The Journal of CPRI,
Vol. 9, No. 1, March 2013 pp. 45–52

A Review on Effective Lightning Protection for Wind Turbine Generators

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A wind turbine generator is the most exposed of all types of generators connected to electric utility systems. Wind turbines are most often erected in hostile lightning environments. Lightning damage to wind turbines is costly in terms of repair and replacement of equipment. Lightning damage is the single largest cause of unplanned downtime in wind turbines, and that downtime is responsible for the loss of countless megawatts of power generation. There is currently no international standard governing wind turbine lightning protection. This paper is a review on the available guidelines for effective protection.

Keywords: *Lighting protection and Wind turbine generators.*

1.0 INTRODUCTION

Windmills have been in use for over 2000 years, the earliest uses of which were grain grinding and water pumping. Areas of favorable locations for wind turbines coincide with areas of thunderstorm activity. Maps prepared by NASA show that in most areas where wind density is high, there are 30 or more thunderstorm days per year [1]. In a study completed in 2002, the National Renewable Energy Association statistics showed that up to 8 out of 100 wind turbines could be expected to receive one direct lightning strike every year [9]. Between 1992–1995, Germany alone reported 393 incidents of lightning damage to wind turbines (124 direct strikes to the turbine, and the remainder through the electrical distribution network) [3].

2.0 EXISTING STANDARDS FOR LIGHTNING PROTECTION

Several international lightning protection standards exist, which have been applied to wind turbines. These include:

- IEC 61024 Protection of Structures Against Lightning.
- IEC 61662 the Assessment of Risk due to Lightning.
- IEC 61312, 1-5 Protection against Lightning Electromagnetic Impulses.

Wind turbines that have been protected using the principles from these three standards, have still experienced significant lightning damage. There is no standard specifically written anywhere in the world for protecting wind turbines against lightning damage. The closest document is IEC/TR 61400-24 Ed.1.0 en:2002 entitled “Wind turbine generator systems: Lightning protection”. This document, which is purely informative, is not to be regarded as an international standard.

3.0 LIGHTNING DAMAGE STATISTICS

The statistics quoted in IEC/TR 61400-24 are highly informative. The document notes that in

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northern Europe (Germany, Sweden, and Denmark) where lightning is comparatively infrequent, 4–8% of all wind turbines will suffer lightning-caused damage every year. However, in areas of greater lightning density, this figure is reported to be considerably higher. The document further reports that in its northern Europe study 7–10% of the wind turbine damage was to the rotor blades. This is important because the rotor accounts for 15–20% of the cost of a wind turbine and thus, damage to rotor blades is the most expensive type of lightning damage. It should be noted that most of the rotor damage reported was to older style blades manufactured out of nonconducting fiber composite materials. Almost all modern turbine blades are constructed with built-in lightning protection in the form of conducting elements. This improved blade design has significantly reduced the amount of blade damage [2].

Another observation from the report's northern Europe data is that only one-third of the lightning faults were caused by direct strikes to the turbine. The other two-thirds were attributed to lightning strikes to the power and telecommunication networks connected to the turbines. Data from a US source suggests that this ratio is closer to 2% damage from direct lighting strikes and 98% from strikes to the nearby AC power and signal lines [4]. One of the most significant statistics in the IEC/TR 61400-24 document is that 50–70% of lightning faults are to the control and electrical systems and this damage accounts for at least twice as many days of "downtime" as damage to rotors.

4.0 LIGHTNING RISK FACTORS TO BE ADDRESSED

The above statistics give credence to the main conclusion of a study commissioned by the European Union and conducted by the University of Manchester: "the protection of wind turbine electronic systems from indirect effects is of equal importance to, if not greater than, the protection against direct effects" [4A, 5]. The three risk factors to be mitigated then are as follows.

