LIGHTNING PROTECTION OF WIND TURBINES

Contract JOR3-CT95-0052

PUBLISHABLE FINAL REPORT

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III

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1. Partnership

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2. Objectives

As wind turbine increase in size the effects of lightning are becoming more significant. The higher structures, up to 90-110m, are more susceptible to lightning while the cost of replacing damaged components on site significantly increases with turbine size. With the continued introduction of wind farms into the EU the yearly cost of turbine damage will increase unless design and installation practice improves. Failure to address adequately the issue of lightning damage, and consequent hazard, will also have an adverse effect on public confidence in wind energy.

At present there is no clear guidance to best practice for the protection of wind turbines and manufacturers have adopted different policies. The main objective of this project was the production of a Guide to Best Practice in Protection of Wind Turbines against Lightning. By making this widely available to the European wind energy industry it is intended that lightning protection practice will improve and the effects of lightning strikes reduced. It is hoped that the information will be of a practical nature and that the guidance to the designers and operators of wind turbines will help them minimise the effects of lightning strikes in a cost effective way.

3. Technical Description

The project consisted of a number of phases.

- **Collation of recorded strike data by questionnaire and document survey:** This project phase identified particular areas where research effort could be concentrated during the project.

- **Estimation of the risk posed to a wind turbine by lightning**: The risk of an individual wind turbine being damaged by lightning varies according to a number of factors. The local lightning strike density, the average strength of the local lightning strikes and the design of the wind turbine lightning protection system are examples of these. This project phase assessed the risk posed to a wind turbine by lightning.

- **High voltage and high current testing of wind turbine blades:** The vulnerability of different blade designs and possible means of protection were investigated. This project phase was aimed at providing guidance relating to blade lightning protection techniques.

- **High current testing of bearings:** If a wind turbine blade is struck by lightning, the resulting lightning current will inevitably flow through the main bearing and any pitch bearing that may be fitted. It was not clear whether these bearings could be damaged by lightning current and this project phase was used to test wind turbine bearings with high current to investigate this issue.

- **Determination and examination of probable current path:** The guidelines of existing good lightning protection practice have been reviewed for their relevance to wind turbines and wind farms. Case studies have been made of existing wind turbine nacelle and tower designs to demonstrate the likely distribution of severe strike current and the consequent effects in generating induced voltages in wiring.

- **Personnel protection:** With the possibility always existing of windfarm personnel being on a windfarm during a lightning storm an analysis of the possible hazards was carried out. The scale of the hazard and means of maintaining the safety of operators on wind farm sites were specific areas of investigation.

- **Windfarm earthing:** The response of wind farm earthing systems to lightning current was investigated using computer simulation. This work was intended to provide a better understanding of the performance of a large earthing system to an injection of current with high frequency components.

- **Production of a designers best practice guide:** The guide, incorporating results from all the other project phases, aims to assist designers to assess the risk from lightning arising from their design, manufacture and siting of their turbines and guide them in the provision of appropriate protection measures.

4. Results and conclusions

All the results detailed below are owned by the whole consortium. The main contractor in the consortium was Aerolaminates Limited (AL).

4.1 Phase One - Collation of recorded strike data by questionnaire and document survey

A lightning strike may damage a wind turbine by striking it directly or by producing magnetic and electric fields that induce voltages in local wiring. Recorded incidents of lightning damage suggest that the wind turbine control system is the most vulnerable component contained in a wind turbine although damage to the blades results in the highest repair costs.

This information was produced using datasets from Denmark and Germany that contained over 14000 turbine years worth of information from 3000 wind turbines. The research showed that approximately 6% of wind turbines in Denmark and Germany could expect to be damaged annually by lightning between the period 1992 and 1997. The average hub height of these wind turbines was approximately 30m. In Germany only 30% of the damage could be positively attributed to a lightning strike hitting the affected turbine directly.

The data obtained from the analysis of the large datasets appears to correlate well with responses to questionnaires also circulated as part of the project. The main conclusion of this project phase was that the protection of wind turbine electronic systems from indirect effects is of equal importance to, if not greater than, the protection against direct effects.

4.2 Phase Two - Estimation of the risk posed to a wind turbine by lightning

This project phase examined the risk posed to a wind turbine by lightning. This risk varies as a function of turbine height, type and location.

