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Wind Turbine Lightning Protection of Blades, Electronics and Humans

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***Abstract*— IEC 61400-24 has been the de facto standard for protecting wind turbines from lightning damage since 2002. For the past 16 years every wind turbine in the world has followed its precepts, yet lightning damage today is at the same level or higher than before the standard was introduced. It is well known that 90 percent or more of direct lightning strikes to wind turbines hit the rotating blades and these direct strikes result in the most costly damages to turbines. The paper shows that this damage is largely the result of two shortcomings in wind turbine lightning protection system design. Additionally, the paper proposes an urgent addition to protect human life on wind turbines, suggests an improved surge protection approach to safeguard wind turbine electronics, advocates simplifying the wind turbine lightning protection standard by eliminating inapplicable sections, and identifies a vital aspect of wind turbine design requiring further research.**

Keywords— wind turbine lightning protection, IEC 61400-24, wind turbine surge protection, wind turbine reliability, wind turbine damage, blade damage.)

I. Introduction

A wind turbine blade catches the wind. The bigger the blade the more wind it can catch; the more wind it catches, the more energy its generator can convert to electric power. That explains the trend towards bigger and longer wind turbine blades. As they grow longer, they must be mounted on higher towers. And the literature is replete with data documenting the fact that the higher they go, the more lightning strikes they will attract.

IEC 61400-24 [1], mandating standard practices for protecting wind turbine generators from lightning damage, was issued by the International Electrotechnical Commission as a Technical Report (TR) in 2002 and approved as an International Standard in 2010. The need for such a standard was clear. A 1996 study had reported 135 instances per year of damaging lightning strikes to wind turbines between 1992 and 1995 in Germany alone. [2] A 2006 IEEE Transactions *Special Edition on Wind Energy* reported that 10-14% of wind turbines were being damaged by lightning every year, that 1/3 of those damaging events were being caused by direct strikes to the blades and that those direct blade strikes accounted for by far the most costly repairs. [3]

Wind turbine component	Frequency of damaging incidents/wind turbine
Electrical & Control System	Once every year
Blades/Pitch & Hub	Once every 3 years
Yaw system & Generator	Once every 5 years

Fig. 1. A conservative estimate of damaging incidents per wind turbine extracted from [6]. Other reports indicate far greater frequency. [16]

Now, 16 years later, damage rates are reported to be greater than before the standard was released. A leading insurer of renewable energy projects, GCube Underwriting Services, reports that 41.4% of all 2012 wind turbine insurance claims in the USA were for blade damage mostly caused by lightning. Average cost of a blade damage claim: $240,000 per claim. [4] Another GCube report published in 2017 [5] entitled Risky *Business: Assessing Future Threats in Onshore Wind Development* reported that globally, the wind industry experiences close to 4,000 incidents of blade damage every year, each costing up to one million dollars. Lightning is the chief cause of these damages.

The most comprehensive recent study of wind turbine damage, published in *Renewable and Sustainable Energy Reviews*, documents that while accounting for less than 1/3 of damaging lightning-caused events (the others being those induced from the grid or strikes to the nearby ground) the direct blade strikes are by far the most costly, doing great harm to the bearings, generator, pitch controls as well as the blades themselves. [6]

The International Association of Certified Home Inspectors confirms that the wind turbine components that most closely interact with lightning sustain the most frequent damage; in particular the control and electronic systems as well as the most costly, the blades and rotor. [7]

European and American researchers have noted enough discrepancies and anomalies (such as wind farms experiencing lightning strikes six times greater than predicted by the IEC standard with up to 98% of them being upwardly propagated from the blade tips) that the very basis of the standard distribution of lightning strike currents adopted by IEC lightning protection standards has been called into question. [9] In Japan, where the average number of yearly faults attributed to lightning can reach as high as 36% [31], stakeholders have called attention to shortcomings in 61400-24. [8]

There can be no doubt of the great consternation (and apathy) the specter of continuing damage has caused when the president of a large insurer of renewable energies observes that by all accounts "the industry can do little to reduce the risk of lightning strikes." [10] It is a premise of this paper that there is plenty that can be done, and it starts with a sharp look at the standard that is meant to mitigate lightning damage.