- **Damage to blades caused by direct strikes:** This damagecan be caused by strikes to the tips of the blades and also to strikes along the length of the blades. Almost all direct strikes to a wind turbine will hit the rotor blades.
- **Damage caused by surge currents:** This damage can be caused by surge currents originating from either direct strikes to the blades or coming from (indirect) strikes to connected power and data lines. This would include the ac power lines as well as the telephone or supervisory control and data acquisition (SCADA) lines used to remotely control the turbines.
- **Damage caused by voltages:** This damage can be caused by voltages induced in circuits (power as well as control) adjacent to the necessary down-conductors that carry the lightning current to "earth".

5.0 RECOMMENDED LIGHTNING PROTECTION GUIDELINES

A. Successful Protection

Models of Kindred Applications IEC/TR 61400-24 suggests that "lightning protection of wind turbines presents problems that are not normally seen with other structures." In fact, there are at least two types of structures that share all the problems implicit in protecting a wind turbine from lightning, except for lightning attachment to a rotating blade.

Both radome antenna towers and lighthouses are geometrically similar to wind turbines, are most often cited in highlightning remote and exposed locations, and have sensitive electronics embedded in their towers. Radomes can be constructed over 150 m off the ground. After years of studying the problem, the Federal Aviation Administration (FAA) analyzed successful principles of protecting its radome antenna towers from lightning and made them mandatory in all FAA's hundreds of installations. Similarly, after years of studying successful and unsuccessful lightning protection applications at hundreds of its lighthouses, D/GPS stations, and maritime coastal installations, the Chinese Ministry of Transportation, at the end of 2005, issued guidelines for protecting hundreds of its maritime installations [12]. Both these guidelines promote the grounding and bonding practices outlined in IEC/TR 61400-24.

These two guidelines have both found it necessary to mandate minimum surge protector current handling ratings for protecting their facilities. Surge protectors specified by the FAA are required to protect against a minimum of 1500 surges (10 kA 8/20 μs) and against one surge (between 180 and 240 kA). The Chinese maritime guidelines concur with that assessment and added the requirement of individually-fused back-up protection paths on every phase to assure continuity of protection. This approach is called out in IEC 60364-5-53. Such successful field experience can and should be consulted in protecting wind turbines.

B. Grounding Practices

- Wind turbine grounding systems should follow the recommendations of IEC/TR 61400-24.
- Minimum dimensions of down-conductors are given inIEC 61024-1 and IEC/TR 61400-24.
- A ring ground around the periphery of the wind turbineshould be constructed to which the tower is connected. The steel reinforcement in the turbine tower should be exothermally integrated into the turbine grounding system.
- The ground system should interconnect with all driven electrodes, any underground metal objects (storage tanks, pipes, etc.), and the grounding system of an operations building, if existing. In a wind farm, the ground systems of all turbines will interconnect.
- The grounding system must be compact. Any part of the grounding system further than 30 m from the point where lightning current is injected will not help decrease the magnitude of the peak lightning over-voltage [6].
- The design goal is set for the grounding system of 10 Ω or less [1, 6].
- The ground system must be kept in good condition at all times. Yearly inspections should be scheduled where the system can be examined for any broken or loose connections, corrosion, and/or changes to the ground impedances.

C. Bonding and Shielding

All systems and metal components must be bonded together into one low-impedance path to the ground as per IEC/TR 61400-24.

D. Rotor Blades

- **Conducting elements**: Rotor blades should be constructedwith conducting elements capable of conducting lightning current to the hub in such a way so as to avoid a lightning arc inside the blade. This conducting material can be either the frame of the blade or on the surface of the blade. An extensive NREL study in USA showed that blades with built-in blade conductors were far less likely to suffer catastrophic damage than blades without these conductors [2].
- **Multiple Receptors**: Studies have now shown that long wind turbine blades fitted with an internal type lightning protection system are vulnerable to lightning strike attachment away from the receptor at the tip. The use of multiple receptors is required to provide better protection for a blade than would otherwise be provided by a single receptor located at the blade tip [7]. Rotor blades shorter than 30 m shall have at least one receptor at each shell. For blades greater than 30 m, multiple receptors are required.

