LIGHTNING PROTECTION FOR OFFSHORE WIND TURBINES

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INTRODUCTION

Wind turbines are rapidly becoming important generators of electric energy, and the size and rated power of new wind turbines continue to increase. As a consequence it is important that wind turbines are treated as other power system components and meets the standards for reliability, protection and safety used in the electric industry in order to reach an acceptable level of operational reliability. In this paper are presented the observations made in a project concerning lightning protection for offshore wind turbines. The objectives were to describe appropriate lightning protection methodologies that ensure a sufficiently high level of lightning protection for wind turbines placed offshore in Denmark, and based on this to open a dialog regarding lightning protection with the major wind turbine manufactures.

NEED FOR LIGHTNING PROTECTION

The number of wind turbines installed in Denmark has increased drastically in the last 10 years, totalling 6000 wind turbines by mid year 2000, with a total capacity of just over 2000 MW and producing about 12 % of the annual electric energy consumption.

Furthermore, the Danish electric utilities Elsam, Eltra and Elkraft are in the process of establishing 6 large scale offshore wind parks. The first and smallest wind park of these Middelgrunden of 40 MW (20 x 2 MW wind turbines) has already been established just outside Copenhagen harbour in 2000, while the other 5 wind parks each of 150-160 MW will follow in the years 2002-2008. Thus wind turbines already generate a substantial part of the consumed electric energy and even more so in the near future.

This increased importance of wind turbines as major generators of electric energy and the offshore installation makes mandatory a much more systematic and professional approach to lightning protection, as compared to what has hitherto been seen with wind turbines on land.

The risk of damages due to lightning is significant and particularly when considering the loss of production and the higher repair costs offshore as compared to locations on land it is mandatory that the large modern wind turbines be effectively protected against the adverse effect of lightning.

The DEFU Recommendation 25 *Lightning Protection for Wind Turbines* was issued in 1999, DEFU. It describes good systematic lightning protection practices, and is intended for wind turbine manufactures and not least for Danish electric utilities procuring wind turbines. It is based on the general IEC lightning protection standards, and to some extent on practical experience particularly regarding lightning protection of the blades.

It is the opinion of the working group that there is a need for developing better lightning protection methods for wind turbine blades and the mechanical drive train, particularly main shaft bearings and gear box. These are the generic problems regarding lightning protection of wind turbines. Contrary to blades and the mechanical drive train lightning protection of the electric systems in wind turbines is straight forward and should be done according to the well established principles described in detail in the relevant IEC standard series 61024 and 61312.

CONCLUSIONS

It is the observation of the working group that all major wind turbine manufacturers have made efforts in order to reduce the amount of damages and interruptions caused by lightning. However, it is also clear that so far lightning protection have not been addressed in the systematic and professional way, that is requested by the Danish electric utilities building and planning large offshore windparks.

It will be necessary and it will be required that wind turbine manufactures present a complete and documented lightning protection concept, in accordance with the IEC lightning protection standards, that effectively limits repair costs and secures the operational reliability necessary for offshore windparks. This is what is normally required for power system components and there is no reason to require less of wind turbines, considering the high costs of repairs and the importance of high reliability for offshore wind turbines

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BACKGROUND

Wind turbine developments in Denmark

The number of wind turbines installed in Denmark has increased drastically in the last 10 years, totalling 6000 wind turbines by mid year 2000, with a total capacity of just over 2000 MW and producing about 12 % of the annual electric energy consumption. In the same 10 years the size of a normal series produced wind turbine has increased from 200 kW machines 45 m in overall height to the 110 m high 2 MW machines of today.

Furthermore, the Danish electric utilities Elsam, Eltra and Elkraft are in the process of establishing 6 large scale offshore wind parks. The first and smallest wind park of these Middelgrunden of 40 MW (20 x 2 MW wind turbines) has already been established just outside Copenhagen harbour in 2000, while the other 5 wind parks each of 150-160 MW will follow in the years 2002-2008. Thus wind turbines already generate a substantial part of the consumed electric energy and even more so in the near future.

This increased importance of wind turbines as major generators of electric energy and the offshore installation makes mandatory a much more systematic and professional approach to lightning protection, as compared to what has hitherto been seen with wind turbines on land.