II. Strengthening the IEC 61400-24 Standard

According to Webster's Dictionary, a standard is "a definite level or degree of quality that is proper and adequate for a specific purpose". [11] If the purpose of 61400-24 is to protect wind turbines from lightning damage, the data in the previous section suggests that the steps and strategies mandated by it are not proper or adequate enough to achieve that purpose. [12] What follows are five suggestions we believe would strengthen it.

A. More transparency is required

It's difficult to get hard data on wind turbine damage because manufacturers go to such great lengths to hide the facts. The first release of IEC 61400-24 contained eight full pages of data and statistics devoted to wind turbine lightning damage. It organized the damage by country, by size of turbine, by season and by type of terrain. It differentiated the number and frequency of faults by individual component and the cost of that damage. It detailed the impact of these faults on energy production and described the damage rates of aging wind turbines. It concluded that before the year 2002: "7 to 10% of all lightning faults have involved blade damage...43% to 51% of lightning faults have involved control system damage... and that lightning faults have been responsible for 40% or more of lost energy and 20% or more downtime compared to the average fault." [13] In the rewrites/revisions of 61400-24 all such information has been expunged. A 2013 joint study by the British Health and Safety Executive (HSE) and the National Renewable Energy Lab (NREL) of the US Department of Energy found that there was no comprehensive, publicly available data base containing details of real life occurrences of wind turbine failures because much of the data compiled by manufacturers, operators, research organizations, and trade associations was deemed by them to be proprietary or confidential due to manufacturers' business concerns. The report concludes: "manufacturers tend not to publicize failure data" and currently there is "no data base of wind turbine failures on which (to) base judgments on the reliability and risk assessments for wind turbines." [14] This is still true today in 2018. [15] No other energy industry works under such secrecy.

The wind industry needs to make damage data available so that the effectiveness of IEC 61400-24 can be accurately assessed, both now and moving forward. Two electrical engineers working for one of the world's largest wind turbine manufacturers reported that there is an average of 2 breakdowns per turbine per year in a class of 25,000 turbines with which they were each personally acquainted. That's 50,000 breakdowns per year. [16] And although transient surges (including those from lightning) were thought to be the #1 cause of that damage, the information had not been tabulated for use or made broadly known.

Since lightning is by far the greatest source of damage to wind turbines, IEC 61400-24 should be made to require the establishment of a database of wind turbine accidents and damaging incidents. The data should be standardized to allow apples to apples comparisons and the data collection made easy for wind turbine owners/operators. Due consideration should be given to the intellectual property rights concerns of manufacturers and operators, but not to any efforts at cover up. The necessity of this database is justified by public safety concerns about wind turbine accidents and because of the huge amounts of public monies that have gone into research and development of wind turbines. In almost every country public funds continue to be spent on wind energy in the form of tax abatements and energy price subsidies. The costs of the database could to be born by the manufacturers, and the full disclosure of their accidents and damages could be made a condition of meeting the requirements of IEC 61400-24. In other words, those that won't participate or provide accurate data would be considered in violation of the standard.

B. Strength by simplification

The 61400-24 document is a busy one. It keeps the wind power industry engrossed in doing exposure assessments, choosing amongst lightning protection levels, and determining lightning protection zones. We will look briefly at these subjects and determine their relevancy to wind turbines.

1) Lightning Protection Levels (LPL's) and Lightning Exposure Assessments Revisited

Clause 6.2 of the 61400-24 Ed 2 document includes a system that invites customers to choose between 4 lightning protection levels, depending on their budget. The standard suggests if the parameters of LPL 1 are used, 99% successful protection may be achieved. LPL 2 reduces those parameters so that the lightning threat is met only 75% of the time. LPL III and IV further reduce those parameters to 50%. The major wind turbine manufacturers all use LPL 1 as a baseline, but as shown above, even turbines that use LPL 1 parameters sustain consistent and serious damage.

To determine the "correct" LPL you must first assess a turbine's risk as per Section 7 of 61400-24 Ed. 2. The basic equation used is:

$$R_X = N_X * P_X * L_X \tag{1}$$

Where Rx is risk to the turbine, Nx is the number of lightning events per year, Px is the probability of damage to the structure and Lx is the amount of loss per event.

