of this order, but will partly be determined by how good the earth is at the other tower which was struck. It is strongly recommended that fibre optics be used for signal lines routed between towers and routed to actual control centre, as it is these wires which are the most sensitive. Telephone lines should be protected by gas discharge tubes (GDT) at the point where they enter the building, and ensuring a good low inductance ground path for the GDT. Transients which are injected along power lines may damage control circuitry, and so mains surge protection should also be employed. However adequate protection for a strike to the tower itself (which is the worst case) should cover the possibility of indirect strikes.

Although bonding and earth resistances are important and often specified, they are not the most important source of voltages induced by lightning.

For lightning current flow from the blade to the foot of the tower, induced voltages in turbine wiring will be mostly generated by the magnetic flux (field) of the lightning current. These voltages are a function of the geometry of the available current paths and exactly how the wiring is routed with respect to the current carrying structure.

For wiring which leaves the foot of the towers, and routes either to nearby cabins, or to the next turbine, the resistances of ground bondings are clearly more important. However the inductance still plays a part, and the more parallel current paths to ground which are available the better.

Direct current injection is a separate case and is considered first.

10.2 DIRECT INJECTION

The case where a lightning attaches to an electrical component and injects current directly into actual wiring itself, is a serious and distinct case and would of course cause considerable damage. A system should be designed and installed so that direct injection is not possible, in other words so that lightning cannot directly attach to a sensor or to wiring which is part of the overall system. Protection from this is normally fairly easily achieved by suitable location of wiring, and by the use of lightning divertor rods such as the air terminal.

In other words devices such as anemometers should be protected by having a mast next to it and at least 1m taller. This will act as the air terminal and take the strike preferentially. Wiring from the anemometer should be routed carefully along metallic structure and shielded.

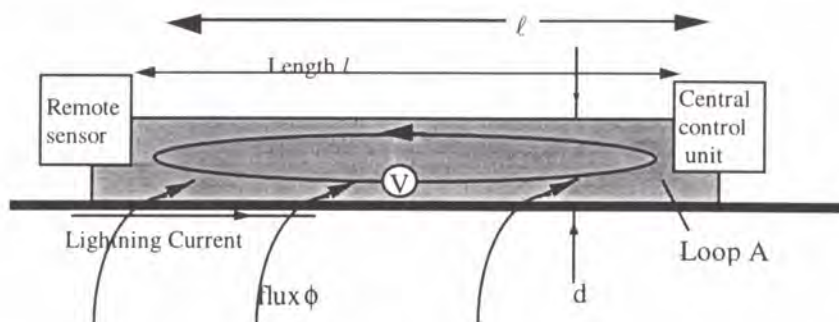
10.3 MAGNETIC FLUX COUPLING (INDUCTIVE COUPLING)

Lightning strikes produce rapidly changing magnetic fields. For wiring in areas such as the

nacelle, or running down non-metallic turbine towers these magnetic fields can generate large voltages in wiring. Such voltages may damage electronic equipment, and if they are large enough may breakdown components such as generators, possibly damaging wiring or insulation. Such damage can initially be latent and result in failure at a later date.

A brief description of this mechanism is given here.

The lightning current flowing down a structure creates a magnetic field, which can generate an induced voltage in wiring loops.



Changing magnetic flux arising from the lightning currents generates a voltage stressing the loop A

As a means of estimating the induced voltage V in the loop for wiring near to a surface carrying current the following approach can be used. Refer to the figure above. Then the voltage induced in the loop A above, of dimensions d (distance from wire to surface) and (length of wire route) is:

$$V = \frac{d\phi}{dt} \text{ where } \phi = \mu HA$$

So for a given strike, the voltage V is proportional to d and l , and it is also proportional to the derivative of the lightning current. A detailed discussion of the mechanism, and how it can be calculated is not given here, but typically found in EMC handbooks. Note the important points; that induced voltages generally can be reduced by:

- (1) Keeping small route wires as close as possible to current carrying structure.
- (2) Minimise the current level along the surface by providing many parallel current paths. Route wiring near to a good conductor whose current density is low because of its position.