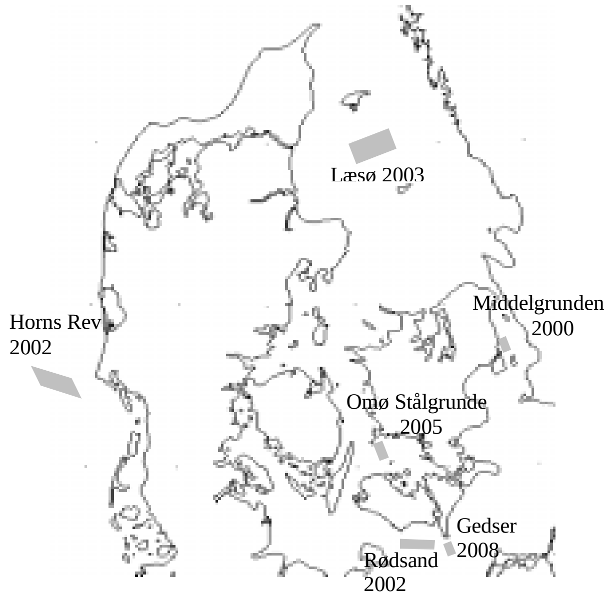

Figure 1: Areas designated for offshore windparks in Denmark.

Risk of lightning strikes

As wind turbines are preferentially placed at high and windy locations in order to achieve high productivity, they are also subjected to a relatively high risk of lightning strikes. Also at the designated offshore wind park locations relatively high risks of lightning strikes are expected.

The usual methods for evaluating the risk of lightning strikes are probably not very accurate for such locations, but it is usually assumed that the risk of lightning strikes to an object increase with the square of the height. In the case of wind turbines this means that the likelihood of lightning striking a wind turbine is more than 6 times higher with modern 110 m high wind turbines as compared to the typical 45 m high wind turbine of years ago.

In Denmark, where the lightning occurrence is relatively low (0,2 - 0,5 lightning flashes per km² per year), it is known from reports submitted by operators of predominantly older and smaller wind turbines that on annual average 4 % of the wind turbines are damaged by lightning. Probably about one third of the damages are caused by direct hits, while the other two thirds are caused by transients from lightning striking the public power or telephone networks.

In practical terms this means, that while older wind turbines were not likely to be hit directly by lightning, as 1/3 · 4 % corresponds to one direct lightning strike per wind turbine per 75 years, it must be expected that all 110 m high wind turbines will be hit several times during their lifetime.

The risk of damages is thus significant and particularly when considering the loss of production and the higher repair costs offshore as compared to locations on land it is mandatory that the large modern wind turbines be effectively protected against lightning.

Damage statistics

The number of lightning faults on wind turbines obviously depends on the occurrence of thunderstorms. This can readily be seen from figure 2, where the number of reported damages per 100 wind turbines is shown together with the number of thunderstorm days in each year since 1985, and there is evidently a strong correlation between faults and thunderstorm occurrence except in the later years. This difference in later years is most likely due at least 3 factors. Firstly lightning protection of new wind turbines has been improved, particularly after 1995 when blade protection was developed. Secondly the number of lightning flashes has been relatively low particularly in 1999 even though the number of days with thunderstorm was slightly above average. Thirdly and not least the willingness of wind turbine operators to file damage reports has decreased in later years, DEFU (3).

Similar statistics are available from Germany and Sweden, IEC (2). In Germany the statistics for the years 1991-98 show that on annual average 14 % of the wind turbines in the mountain areas in the south are damaged by lightning. In the flat land in the north it is 7,4 % and in the coastal areas in the north it is 5,6 %.

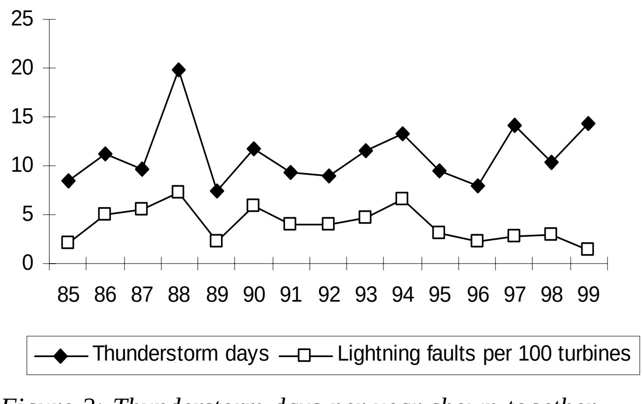

Figure 2: Thunderstorm days per year shown together with number of lightning faults per 100 turbines per year.