Let's consider Nx: lightning flashes that may effect a single wind turbine or a wind farm. Clause 7.2.1 divides these into the following categories which must each be considered and calculated: N_D [year^{-1}] lightning flashes to the wind turbine, N_M [year^{-1}] lightning flashes within 350m of the turbine, N_L[year^{-1}] lightning flashes **to** the service lines connected to the turbine, N_M [year^{-1}] lightning flashes **near** the service lines connected to the turbine, N_D[year^{-1}] lightning flashes to another wind turbine or structure connected to the original wind turbine. (Maybe the wind turbine is in a farm connected to 100 or more other turbines.)

Not one of those lightning flash categories can be measured or calculated with any degree of accuracy. Not included in the risk assessment computation, but essential to any valid prediction, is the fact that, as mentioned above, tall structures like wind turbines initiate and trigger high amplitude positive lightning flashes. In other words, lightning will hit wind turbines at locations that would not be experiencing that lightning if the turbines were not there. [9] Also missing is the data that the taller the wind turbine, the greater the number and higher the amplitude of the lightning that will hit it. One study found that towers taller than 400m induce an average of 150% more CG lightning than the flat areas within 2km to 5km of the tower. [33] [34] Finally it has been established that the rotation of the blades itself significantly increases the likelihood of lightning strikes. [17] In the real world one can find wind turbines getting hit by 600% more lightning strikes than predicted by the standard. [9]

The irony is that the 61400-24 document writers themselves realize it. Clause 7.1 recalls the axiom that 'garbage in equals garbage out' and cautions the reader against expecting too much accuracy from the risk assessment procedure. Clause 7.2.2 warns, "For complex environmental conditions, high prediction errors can occur." ('Complex environmental conditions' describes the site conditions of almost all wind farms.) Clause 7.1 seeks to avoid having to use the risk assessment procedure altogether by suggesting one just takes LPL 1 as the default. That makes some sense except that as mentioned above, even LPL 1 does not deliver on its promise to provide effective lightning protection.

Decades ago, NASA called a very useful fact to attention concerning wind turbine lightning exposure. This was that the areas of greatest wind generally correspond to the areas of greatest lightning frequency. Maps prepared by NASA show that in most areas where wind density is high, there are 30 or more thunderstorm days per year. [18] Assuming you've sited your wind farm in an area of relatively high wind density, lightning is going to be a clear and present threat. Because it makes no difference to lightning protection strategies or cost whether there's 25 or 50 lightning strikes per kilometer per year, there is no need for the standard to complicate itself with a process like LPLs that gives no practical benefit to a wind turbine.

The LPL and Risk Assessments should be deleted from the standard and either new lightning prediction tools created based on the factors and references mentioned earlier in this section or more simply, the NASA references mentioned above should be adopted with all wind turbines classified in the highest risk category.

2) The rolling sphere method

The rolling sphere method is a procedure whereby imaginary spheres are rolled over a structure in order to predict which areas may and may not be directly struck by direct lightning. The size of the sphere used is determined by the previously discussed (and discredited) LPLs. In this case we have an assumed lightning current taken from a flawed lightning protection level estimation system chosen as the basis for determining the rolling sphere radius. In researching this paper, no study could be found to prove the accuracy or effectiveness of the rolling sphere system when applied to wind turbines.

It is known that up to 95% of direct strikes to wind turbines strike the blades, [19][20][12][21] yet Clause § 8.2.4.1 of 61400-24 Ed. 2 advises that the rolling sphere method "cannot be used for blades." So does the rolling sphere have any usefulness or relevance to a wind turbine? We can find little to justify its existence in this standard. Some experts take the view that the rolling sphere method is needed in order to define and differentiate lightning protection zones in a wind turbine. We shall look at this subject in the next section.

3) LPZ (Lightning Protection Zones)

61400-24 imported its lightning protection zone concept whole cloth from the IEC 62305 series. The original idea of the LPZ concept was to divide a building into a series of risk zones nested within each other, each with a successively less dangerous electromagnetic environment. When it first appeared in IEC 62305-1 it was designated for buildings 20 - 60 meters high. Modern wind turbines reach 3-4 times that height--way beyond the range originally intended for it.

The LPZ concept has been in widespread use applied to ordinary buildings for close to 30 years. When Rakov and Uman searched to find statistical evidence confirming its effectiveness for their encyclopedic work, *Lightning Physics and Effects* they were unable to find any [22]. Further searches in 2017 and 2018 also returned null results. Apparently no study has ever been able to authenticate the workability of the 62305 LPZ system even for simple structures.

