ASSESSMENT OF SAFETY RISKS ARISING FROM WIND TURBINE ICING

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ABSTRACT

Developers and owners of wind turbines have a duty to ensure the safety of the general public and their own staff. However, there are currently no guidelines for dealing with potential dangers arising from ice thrown off wind turbines. This puts developers, owners, planning authorities and insurers in a difficult position. To rectify this situation, the work presented here has commenced in order to produce an authoritative set of guidelines. Initial work has resulted in the development of a risk assessment methodology which has been used to demonstrate that the risk of being struck by ice thrown from a turbine is diminishingly small at distances greater than approximately 250 m from the turbine in a climate where moderate icing occurs.

1. INTRODUCTION

The work presented here is being undertaken as part of a project entitled "Wind Energy in Cold Climates (WECO)" part-funded under contract JOR3-CT95-0014 of the Non-Nuclear Energy Programme managed by the European Commission, DGXII, and by the UK Department of Trade and Industry. This project is being co-ordinated by the Finnish Meteorological Institute with DEWI (D), Garrad Hassan (UK), Risø (DK) and VTT (FI) as contractors. The project also involves associate contractors and subcontractors from many other European countries. The WECO project has three central objectives:

- To refine current assessments of the European wind energy resource through development of ice maps for the constituent countries.
- To identify methods for the improvement of the performance of wind turbines and anemometry technology in ice-prone climates and to quantify the cost implications of these methods.
- To produce safety guidelines for wind developments in ice-prone areas.

The work presented here addresses the last of these and has been motivated by an absence of authoritative reference material on the subject when it is raised as a concern by planning authorities and neighbours to proposed wind turbine developments. The findings of this research have been previously published [1,2] and this paper aims to summarise and update those previous publications. The lack of previous work by others on the subject may reflect the fact that there has been no reported injury from ice thrown from wind turbines, despite the installation of more than 6000 MW of wind energy world-wide. In addition, relatively few turbines have been installed in climates where icing is a serious problem. That situation is rapidly changing as extensive development of the wind resource in many Northern European countries has now commenced. Indeed, the potential risk has recently attracted significant publicity in Germany, where a number of significant incidents have been reported in the past year, indicating an urgent need for suitable safety guidelines.

2. THE PHENOMENON OF ROTOR BLADE ICING

Under icing conditions, all exposed parts of the wind turbine are liable to ice build-up. However, it has been observed that a moving turbine rotor is liable to accrete significantly heavier quantities of ice than stationary components for reasons which are explained below. Furthermore, the rotor blade ice has the potential to be cast some distance from the turbine if it breaks off a rotating blade. It is these aspects which set rotor blade icing apart from icing of stationary turbine components or indeed any stationary structure, and make it worthy of research.

There are several mechanisms of ice accretion on structures. The most important of these, for wind turbines, is rime icing which occurs when the structure is at a sub-zero temperature and is subject to incident flow with significant velocity and liquid water content. The precise deposition mechanism is the subject of ongoing experimental and theoretical research. However, the authors have a substantial body of field observations which has played an important role in the work reported here.

A typical example of heavy rime icing on a wind turbine rotor is shown in Figure 1. It can clearly be seen that the heaviest ice build-up is at the tip of the blade but what is surprising is the amount of accretion with a chordwise thickness of up to about 0.5m. The build-up at the root of the blade is much less severe compared to nearby stationary structures.

The rime build-up is quite hard but it is also less brittle than might expected and remains attached to the rotor under significant flexure of the blades. Field observations indicate that most ice shedding occurs as temperatures rise and the ice thaws from the rotor. A typical scenario is that ice builds up on the rotor and on the wind speed and direction sensors which are mounted on the nacelle. Sensor malfunction causes automatic turbine shutdown. In this

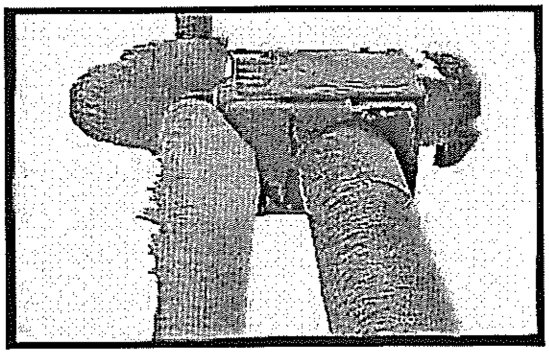

Figure 1: Heavy ice accretion on a 300 kW turbine rotor

situation, most turbines will restart only when the ice has thawed and fallen from the stationary turbine which the operator then resets. However it is common practice for the operator to accelerate the process by thawing the sensors and restarting the turbine with ice still on the rotor. This circumstance has been observed to lead to heavy shedding of ice.