The German statistics furthermore show that 70 % of all faults were caused by indirect lightning strokes (i.e. typically lightning striking the public telephone or power systems).
In Sweden all operators are requested to report damages in return for the subsidies, and the Swedish statistics from the years 1992-98 show that on annual average 5,8 % of the wind turbines are damaged by lightning.

The German statistics also includes repair costs. It shows that repair costs per damage generally increase with wind turbine size and that repairing blades is by far the most expensive followed by generator repair costs. This is a consequence of the higher prices and the higher handling costs for larger components.

In total 900 wind turbines in Denmark were reported damaged by lightning in the years 1990-99. The damaged wind turbine components were distributed as shown in figure 3. Damages to the control system were clearly the most common with 51 %, while damages to the power system (to some degree including simple interruptions), generator and blades each accounted for about 10 %, (3).
The Danish as well as the German statistics indicate that the damages to control systems in the newer and larger wind turbines occur less frequently, probably as a consequence of improved lightning protection, (2).

For offshore locations it is known that repair costs will be very high in general, and particularly for the major components: blades, gear box, generator and power transformer. It is therefore considered mandatory that lightning protection for offshore wind turbines is of a very high standard in order to ensure the necessary safety and reliability and in order to keep repair costs at a minimum, (3).

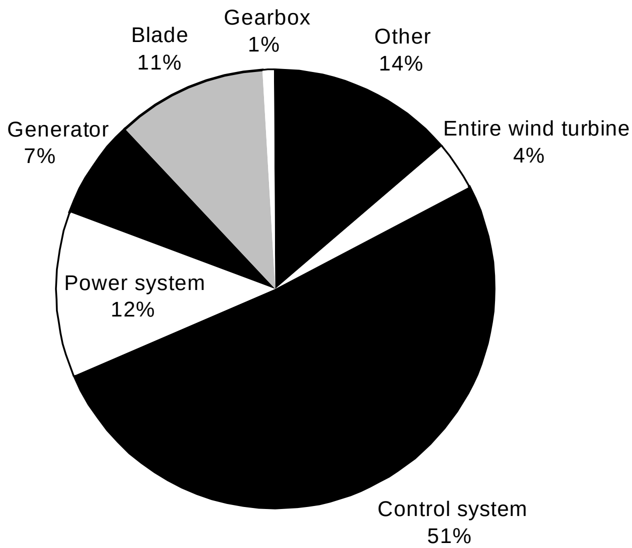

Figure 3: Lightning damaged wind turbine component distribution (Denmark 1990-99)

PRESENT STATE OF LIGHTNING PROTECTION FOR WIND TURBINES

Naturally the damage statistics presented above is historic information and does not necessarily represent the state of lightning protection for new wind turbines.

The DEFU Recommendation 25 *Lightning Protection for Wind Turbines* was issued in 1999, DEFU (1). It describes good systematic lightning protection practices, and is intended for wind turbine manufactures and not least for Danish electric utilities procuring wind turbines. It is based on the general IEC lightning protection standards, IEC (4 and 5), and to some extent on practical experience particularly regarding lightning protection of the blades.

Based on dialogs with major wind turbine manufactures prior to and after the publication of DEFU Recommendation 25 it was the observation of the working group, that the major wind turbine manufacturers have made some efforts regarding lightning protection over the years. However, in most cases with the help of consultants and in order to alleviate specific problems such as the high number of damages previously seen on control systems and blades. It was the clear impression that the wind turbine manufacturers themselves neither had a clear policy regarding lightning protection nor could any manufacturer present documentation that would allow a professional evaluation of the efficiency of the lightning protection systems used (3).

It is the opinion of the working group that there is a need for developing better lightning protection methods for wind turbine blades and the mechanical drive train, particularly main shaft bearings and gear box. These are the generic problems regarding lightning protection of wind turbines. All other parts of the wind turbines should be protected in accordance with the detailed IEC standards for lightning protection of structures (4), and power and communication systems (5). This was also the conclusion of the IEC working group who recently submitted a draft technical report regarding lightning protection of wind turbines to IEC TC88 Wind Turbine Systems (2).