But for wind turbines, with frequent direct lightning currents, some running as close as a meter or less from sensitive electronic equipment, the Lightning Protection Zone concept has little to no relevance. And as we will see in the next section, it can get people killed.

C. Protect the humans on a wind turbine

Lightning is a deadly hazard to all personnel on a wind turbine, and explicit, clear-cut instructions must be given them for what to do in a lightning storm that are not open to interpretation or misunderstandings. The 61400-24 standard has never included such a statement.

Figure 2 shows the evolution of the rolling sphere/LPZ systems as they pertain to human safety in the 61400-24 standard.

The 2002 version included a warning that "work should not be performed on wind turbines during thunderstorms" although this was tempered with Fig. 2-A and the advice that anywhere

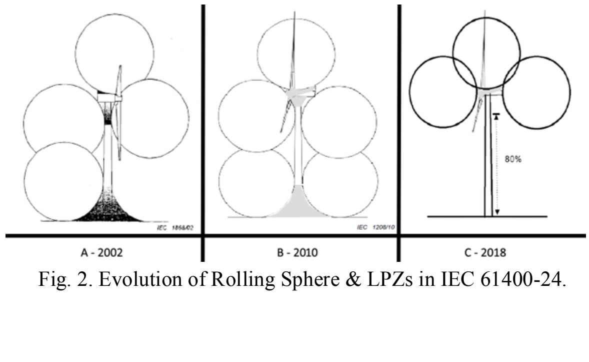

Fig. 2. Evolution of Rolling Sphere & LPZs in IEC 61400-24.

in the grey area would be safe for humans in a lightning storm. A close look at Fig. 2-A shows this would include anywhere just below the nacelle or hanging on to the anemometer atop the nacelle. This was removed in the next revision.

In the 2010 revision, *Section 10: Personal Safety* advised personnel to "go to the closest platform inside the tower and stay there until the thunderstorm has passed." This is based on the assurances (also in Section 10) that: "platforms inside tubular towers are in general considered safe locations, as the tower is a near to perfect Faraday cage." Both statements were falsehoods and were removed in the 2018 revision.

The 2018 edition abnegates any responsibility for human safety and leaves it totally up to the whim of the manufacturers to stipulate in wind turbine documentation which areas in the turbine are safe for humans during lightning storms and which are not.

A proper function of the 61400-24 standard would be to establish specific guidelines for what constitutes a safe area for humans in a turbine. In the United States whenever lightning is reported nearer than about 40 kilometers from a wind farm, personnel are immediately evacuated off the turbines until the storm has passed. Until the standard can define actual safe areas for humans in a wind turbine and requirements for verifying such areas, a much more responsible instruction would be something like that 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." [23] or from NASA: "Personnel around a wind turbine can be in serious trouble during a lightning storm. The safest procedure is for personnel to vacate the site. [24]

D. Improve the surge protection of wind turbine vital electronics

1) Transient surges from lightning & other sources

Aside from direct lightning strikes to the blades, currents and voltages sufficient to damage vulnerable electronic components can be induced from nearby lightning flashes and other sources of electromagnetic impulses. Such induced transients may produce electric fields that exceed 100,000 volts per meter along the wind turbine structure, whereas only a few volts above normal operating voltages can destroy many electronic components. [24] Internally created voltage transients are the most commonly encountered power quality disturbances in wind farms. [28] Such transients have devastating results for sensitive equipment and occur when wind turbine generators turn on and off, during capacitor bank switching, and during other fault conditions. [29] [30] Damaging transients can also originate from the operation of pitch control systems, transformers and circuit breakers and from surges induced through the grounding system by nearby strikes. Because such transients cause twice the number of damaging incidents as any other cause, lightning protection of a wind turbine is required to take into account all sources of transient surges. Typical frequency ranges for various transient phenomena in a wind turbine can be found at [25].