As regards the size of ice fragments shed from rotor blades, their mass and the distance which they are cast, there is very limited objective and subjective information. The only objective source of information is that collected in the recently completed EU Joule project "Icing of wind turbines", also funded by DGXII. As part of this work, carried out by DEWI and FMI, a questionnaire was circulated to a large number of turbine operators as described by Seifert [3]. The questionnaire asked for information on the occurrence of icing including mass and location of any observed ice debris flung off the rotor. The distribution of this questionnaire has continued as part of the WECO project.

Figure 2 summarises the data collected so far, as supplied by DEWI [4]. The data presented in Figure 2 show that most fragments which were found on the ground were estimated to be in the range 0.1 to 1 kg mass and were found 15 to 100 m from the turbines. Of course these figures must be taken as very approximate, and it is not possible to know how well the ground was searched especially at larger distances from the turbines.

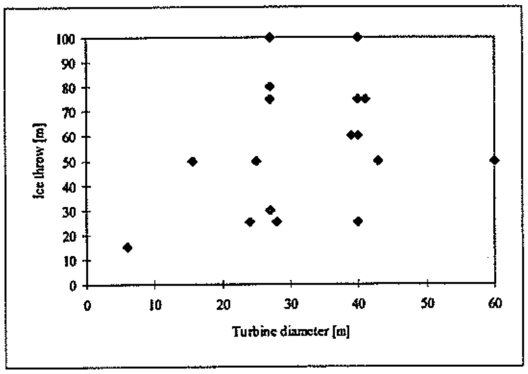

Figure 2: Ice throw data collected by icing questionnaire

In addition to this objective information, anecdotal evidence suggests that the tendency is for ice fragments to be dropped off, rather than thrown off, the rotor. Also, it tends to be shed off the tips in preference to other parts of the blade and large pieces of debris tend to fragment in flight. There is significant evidence that rime ice continues to form when the turbine is operating and is not shaken off by blade flexing, even though this may be the case for other types of ice formation. Also, rime ice formation appears to occur with remarkable symmetry on all turbine blades with the result that no imbalance occurs and the turbine continues to operate.

3. MODELLING OF ICE THROW

3.1 Aspects to be modelled

The risk of a person being hit by a fragment of ice thrown from an operational wind turbine depends on the following factors:

- The probability of the turbine having ice build-up on the blades
- The likelihood of ice fragments becoming detached from the blade, which is undoubtedly a function of radial position on the blade and on blade azimuth. It may also depend on the speed of rotation of the blades, as well as on blade pitch, blade profile and flexibility.
- The point where the detached ice fragment lands, which also depends on the radial position and azimuth at the time of becoming detached, and on the rotor speed and wind speed. The speed of the fragment at the end of its trajectory is also of interest, and this depends on the same factors.
- The probability of the person being in an area of risk and any safety precautions taken.

3.2 Method for ice throw trajectory prediction

While little is known about the probability of ice fragments becoming detached from various parts of the blade, it is relatively easy to calculate the distance travelled and the final velocity of the fragment once it has become detached, assuming that it does not break up in flight. A method for doing this has been developed as part of WECO and has been previously described by the authors [1,2]. This model has been further developed and now includes modelling of the effect on the trajectory, of:

- Blade azimuth at the instant when the fragment is released
- Radial location of the fragment on the blade at the instant of release
- Any radial sliding velocity developed by the fragment prior to release (the 'slingshot' effect)
- Turbine dimensions and rotor speed
- Gravity
- Fragment dimensions
- Aerodynamic drag
- Aerodynamic lift
- Mean downstream wind speed

3.3 Calculating the risk at a given distance

In practice the ice fragments shed from a turbine will follow a whole range of trajectories depending of the mass and shape of each fragment, the wind speed and direction, the point on the rotor at which the ice is released, etc. As previously described [1,2], Monte-Carlo simulation is used to generate a large number of possible trajectories and the probability of each one, so as to arrive at an assessment of the risk of of ice fragments landing in any particular square metre of ground area.