However note that where wiring routes across interfaces, where there are few current paths and high currents (such as from generator to structure, where current density is high in perhaps three or four bonding straps), then voltages induced in wiring crossing these gaps can be relatively very high. Depending on exactly how the wires are routed voltages can vary from say tens of volts to a few kV.

Sensitive wiring here should be ideally routed in raceways bonded at both ends when routed from structures such as generators or gearboxes which could carry significant lightning currents. This means that shields should be referenced to the bed plane at the top of the tower and any control installations at the bottom.

Therefore to obtain maximum protection, wiring should be routed as close as possible to metallic structure. For metallic towers the shielding anywhere inside would be excellent; current tends to flow on the outside of the tower so the current density inside is small. The routing of wires close to metallic structure becomes more important in areas such as the nacelle, and the hub.

Screening of Wires

Where wires are screened and bonded at both ends then the voltage drives a current along the screen. The inner wires see a much reduced voltage given by $V_I = IRT$, where I is the current along the screen and RT is its transfer impedance (effectively the DC resistance of the screen). If the lightning current flowing down a screen can be estimated then so too can the voltage on the wires using this formula. A screen will have a resistance usually between 5 and 50m/ Ω depending on type.

Note that wire screening is only effective for lightning protection if screens are bonded at both ends.

Screening of cables in this way provides very good reduction of maximum induced voltage, typically be a factor of 20-100.

11 Protection of Electrical Components by Suppression Devices

Lightning protection measures can be reinforced by the use of transient suppression devices, particularly those incorporating gas discharge tubes and MOVs (Metal Oxide Varistors); such devices widely available commercially. Care should be taken in choosing and installing such devices considering the likely threat.

IEC 1312-1 [Reference 1] specifies the threats for complex installations, in terms of topological zones, so that at zone interfaces systems are referenced to the earthing system directly or via such protection devices. A wind generator is a simpler system to consider and more specific recommendations can be made. Even so the induced transients, and the application of appropriate suppressors will be specific to the type of installation (due to location of sensors, routing of wiring, etc.) Ideally suppression devices should be chosen after considering the feature of the installation and it is recommended that an authority on protection from lightning induced effects be involved in this process.

The incoming and outgoing services from remote locations are clearly necessary to be protected following the recommendations given in 1312-1. Thereafter the degree of protection is to some extent installation dependent. Areas where induced voltages can be expected to be generated are:

- (1) In the nacelle and across the yaw bearing.
- (2) In ground cables to the nearby cabin. Electrical control equipment on either side of such areas may have to be protected and suppressors installed at the equipment itself.

Sensors on the generator and in the gondola will often be by their function electrically isolated from their housing (e.g., microswitches, speed measuring devices). As long as the induced vol-

tages are not sufficient to break down this isolation, then arrestors locally to ground should not generally be used. The exception is if the spark breakdown could cause damage, in which case the arrester should operate just below this expected breakdown voltage. Equipment should be bonded to ground by as short a path as possible, otherwise function of suppressors is reduced.

Power cables running between the nacelle and the nearby power plant normally connect to transformers, which are designed to work at voltages of a few kV, so that these parts of the installation are better protected. Surge protection installed here should not be designed to operate at too low a level, but should protect at significantly below the voltage of which damage to transformer/generator insulation could occur. The armouring on the power cables can be used to assist in shielding if the armour is bonded to ground at each end.

12 Earthing/Grounding

12.1 INTRODUCTION

There are well accepted practices for grounding installations such as towers, and the use of interconnecting ring earth electrodes is widespread [e.g., References 7, 18]. Such electrodes reduce the hazardous step voltage on the adjacent ground, and also assist in reducing injection of current into power and instrumentation cables.