E. Bearings

Next to blade damage, bearings are most subjected to damage from direct lightning strikes to the turbine. Statistics suggest that pitch bearings are not likely to suffer any lightning damage while in service. The bearings in the main shaft and those in the drive train are subject to damage because they are smaller and rotate rapidly. And these are more likely to sustain damage if lightning strikes when the rotor is turning [6]. To avoid this, one could stop the turbines briefly during times of lightning risk. Just as turbines are taken offline during high winds to protect them from damage, so they could also be stopped briefly when lightning threatens in order to protect the bearings.

F. Control System

Recorded incidents of lightning damage from 3000 wind turbines of over 14000 turbine years worth of information suggest that the wind turbine control system is the most vulnerable component contained in a wind turbine [6]. It is clear that lightning striking a single wind turbine can produce damage in wind turbines connected with metallic data cable [6]. The mix of electronic equipment in a wind turbine includes control and measurement sensors distributed throughout the turbine. Two microprocessors are often installed, one in the nacelle and the other at the tower base. These must be linked by some sort of cabling. Turbines also have SCADA connections to permit remote data monitoring and control.

Due to the impacts of the interconnection with the main power grid, some certain requirements such as "Fault Ride Through" are utilized to keep the system stability. The interaction among these operation modes and the employed relaying schemes should be considered to realize the proper and well coordinated protection performance.

G. Electrical System

Generally, output voltage from a wind turbine generator is not more than 690 V. This output voltage is stepped up to 66 kV or more by a transformer and supplied to a transmission line.

- **Transformer**: Lightning surge problems of wind power generation take place in the primary (a low-voltage side) not in the secondary (high-voltage side) of a transformer, unlike conventional power distribution transformers.
- **Generator:** Lightning strikes that hit the high voltage electrical grid will appear on (couple into) the low voltage (400/690 V) side of the transformer. For that reason the 400/690 V power line that connects the generator to the transformer must have a surge protector installed. Surge protectors specifically designed for a 400/690 V system, and with a minimum I-peak handling capacity of 180 kA (8/20 μs) should be used to protect the turbine's electrical system.

H. Specifying Surge Protectors

A wind turbine's main surge protectors must be capable of handling a minimum of 180 kA of surge current and have multiple individually fused back up protection paths on every phase, so that the wind turbine is never left without protection (see Section V-A above).

Back-up protection paths: IEC/TR 61400-24 includes the configuration of lightning strikes that are likely to hit wind turbines.

A lightning "flash" to an object consists of more than one "stroke." An SPD needs individually fused redundant (back-up) protection paths so that protection to the wind turbine will be maintained even if one path sacrifices itself on the first stroke. This approach is called out in IEC60364-5-53 and is particularly relevant to wind turbine surge protection.

I. Nacelle External Attachments

The anemometer and wind vane mounted on the rear top of the nacelle feed information to the controller and need a surge protector to prevent over voltages from destroying controller components. The outside obstruction lights that warn air crafts also need to be protected with a surge protector.

J. Inverter

Most large wind turbines use a synchronous generators, which allow direct connection to the power grid. These generators do not use inverters. In situations where inverters are used, they would need surge protection.

K. Lightning Attachment Points

Attention must be paid to all points that are vulnerable to lightning attachment. We should not rely on the "rolling sphere method" since it has never been evaluated or tested on a wind turbine.

Lightning can strike almost any place on a wind turbine. One commonly overlooked area is the meteorological instrument support at the rear of the turbine nacelle [8].

L. Personnel Safety

An in-depth study of danger to wind turbine personnel during a lightning storm found three main risk 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 wind-farm grounding 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 wind farm personnel .All wiring used in a wind turbine should bead equitably rated to carry safely the transient current produced by a lightning flash. Finally, the hazard from ejected blade material can be prevented by the use of blade lightning protection systems [6].