2) Surge protection failures in wind turbines

All surge protection strategies are premised on the principle that overvoltages must be shunted to ground over low impedance paths that bypass electronic equipment. [22] Wind turbine surge protection failures largely stem from 3 sources:

a) Failure to take into account the magnitude of the lightning threat to turbines, such as by installing 40kA-rated SPDs on wind turbines that see 200kA lightning strikes;

b) Leaving vital modes unprotected. A wind turbine often employs no direct/dedicated protection between phase-to-ground, yet vital control components are placed at risk from a number of sources when such protection is omitted. Overvoltages of 6kV have been measured from 10kA surges hitting the ground outside a wind turbine--far more than enough to damage equipment. [26] Wind turbine generators, pitch controls & circuit breakers can and do inject transient surges straight into the turbine's grounding system, stressing wind turbine electronics where no dedicated phase to ground protection exists. Surge protectors with dedicated, individual protection circuits for each of the 7 modes of a Y-connected wind turbine are available and should be deployed.

c) Failing to defeat the multiple impulse character of lightning. More than 80% of lightning flashes are comprised of 2-10 impulses. [27] Using a surge protector incapable of responding to more than 1 impulse within a few microseconds (such as encapsulated spark gaps with air or gas between the spark horns) places wind turbine electronic equipment at risk.

E. Why Wind Turbine Lightning Protection Systems Fail to Protect the Blades.

At this writing the world's tallest operating wind turbine is 246.5 m high (from ground to tip of blade.) A blade of a 200m high wind turbine can experience 100 million volts with respect to ground and the high peak currents injected by lightning strikes (as high as 200kA or more) are a source of significant energy. If a lightning protection system (LPS) does not divert this energy safely to ground through a low impedance path, much damage can result. [9] The challenge to any LPS is that larger than expected voltages and currents will appear instantaneously wherever a surge encounters a **discontinuity** in the conducting path. This impedance is the mechanism behind blade explosions, flashovers, plus generator & bearing destruction.

Much attention has been given to the composite materials used in blade construction. These materials are poor electrical conductors and easily destroyed by lightning if a lightning protection system is not provided. [31, 32] Aside from the blade material itself, attempts to mitigate blade damage have concentrated on blade shape, on where to install the termination points on the blades, and how many conductors are to be used within each blade. Although today's carbon fiber and glass fiber materials may be new, the problem they pose has been high on the list of wind turbine design priorities for the past 40 years. [35][36] In this period, many excellent proposals have been advanced to protect low-conducting wind turbine blades from lightning damage. These designs often perform well during standardized testing; yet universally fall flat when facing actual lightning on a modern wind turbine. Experts have advanced the idea that these failures suggest that the waveforms used to test these blade LPS designs should be revisited, [31] an idea, which may well have merit, yet we believe, misses the bigger issue.

The fact is that most modern blade LPS solutions work fine when they are effectively connected to ground, as they are in test labs. Every test set-up evaluating the efficiency of blade LPS solutions shunts the impulse current directly to ground. See, for example [37]. These test procedures miss the fact that modern wind turbine blades generally lack effective connection to earth ground. The high impedance path between blade and ground is the gorilla in the wind park that has been universally ignored.

Lightning protection systems today consist of the same three functions that Benjamin Franklin first proposed over 200 years ago: a means to intercept the lightning, a means to conduct the lightning charge downwards, and the means to safely discharge that energy into the ground. Applied to wind turbines we get: (A) lightning termination points in the blades, (B) down conductor, and (C) grounding system. Wind turbine literature is full of useful information pertaining to (A) and (C). Neglected is the **connection** between these two elements (B).