12.2 GROUND (ELECTRODE) ROD AND GROUND RESISTANCE

The grounding rod must be sized according to the appropriate length. Typical electrode resistance of a grounding rod of 3m length and 0.016mm diameter are listed below:

Distance from Electrode Surface in m	Approximate percentage of total resistance (* refer to IEA Meeting 1994)
0.03	25%
0.06	38%
0.09	46%
0.15	52%
0.30	68%
3.00	94%
7.60	100%

From the above table, it is shown that the ground resistance within 0.15m radius from the ground electrode comprise of more than 50% of the total resistance within 7.6m radius from the ground rod. Thus if the ground is highly resistive, and there is lightning current injected to the ground, the step voltage and the touch voltage can be very high because more than 50% of the voltage drop on the ground fall within 0.15m radius.

Receptivity of the soil is also affected by the type of soil. For example using a single rod of the same size mentioned above, the ground resistance may vary between 2 ohms for salt marsh to 1516 ohms for gravel or sand. The resistivity of the ground are affected also by the moisture content and temperature of the soil. The more moisture and the higher the temperature of the soil, the lower the ground resistance will be.

Grounding resistance can be improved by installing multiple grounding rods or grounding grids to provide parallel paths to the ground. Some chemical treatment can also be done periodically to ground to improve the grounding condition.

13 Test Methods for Lightning Protection

13.1 HIGH VOLTAGE TESTING

Such testing is normally carried out in a dedicated high voltage laboratory, producing arcs which are long but have very little energy content. For structures such as wind turbines which are very large compared with any laboratory generated test arcs, it is not possible to make full scale tests which are representative, and care has to be taken with such tests if they are to have any meaning.

The tests can be used for example to determine whether a lightning attachment will flashover the external surface of a component such as a fibreglass blade, or puncture through the skin to internal conducting material (this may include moisture). This allows weak points in the blade construction and insulation system to be identified.

However high voltage testing simply provides helpful information, not an absolute test for a large structure such as a blade. The full scale of lightning attachments, in which the final jump of the connecting leader is some tens of metres, cannot be reproduced in a test which has arc lengths of a few metres at most. Such tests must be designed with care, and the results interpreted with care.

13.2 HIGH CURRENT TESTING

If:

- (1) The current from a lightning attachment can take a path whose ability to carry the levels current is in doubt, or
- (2) There is concern about the extent of arc root damage which can occur at the lightning attachment itself, then high current lightning testing may be appropriate, and there are a number of laboratories which offer this service.

The typical testing methods are well defined [e.g., Reference 13] although because of the environment on the ground some of the test levels being suggested here for wind turbines are more severe than for aerospace applications.

To answer the doubts raised in (1) or (2) above the high current test can be either a conduction test in which the test current waveform is injected along the current route under test, or an arc attachment test in which the current is injected via a short arc a few centimetres along onto a conducting surface of the test sample. In the second test type the current must flow from the attachment point through the conducting structure to the point at which it is extracted from the test sample, so an arc attachment test will also act as a conduction test for adjacent structure.

Test houses would advise on the most appropriate way of performing such tests.

The applied current waveform during such a high current test is usually composite; consisting of more than one component. This usually means that there are two separate current waveforms from different capacitor banks which are applied sequentially within a fraction of a second. In some cases only one component may be applied, if the expected damage effects arise from only one specific current component. The most significant components are given in Section 6.

13.3 EQUIPMENT TESTING

Individual equipment can be tested by injecting transient pulses, to see whether damage can result. As for other test methods, equipment testing approaches are well defined for aerospace, for example in Reference 13 as well as in some IEC documents IEC-1000-*

A particularly useful test for many electrical/electronic components would be an insulation strength test, between the components wiring and its casing. A component whose wiring is insulated from the grounded casing, such as generator or transformer windings, is effectively protected against lightning transients since there is no direct connection to ground along which high energy transients can be injected. That is, unless the transient voltage is high enough to breakdown the insulation. In this case not only will current be directly injected into the wiring, but the insulation breakdown will result in permanent degradation of the insulation. Therefore a knowledge of the breakdown voltage allows:

- (1) Analysis of the installation, and if necessary an improvement of the wiring routing and shielding to reduce the predicted induced voltage levels to below that of breakdown.
- (2) Choice of suppression devices which switch at a voltage just below breakdown preventing damage by breakdown, but also minimising the occasions of direct transient injection into the wiring.

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