The effectiveness of WTG subsystem protection methods will be evaluated using an array of lightning current counters, cameras, and operator damage reports. The locations of interest include:

- Brushes/slip rings to allow lightning currents to bypass main and yaw bearings
- Up tower generator protection
- Down tower control system or communication system protection
- Air terminals (lightning rods)
- Droop grounding cable (instead of using tower and yaw bearings as path)
- Blade protection methods.

All of the turbines can be instrumented with current measuring and stroke counting devices to track the lightning path to ground. It is expected that, as a minimum, lightning current can be detected at

- The grounding strap (or on tower leg) from the structure to earth-ground
- The grounding strap between the control system and earth-ground
- Possibly, the ground fault detection to the utility mains.

From these items we can detect whether a stroke was conducted down the tower, into the control system, or into (or from) the utility mains.

6.0 FURTHER RESEARCH NEEDED

There are a number of areas that could bear further research.

i. **Blade Protection:** All major turbine manufacturers now include lightning protection as part of blade design. This improvement has significantly lessened the incidence of catastrophic damage from direct strikes, but it has not totally solved the problem. As manufactured blades become longer and longer, a more effective and more easily manufactured method of blade receptors must be developed [5].

ii. **Main Bearing Protection:** Need for an Equipotential Bonding Device Protecting the wind-turbine bearings from direct hits to the rotor blades is an unsolved problem. At least 80% of the lightning current from a direct hit to a blade-flows from the blade conductor into the nacelle bed plate through the main bearing closest to the rotor [12]. As there is evidence that such incidents may badly stress any rapidly moving bearings, it would be a design goal to reduce the amount of this charge that flow through the bearings.

iii. **Attachment Points**: In the absence of any other method, IEC/TR 61400-24 resorted to the “rolling sphere method” in predicting where lightning may attach to a wind turbine. Since this method has never been tested on either high buildings or on wind turbines, a more precise technique should be developed.

7.0 IEC/TR 61400-24 SUGGESTED IMPROVEMENTS

Following are five suggested improvements to IEC/TR 61400-24 [11] in the interests of reducing serious damage and death resulting from lightning strikes to wind turbines suggested by [13].

1) Lightning Parameters IEC/TR 61400-24 places special importance on the parameters of positive CG lightning. These lightning parameters have no basis in scientific facts and have been and continue to be criticized all over the world [9, 12]. A reality-based lightning protection system must be founded on a lightning model comprised of accurate lightning parameters.

2) IEC/TR 61400-24 introduces the "rollingsphere method" for determining potential lightning attachment points. The rolling sphere method is often used as a guide for the placement of air terminals on structures. However, it uses a fixed striking distance (typically 45 m) irrespective of the height or geometry of the structure. It has never been tested or evaluated on tall buildings and rarely on wind turbines. The "rolling sphere method" may be of some use in the placement and height of air terminals, but cannot be relied upon to guarantee where lightning may attach to a wind turbine and where it will not. Reference to it should be struck off from IEC 61400-24 until it has been successfully tested on wind turbines.

3) IEC/TR 61400-24 seeks to apply the "Lightning protection zone" (LPZ) system to wind turbines. The LPZ system is difficult to justify for wind turbines because it has never been evaluated on them. Additionally, it is based on the old IEC 61312-1, which used the 10/350 μs wave form as its lightning model. It is risky to adopt such a system as the basic approach to protect installations as important as wind turbines.

4) Personnel Protection because lightning is a deadly hazard-to-all personnel on a wind-farm, explicit and clear-cut instructions must be given to them which are not open to interpretation or misunderstandings. A much more realistic and responsible instruction is given in the British Wind Energy Association's Guidelines for Health and Safety: "All operatives to be evacuated immediately if lightning has been forecast for the wind farm location, or if lightning is observed in the direction of prevailing weather" [10], or from NASA: "Personnel around a wind turbine can be in serious trouble during a lighting storm. The safest procedure is for personnel to vacate the site" [1].

5) Analysis of Lightning Protection System Costs: IEC/TR 61400-24 document deal with an analysis of the viability of lightning protection costs.

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