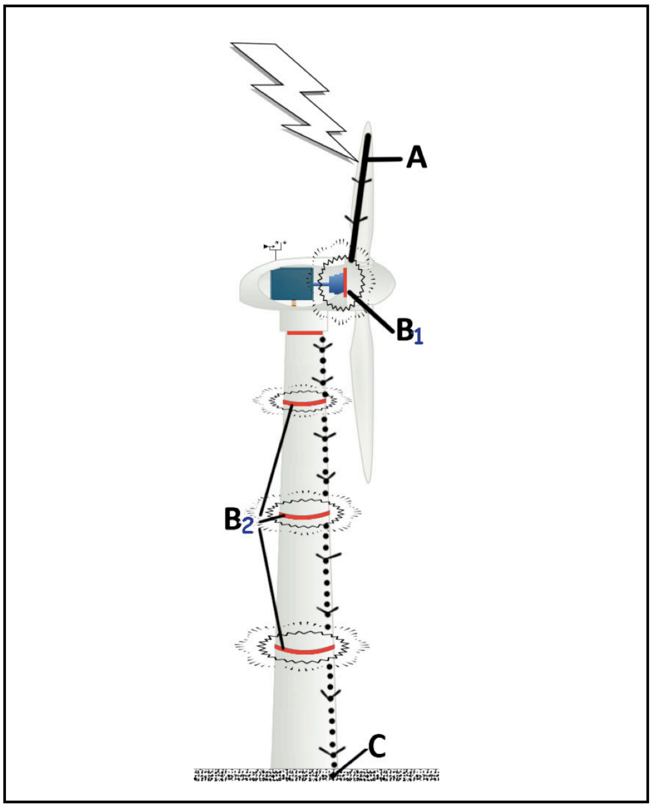

Fig. 3 Interferences with the smooth flow of lightning current to ground in a wind turbine LPS.
A- lightning attachment point;
B-1- Hi-impedance LPS connection at main shaft bearing;
B-2- Hi- impedance LPS connections between tower sections;
C- Ground

To be considered a lightning protection system, the lightning attachment point and the ground need to be well connected electrically, [22] but, in wind turbines, they are not.

1) Wind turbine high impedance LPS

When lightning hits a wind turbine blade, the charge is motivated by a single mechanical impulse: to get to the ground. **Impedance** (Z) expresses the total opposition that the lightning current encounters on its route from attachment point in the blades to the ground. The buildup of high voltages and excessive heat are two signs of the lack of a low impedance path from blade to ground. That is how you can reality-check the effectiveness of a wind turbine LPS: are these deleterious effects present or are they not? In debugging an LPS impedance problem in other types of structures the lightning protection expert generally looks for high resistance grounds, or corroded or poor connections to the grounding system. A wind turbine is a special case that requires a broader approach. Wind turbines operate according to a special form of Ohm's law:

$$V = I * Z \qquad (2)$$

where V = Voltage, I = Current, & Z = Impedance

(Also written as V = I (R + L)

The two factors comprising wind turbine impedance are ***Resistance*** (R) and **Inductance** (L). Resistance is largely determined by the material of which the down conductor is composed. For example, copper is considered a better conductor than steel because its resistance is 1/10th that of steel. In a given down conductor, the resistance will also vary with the diameter and length of the belt or cable. Per Ohm's law, the higher the resistance, the higher the voltage created. Another way of looking at this is that when resistance tends towards zero, the potential flow of lightning current through a conductor to ground tends toward infinity. [1] That is exactly what you want from an LPS. But as resistance can never actually reach "0", the goal should be "as low as possible."

The other factor directly impacting the impedance of a wind turbine LPS is its inductance. Inductance occurs when the flow of lightning moving through the wind turbine LPS is disrupted or hits some turbulence. As the current moves down the structure (at speeds of nearly 300 million meters per second) the magnetic flux in and around the turbine changes. The changing magnetic fields set up eddy currents around the structure that **oppose** the flow of the lightning current to ground. There can be many places on a wind turbine where inductance is created, but we will discuss here the two major ones: (a) the connections between the tubular tower steel sections and (b) the main shaft bearing (connecting hub and nacelle). See Fig 3.

2) The steel tower sections

[1] Resistance, in the form of soil resistivity, is also important to the grounding system, but here we are only considering the impedance of the down conductor part of the wind turbine LPS.

Towers supporting tall wind turbines are usually constructed of conical steel sections 20 - 30m long. A tower may have as many as 5 of these sections sitting one on top of another, fastened together with bolts.

IEC 62305-3 gives sound advice about down conductors including that towers be protected with as many parallel down conductors as possible but never less than 2. And each conductor, by definition, should be "electrically continuous." That sound advice is disregarded in IEC 61400-24 which allows the tower's steel tubular structure to be used as the turbine's primary LPS down conductor. (Ed. 2 §9.3.2). Structurally, when one of these massive steel sections is sitting on top of another of them with nothing but a few M-30 bolts holding them together, a high impedance connection is created. See three such junctions at Fig. 3-B2. IEC 61400-24 assumes, unwarrantedly, that the wind turbine tower provides a more or less electrically continuous path to ground. Manufacturers know that is not the case and seek to mitigate the resulting side flashes by installing electrical clamps or braid between the conical sections. It is unclear how good an electrical connection this provides, but what is clear is that the potential effects of these high impedance connections between tower sections is not considered anywhere in the standard.