4. GUIDANCE IN RISK ASSESSMENT

It is possible that guidelines for use by developers and planning authorities should take the following format:

A. Public safety and turbine icing - background information.

i. Under certain meteorological conditions, it is possible for ice accretion to occur on wind turbine rotors. The accretion process is no different to that experienced by many exposed structures although heavier accretion has been observed on wind turbine rotors.

ii. Fragments of ice will drop or be cast from the rotor when this ice melts or is shaken off the rotor. In theory, these fragments may present a risk to the safety of the public or operational staff. This risk can be assessed and mitigated by steps given below.

iii. When more than a few metres from the turbine, the risk of ice landing at a specific location is found to reduce quite quickly with the distance of the location from the turbine. It is also found that ice falls predominantly downwind of the rotor plane.

iv. Fragments of ice have been observed to have masses in the range of less than 1 kg.

v. As operational staff work more regularly and in closer proximity to the turbines, they can be exposed to more risk than members of the public.

B. Assessment of risk

It is proposed that the risk assessment should be undertaken in three stages:

i. Occurrence of icing conditions
An estimate should be made of the time (number of days per year) during which icing conditions occur at the turbine site:

- "Heavy icing" - more than 5 days, less than 25 days icing per year.
- "Moderate icing" - more than 1 day, less than 5 days icing per year.
- "Light icing" - less than 1 day icing per year.
- "No icing" - no appropriate icing conditions occur.

The method for this estimation is the subject of another aspect of the WECO project [5]. To state the obvious, if the site falls within the "No icing" category, it can be assumed that no risk exists and no further assessment is required.

ii. Allowable risk of ice impacts on ground.
The level of risk which is acceptable should be determined. This is subject to case-specific factors such as ease of access, however a suitable level may be 10^{-6} strikes/m^2/year which is the typical probability of lightning strike in the UK [6].

iii. Determine safety distance.
Use data presented in Figure 3 to determine the safety distance for the chosen level of allowable risk. Clearly the smaller the level of risk which is to be tolerated, the greater the safety distance which must be allowed.

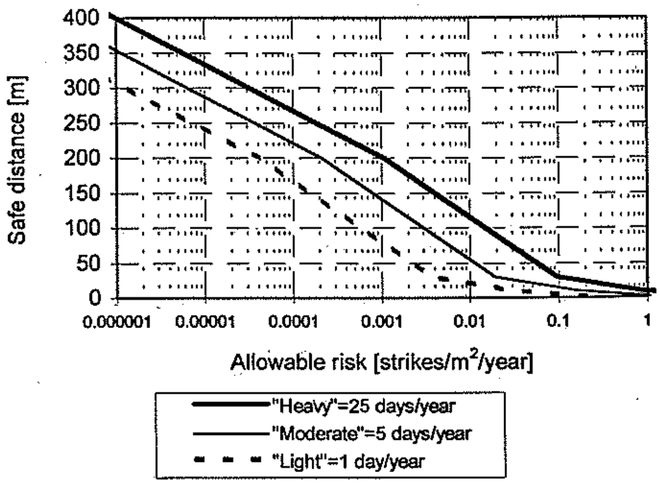

Figure 3: Safety distance for different icing levels (50m rotor)

Figure 3 is based on a rate of ice accretion averaging 75 kg/day during icing conditions, a figure which has been estimated for a 3-bladed turbine of 50m diameter. The allowable risk should be scaled *pro rata* under different assumptions.

5. MITIGATION OF RISK

In a situation where a significant risk to the public or operational staff is believed to exist, the following measures are suggested:

i. Curtailing operation of turbines during periods of ice accretion.

ii. Implementing special turbine features which prevent ice accretion or operation during periods of ice accretion.

iii. Re-siting of the turbines to remove them from areas of risk.

iv. The use of warning signs alerting anyone in the area of risk.

v. Operational staff should be aware of the conditions likely to lead to ice accretion on the turbine, of the risk of ice falling from the rotor and of the areas of risk.

6. ACKNOWLEDGEMENTS

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