Lightning protection of blades

Until the early 1990'ties most manufactures of series produced wind turbines did not use lightning protection for the blades, probably because lightning strikes were not a big problem for the small wind turbines of that time, as discussed above. The few blades that were protected usually had metal mesh incorporated in the blade surface (figure 4-D). Since about 1995 most blades produced in Denmark are protected with air terminals at the blade tip and an internal down conductor (figure 4-A and 4-B). Another system used by a German manufacturer consists of a down conductor along the leading and trailing edges of the blade (figure 4-C).

The system with air terminal receptors at the blade tip was developed for blade lengths of 17 -20 meters, and it has clearly reduced the amount of damages. However, it remains unknown whether it will be sufficient for wind turbines with blades twice as long that will be struck by lightning much more often. Considering the large costs associated with repair or replacement of blades offshore, there is great concern about the efficiency of the blade protection. Further development, testing and validation are therefore much needed.

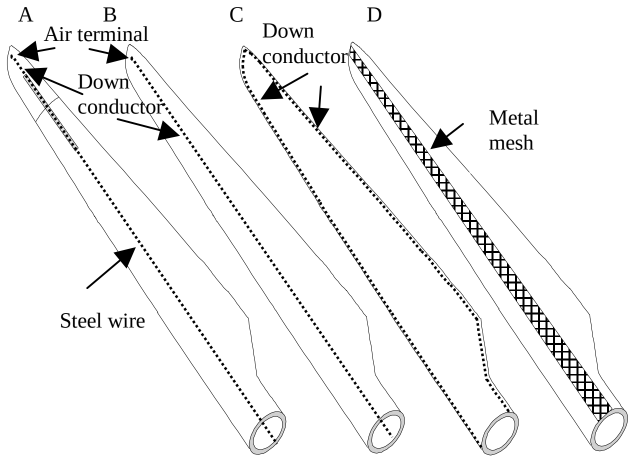

Figure 4: Types of lightning protection for wind turbine blades.

Lightning protection of the mechanical drive train

The need for lightning protection for the mechanical drive train has been much debated, particularly regarding the main bearings. It is clear that whenever lightning strikes a blade the current must pass from the blade root to the tower, as illustrated in figure 5. The need for protection has to be assessed, as some cases of lightning damages to bearings have been seen

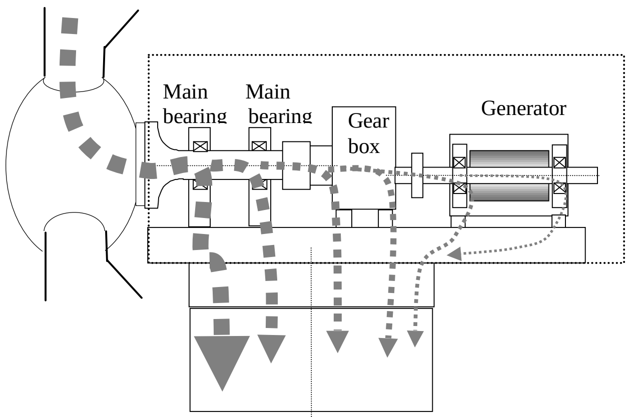

Figure 5: Distribution of lightning current between bearings, gearbox and generator

Most manufactures use some kind of spark gab, brush or sliding contact system on the main shaft to divert lightning currents to the machinery bed plate and away from the bearing. However, the effectiveness of such arrangements is unknown.

It has been suggested that the amount of lightning current trough bearings and gear box can be reduced by inserting resistive layers in the current paths through these components, while at the same time using a diversion system as described above, DEFU (1) and IEA (6). This however, has been met with strong scepticism because of the mechanical difficulties involved. Another approach has been suggested by Scheibe (7) in which the lightning current is diverted from the blade root and directly to the housing over the machinery.

Again considering the costs involved with replacing major components offshore it must be required that the wind turbine manufactures provide documentation for the effectiveness of the lightning protection that ensures that no components in the mechanical drive train are subjected to damaging levels of lightning current

Lightning protection of electric Systems

Contrary to blades and the mechanical drive train lightning protection of the electric system in wind turbines is straight forward and should be done according to the well established principles described in detail in the relevant IEC standard series 61024 and 61312.

In DEFU Recommendation 25 it is required that lightning protection of all electric systems is made, tested and documented in accordance with the lightning protection zoning principle described in the IEC 61312 series and more fundamentally in the EMC standards of the IEC 61000 series.