As turbines increase in height a natural assumption to make would be that they will be struck by lightning with an increased rate and this is indeed true. What is not usually accounted for however is the potential for the development of upward propagating lightning from the top of the wind turbine during thundery conditions. This type of lightning only affects tall structures or those situated on high ground. A modern wind turbine often meets both these criteria.

The type of wind turbine, more accurately the type of lightning protection system installed on it, will also be important in determining the risk posed to it by lightning. If adequate lightning protection from both direct and indirect effects is not installed into the machine it will be damaged with a higher frequency than corresponding protected machines.

Finally, turbine location is also important in determining the risk posed by lightning. The threat of upward propagating lightning in areas of high altitude has already been described. In addition, lightning types and strengths also vary around the world. Certain areas of North-West Europe for example will suffer many positive downward propagating lightning strikes that can be of relatively high peak current and energy. The frequency of lightning, or ground flash density, also varies according to geographical location. Example maps have been provided in the Designers Guide described in section 4.8.

It is important to be able to estimate the lightning strike frequency to a wind turbine to ensure the provision of an adequate lightning protection system according to the national standards. The lightning strike frequency estimation models that are commonly used for buildings and tall masts can be applied to a wind turbine with only minor modifications. When protecting a wind turbine against lightning damage attention should be paid to the points vulnerable to lightning attachment. One commonly overlooked area is the meteorological instrument support at the rear of the turbine nacelle.

4.3 Phase Three - High voltage and high current testing of wind turbine blades

During Phase Three of the project a large number of tests using high current or high voltage were carried out to pieces of wind turbine blade and pieces of the carbon fibre shaft often used in the tip-brake mechanisms. The high voltage tests were designed to simulate the attachment of lightning to a blade or a blade lightning protection system while the high current tests could cause physical damage to an object with the use of high energy waveforms.

The tests showed that lightning protection should be fitted on blades because they are vulnerable to serious damage even if carrying no conductive material. The drain hole was a primary attachment point during the high voltage tests and allowed arcs to propagate within the blade structure. Internal lightning conductors emerging at or very close to the tip are generally effective and offer a practical way of protection with perhaps less problems than external conductors (the exception may be CFRP blades).

If no lightning protection system is installed on a blade or a blade lightning protection system fails to successfully intercept a lightning strike, resulting damage appears to be the primarily caused by the high pressure shockwave produced by the internal arc. As such the response of the blade is very dependent on particular structural details such as joint strength

Tests to a blade fitted with a tip-brake mechanism highlighted the need to bond all metallic parts of this system to the lightning protection system. The high voltage tests showed that pieces of metal floating electrically, such as those contained in locating pins placed to ensure the tip brake mechanism is seated properly when closed, where vulnerable to lightning attachment. Once these had become the attachment point an internal arc would be produced between the floating metal and the earthed lightning protection system.

Protection of the carbon fibre shaft used in the tip-brake mechanism with copper mesh was shown to be ineffective.

4.4 Phase Four - High current testing of bearings

If a wind turbine blade is struck by lightning, the resulting lightning current will inevitably flow through the main bearing and any pitch bearing that may be fitted. It was not clear at the start of the project whether these bearings could be damaged by lightning current and this project phase was used to test wind turbine bearings with high current to investigate this issue. Two sets of bearings were tested, one set of pitch bearings of 600mm diameter and one set of gearbox bearings of 160mm diameter.

The initial tests carried out on the pitch bearings were designed to investigate the effect of pre-loading on the level of lightning damage seen in a bearing. The tests were carried out using a generator that could supply 200kA, $2.2\text{MJ}\Omega^{-1}$ or 640C. The tests showed that an insignificant amount of damage could be produced with a production bearing whether it was preloaded or not. Increased levels of damage were produced when the number of balls in the bearing was reduced hence increasing the current density.

The second set of tests were carried out on two identical gearbox bearings one of which was tested while it was rotating, the other being tested stationary. This test was designed to examine the effect of the hydrodynamic layer, a thin oil film layer between the rollers and the race, on the magnitude of lightning damage. The tests showed that a rotating bearing was particularly vulnerable to lightning damage in comparison to a stationary one.

In summary, the results from the project phase suggest that pitch bearings are not likely to suffer any lightning damage while in service. Main shaft bearings and those contained in the drivetrain are more likely to be damaged if the lightning strike occurs when the rotor is turning.