3) Rotor and bearings

A wind turbine's blades are where most lightning hits, and when that occurs the entire turbine structure becomes a part of the lightning discharge path. The main shaft bearings sit squarely in the center of that path and serve as a very high impedance junction. The mechanism employed today to channel the lightning currents striking the blades is unchanged from that used 50 years ago: either allow the bearings to conduct the full current or try and divert some of that current through shunt conductors or slip rings utilizing brushes. Neither provides a low impedance connection.

Fig. 4-A shows the connecting mechanism between rotor and nacelle as viewed from the nacelle looking into the hub. Marked are the stationary parts of the nacelle (the single outer ring of bolts) and the rotating parts of the rotating hub. That bearing must support the tremendous load of the hub and blades as well as permit them to rotate while connected to the stationary nacelle. Depending on the model and size of the turbine, the bearings are likely to be of one of the types shown in Fig. 4-B. None of them provide a very good electrical connection. That isn't their purpose.

Lightning-caused damage to blades, already recognized as a wind turbine's costliest nemesis, could be as much as double that which has been reported. The HSE/NREL study previously cited laments that "Most of the time, information on failures is not provided by owners and operators." Besides lightning, other primary causes normally cited for blade damage such as design defect, wear and tear, and mechanical defect, may also be majorly attributed to lightning. [8]

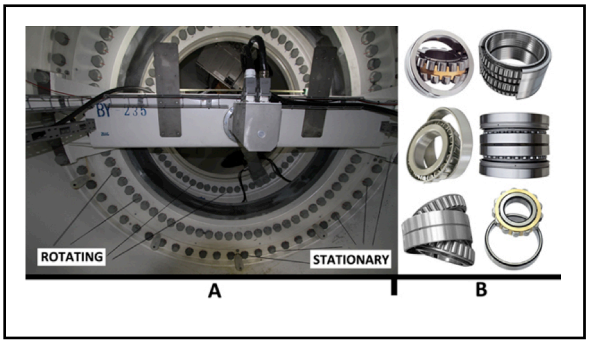

Fig. 4-A - wind turbine main shaft bearing as seen from nacelle.
Fig. 4-B - types of typical wind turbine bearings.

When lightning hits a wind turbine, voltages can be raised to millions of volts and temperatures to 30,000°C. These mechanical and thermal stresses continuing over time take their toll. After a few years in service, when a blade fails one beautiful summer day with not a cloud in the sky, inspectors must resort to blaming poor maintenance for the failure even though, as day follows night, lightning was the actual culprit.

Tests confirm that when blades melt or explode in the presence of a lightning strike, those losses are proportional to the level of peak current. [8] But the problem is not only the current amplitude. The duration of the current plays a decisive role in the heat generated and dissipated. IEC 62305-1 calls this to attention in Annex D (Test Parameters simulating the effects of lightning on LPS components) but concludes, "In most cases the duration of the impulse current is so short that the heating process can be considered adiabatic[2]." This is true for solid copper down conductors with next to no impedance, but it is not true for the high impedance connections discussed in this section or for wind turbine blades, and ignoring the duration of current on wind turbine blades has been a costly omission. The mechanism of heat and voltage build-up in a blade is the subject of impedance.

If the lightning discharge directly reaches a low-impedance down conductor and thence to ground, the blade is unlikely to be damaged. Unusually high voltages and temperatures are created when only when the LPS includes high impedance parts and connections.

Figure 3 shows a lightning strike hitting a wind turbine blade (A). If fitted with adequate conductors, the flow of current would flow swiftly and smoothly down to the ground, dissipating itself via the grounding system (C). LPS systems around the world have demonstrated their ability to do just this and studies prove that structures fitted with LPS do avoid structural damage. This is so evident that insurance companies will reduce premiums for structures with lightning protection systems installed. Unfortunately, for the reasons listed above, this tried and proven strategy of protection against structural damage has not worked on wind turbines.

[2] A process that causes no heat exchange.