In most cases it will be natural to consider the inside of wind turbines as lightning protection zone 1 and the inside of metal cabinets as zone 2, as shown in figure 6. Protection of the housing covering the machinery against direct lightning strikes may be done with traditional means such as Franklin rod air terminals, or it may be that the covering itself is either metal or has metal parts that can be used as air termination system. Protection must then be considered at all zone boundaries. It must be documented that the protection at the zone boundaries with overvoltage protection of cables, shielding and bonding reduces the level of currents, voltages and electromagnetic fields to a level tolerable for all components inside the zone with the higher number. Inside each zone proper grounding and bonding must be provided.

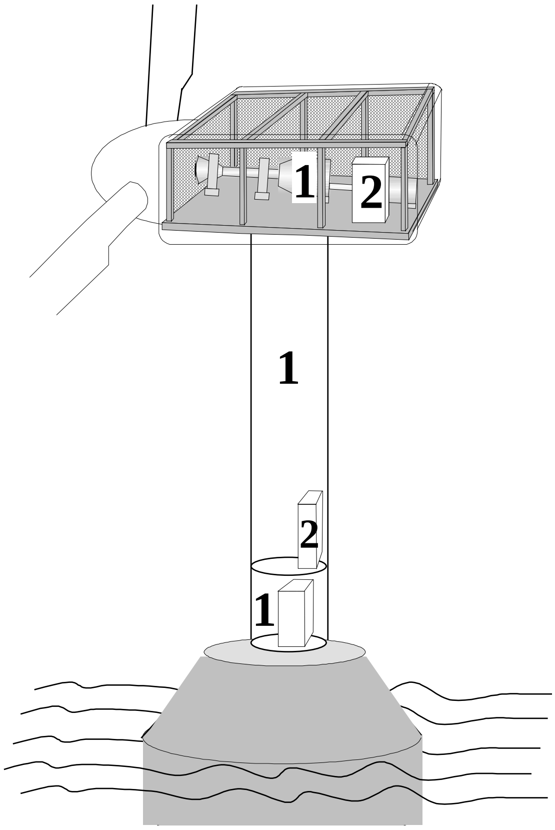

Figure 6: Division of offshore wind turbine into lightning protection zones.

It may be convenient to consider cabinets for sensitive equipment such as control and communication equipment as distinct zones. This would also make it easier to provide documentation as such cabinets may then be tested in an EMC testing laboratory.

Earthing and corrosion

Considering the harsh offshore environment it must be ensured that all components of the external lightning protection system are made of corrosion resistant materials. It must be avoided that components of copper are placed so that water with copper ions drips onto more corrosive metals. Furthermore, all connections between components such as clamps etc. must be sealed. Particular care must be taken when connecting metals of different electrochemical properties. Experience show that inside the tower and the machinery housing it may be dry enough to prevent corrosion - by the use of dehumidifiers if necessary.

The earthing for offshore wind turbines may easily be made in such a way that the earthing resistance is much lower than for wind turbines on land. In the Middelgrunden windpark the foundations are made of reinforced concrete, and foundation-earthing systems are used, where the sacrificial aluminium blocks for the corrosion protection of the steel reinforcement provide direct contact to the seawater.

For the other offshore projects different types of foundations will probably be used such as the so-called "mono-pile", which is a steel pipe about 4 m in diameter driven as deep as 25 m into the seabed.

The resulting earthing resistance for either type will be so low that overvoltage protection of the medium voltage cables and high voltage terminals of the power transformers will probably not be necessary, as the earthing system potential rise will be below the basic insulation level even when the wind turbine is struck by lightning with extremely high current values (3).

Lightning detection and warning

With offshore windparks surveillance and control are of much greater importance as compared to wind turbines on land. As part of the surveillance it is necessary to register when lightning strikes. To this end only few sensor systems are available today. Notably one lightning sensor system developed for wind turbines in a project headed by DEFU is now supplied by the Danish company Jomitek, DEFU (8). This sensor system has been tested successfully for a two-year period, and is now used on the wind turbines in the Middelgrunden offshore windpark.

CONCLUSIONS

It is the observation of the working group that all major manufacturers have made efforts in order to reduce the amount of damages and interruptions caused by lightning. However, it is also clear that so far lightning protection have not been addressed in the systematic and professional way, that is requested by the Danish electric utilities building and planning large offshore windparks.

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This is what is normally required for power system components, and there is no reason to require less of wind turbines, considering the high costs of repairs and the importance of high reliability for offshore wind turbines

ACKNOWLEDGEMENTS

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