4.5 Phase Five – Determination and examination of probable current path

When lightning strikes a wind turbine, any resulting damage can be subdivided into two types. The first type of damage is caused by the direct conduction of the lightning current. This is often known as a direct effect. The second type of damage results from mutual coupling between wiring not directly connected to the lightning protection system and the lightning protection system itself. In a wind turbine this mutual coupling will often result in high voltages being present at the terminals of sensitive control equipment. This is often referred to as an indirect effect.

It is important to predict the path of the lightning current through a wind turbine so that measures can be taken to protect the rest of the machine against lightning damage. This has been done during this project phase with the use of computational codes and theoretical analysis. A number of visits to windfarm sites and wind turbine owners were also carried out to see examples of wind turbine wiring used in various ages of machine. It has been shown that induced voltage levels can be reduced by a factor of ten by predicting the path of lightning current and then applying simple protective measures to the vulnerable control system wiring.

Studies of the meteorological support mast equipment, control system sensors and generator have all provided guidelines on good practice that are included in the Designers Guide described in section 4.8. It is shown that the use of cable trays, screened wires and transient suppressors can all help prevent indirect damage.

4.6 Phase Six - Personnel protection

A possibility always exists of windfarm personnel being on a windfarm during a lightning storm. In addition, members of the public often walk through windfarms and may use turbines as shelter from the rain during lightning storms. The scale of the hazard and means of maintaining the safety of any persons on wind farm sites during lightning storms were specific areas of investigation. The risks during a lightning storm can be subdivided into three main categories; electric shock, exploding wire effects and ejection of blade material.

The first of these issues, electric shock, applies to personnel in a wind turbine and anyone in the vicinity of the windfarm earthing system. Although an electric shock may not kill, it can be dangerous in other ways such as causing people to lose grip when climbing down a ladder.

The risk from exploding wires is only relevant to windfarm personnel. All wiring used in a wind turbine should be adequately rated to carry the transient current produced by a lightning strike safely Finally, the hazard from ejected blade material can be prevented by the use of blade lightning protection systems. These were dealt with in Phase 3 of the project.

Recommendations that are intended to go some way to ensuring the safety of personnel working on a windfarm and those members of the public around it when lightning strikes a wind turbine were constructed during this project phase.

4.7 Phase Seven - Windfarm earthing

When lightning current flows into a windfarm earthing system the potential of that earthing system will rise which in turn will raise the potential on the soil surface. This phenomena produces two possible hazards. One hazard is to people walking around the windfarm in the form of touch and step voltages that result from the potential gradient that will exist on the soil surface. The rise in earth potential at one wind turbine causes the second hazard as it can result in insulation breakdown either locally or remotely depending on the configuration of the earthing system.

While these topics are routinely dealt with in terms of power system earthing they are not regularly addressed with regards to lightning. The simulations that have been performed using a commercially available earthing package and one developed at ICCS/NTUA have indicated that the performance of a windfarm earthing system varies dramatically when transient current, as opposed to 50Hz, is injected.

Specifically, the results show that any part of the earthing system further than 50m from the point where lightning current is injected will not help decrease the magnitude of the peak lightning overvoltage. This therefore highlights the need for a wind turbine to be provided with a compact earthing system of a low resistance (10Ω or less is often stated in relevant standards).

4.8 Phase Eight - Production of a designers best practice guide

The guide, incorporating results from all the other project phases and aims to assist designers to assess the risk from lightning arising from their design, manufacture and siting of their turbines and guide them in the provision of appropriate protection measures. The guide will shortly be made available for duplication cost only. Details of how to obtain the guide will be published in trade journals such as ‘Wind Power Monthly’.