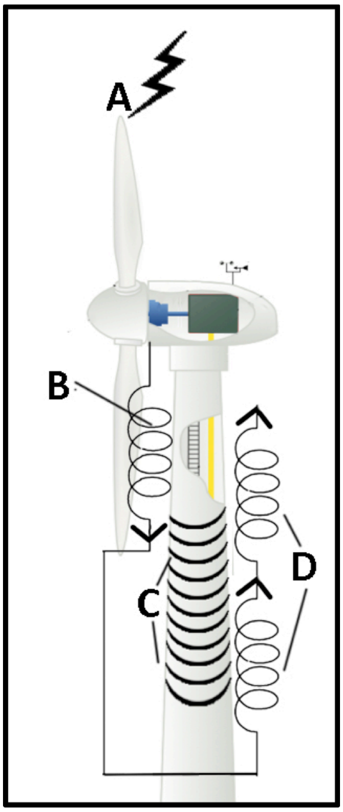

Fig. 5. Wind Turbine Self Inductance
A - Lightning strikes blade
B. - Current & magnetic flux flow towards the ground
C. - High impedances on the path to ground cause:
D. - Self Induction, wherein the current flow and magnetic flux reverse direction to oppose the flow to ground.

F. Self-Inductance intensifies all the above wind turbine problems

When existing wind turbine LPS connections carry lightning currents to earth, any high impedance connections create turbulence and disruption to the smooth flow of energy. This turbulence generates a viscosity in the electrical flow (an impedance) that slows down the current allowing heat to build up and increasing voltage to levels resulting in side flashes. This brings us to the last phenomenon present in this process, which is explained by Lenz's Law and called self-induction. Figure 5 shows lightning hitting a wind turbine blade (A). The electrical force flowing down towards the ground is labeled (B). The lightning current moving down the tower produces a magnetic field proportional to the current. Whenever that flow meets high-impedance connections (Fig. 5-C) the resulting changes in the speed or direction of the flow creates an electromotive force that acts to oppose the direction of current (Fig. 5-D.) Lenz's law states that the current so induced will oppose the flow of current to ground. It will exert a mechanical force opposing the efficiency of the lightning protection system. This is called wind turbine self-induction because the structure of the turbine itself pushes back against the lightning current, opposing its smooth flow to ground.

Removing the high impedance elements mentioned above will go a long way towards nullifying the adverse effects of wind turbine self-induction. Two obvious improvements could be made by: (1) Providing a low impedance connection between the rotating hub and the tower. This major shortcoming has been known about for 50 years, yet remains unsolved; and (2) Ceasing to use the tower steel as the primary wind turbine LPS down conductor. Much better conductors can be designed and deployed.

G. Conclusions

Lightning's direct and indirect effects cause by far the most damaging incidents, the most downtime, and the costliest repairs to wind turbines. Manufacturers and wind farm operators look to IEC 61400-24 for guidance in improving the safety and efficiency of wind turbines, but a widespread lack of transparency concerning wind turbine accidents and damaging incidents makes it difficult for the wind turbine lightning protection standard to perform its duty. A database of wind turbine damage and accidents is needed so the workability of proposed 61400-24 protection strategies can be ascertained.

The standard can be simplified and strengthened by eliminating strategies that do not apply to modern wind turbine generators such as LPLs, Rolling Spheres, and LPZs.

IEC 61400-24 should establish specific guidelines for what constitutes a safe area for humans in a turbine. Until it has done so, it should advise "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."

Lightning surge protection on a wind turbine can be greatly improved by realizing that 200kA lightning currents are likely to appear on the turbine, by requiring that every electrical mode (including phase to ground) be fitted with dedicated protection, and by deploying only surge protectors capable of handling the multiple impulse character of most lightning.

Finally, it is clear that the high impedance connections between rotor and ground are a major shortcoming in wind turbine LPS design that must be targeted for improvement. Unlike the LPS systems used in other tall towers such as telecommunication sites, radar installations, etc., a wind turbine LPS provides no solid electrical connection between the lightning attachment point in the blade and the ground. Instead it is interrupted at the connection between rotor and nacelle, and further interrupted at the connections between each of the tower sections. Most of the blade lightning protection systems in current use would work fine if they were connected to a low-impedance, electrically continuous conductor to ground.

Researchers and designers of wind turbine LPS systems would be well served to place at the top of their list of priorities the invention or development of a true low impedance connecting network between the rotating hub and the ground.

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