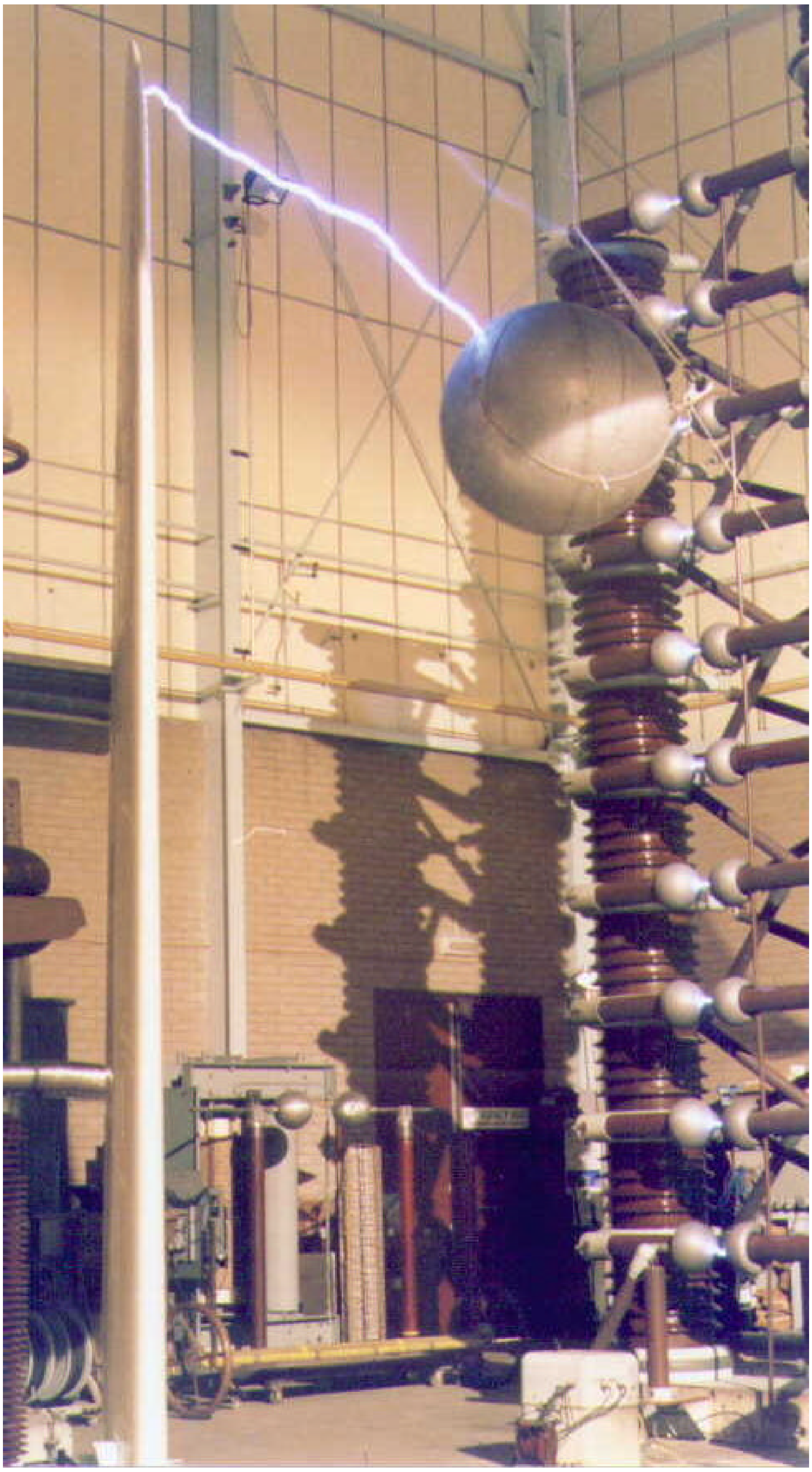
5. Exploitation plans and anticipated benefits

The results of the project have been presented in the form of a designers guide which will be made available to European industry so that wind turbines and wind farms are designed and constructed with a level of protection that makes the risk of lightning strikes acceptable. All project results apart from selected high voltage test results are to be made public in the Designers Guide. It is hoped that the Designers Guide will provide the following benefits:

- Reduction in the annual repair bill resulting from lightning damage to wind turbines
- Reduction in the annual lost energy production resulting from lightning damage to wind turbines and an increase in the reduction of CO_2 emissions that are attributed to wind energy
- Improved public perception of wind power by increasing turbine availability which will benefit the wind energy industry as a whole
- Better understanding of the mechanisms that cause lightning damage to a wind turbine. The reporting of methods to prevent such damage and assist a wind turbine designer in the provision of a cost-effective lightning protection system

The information is of direct relevance to those wind turbine manufacturers wishing to improve the lightning protection systems used on new designs of wind turbines and to wind turbine owners wishing to retrospectively improve the lightning protection system used on older wind turbines. It is hoped that the results will be used by the whole wind energy industry as a basis for the continual improvement of lightning protection system design. Although no innovative results have been produced by the work it is hoped that the extensive range of topics covered has resulted in a comprehensive study of the topic.

6. Photograph To Illustrate Potential Product Applications



Capture of simulated lightning strike by blade lightning protection system