# In situ Lightning Monitoring Systems (LMS) for improved wind farm operation

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# SUMMARY

The present paper addresses the experience gained with operating wind turbine blades in a lightning prone area and utilizing lightning measurement systems (LMS) to optimize inspection and maintenance schedules. The process followed has been to correlate blade damage patterns with measured lightning waveforms, such that these accumulated findings enable a preventive maintenance. The work has underlined the fact, that it is significant cheaper to fix minor problems before they escalate to complete blade breakdown. Annual savings in repair cost of 1300-4300 EUR/MW installed, plus increased availability of value 1500 EUR/MW installed are demonstrated.

# INTRODUCTION

Let's be honest, some wind turbine blades are not working properly with regards to lightning. And why is that? - they are all designed according to the industry standard IEC 61400-24, and verified - and most likely even certified by a third party?

Lightning protection is complex, and at most wind turbine manufacturers, it is assigned to the junior mechanical engineer spending time with it for a few years before they move on in their career. Only few engineers understand the physics of lighting and the interaction with common wind turbine blade designs, and hence master how to assess the attachment point distribution, how to calculate the current flow from blade tip to root, the insulation coordination between parallel conductive paths, and the mandatory verification testing pr. IEC 61400-24 Ed2. The text and requirements are clear, so for new blade designs there are no excuses.

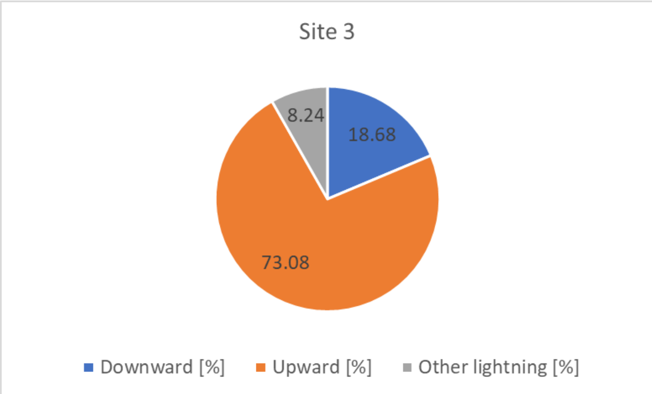
For older designs, poor performance can be mitigated to a certain extent by retrofit installations, although it is expensive to reach LPL1 efficiencies. Luckily, the operation of even inadequate blade LPS can be optimized, by measuring the actual lightning striking the blades, and correlate with the blade design performance gained from accumulated field experience, or testing. This paper address how lightning measurements using a blade specific Class I blade LMS, can be used to reduce OPEX drastically, both in terms of reduced repair cost, and increased availability.

# SITE AND WIND TURBINE TOPOLOGY

The onshore site in question is very active, both in terms of wind resources and lightning. It is located in a mountainous area in a temperate climate zone, where the elevation is seen to have a clear impact on the amount and type of lightning strikes affecting the site. The 26 turbines are 5 years old, equipped with 60-70m blades made of both glass fiber and carbon fiber composites. The LPS design considers a metal tip, an array with side receptors, also connecting the tip to the Expanded Metal Foil (EMF) which covers the shells. The down conductors are made in a combination of internal HV cables and external EMF. The lightning protection coordination effort is unknown.

Considering the time frame from 01/01/2022 to 31/12/2024, 2341 strikes have been recorded, and classified according to [1]. The distribution of strikes from a limited subset (182 strikes detected in 1month) is shown in Figure 1.

**Figure 1** Strike classification based on 182 lightning events measured during 1month of lightning recording *[1]*.




As described in [1], it is evident that thunderstorms are originating close to shore, pushed from the SW direction towards the shore and lifted over the mountains, in which the turbines have suddenly emerged in the charged clouds. The consequence is a general high lightning intensity and a substantial number of upward strikes. The majority of these strikes attach successfully to the air terminations, but some of the strikes happen to attach at blade inboard sections.

# LIGHTNING MEASURING SYSTEMS

The Lightning Measuring Systems deployed is the LKDS™ by Polytech [2]. The LKDS is the only Class I blade lightning measuring system according to IEC 61400-24 Ed2.1 [3], measuring all quantities of the lightning strike, in the individual blades, necessary to steer your maintenance. It was introduced in the market in 2015, and have experienced natural updates in terms of software, processing speed, robustness, etc. The measured quantities and accuracies haven't changed.

Many vendors provide so called "Lightning Measurement Systems" (LMS), but experience have shown that this term covers a wide range of products. Some don't even measure lightning, some exhibit unreasonably high trigger levels, and some come with measurement tolerances which are far from suitable for the purpose. IEC TC88 MT24 issued an amendment 2.1 (revised Annex L) on lightning measuring Systems the 13th of November 2024, which sought to clarify the important properties of LMS, and demonstrate use cases for OEMs, operators and insurance companies. This Annex also defines four different classes of LMS, and obviously, the operators who want to gain the most in terms of OPEX savings, can now chose a system which enable that saving by measuring accurately in each blade.

For the LKDS, each blade is fitted with a Rogowski coil sensor, embedded in HV insulation material to ensure that the differential voltage between the down conductor and the sensor coil during lightning current flow can be withstood. Rogowski coils are a well-known principle for measuring transient currents, and the coils optimized for LKDS, exhibit "-3dB" cut off frequencies from 0.03Hz-10MHz. The sensors are connected to a central recording unit mounted in the hub, which is responsible for recording the entire lightning current waveform, processing the data into the four key parameters, and enabling remote access for both raw data and processed parameters for the operator of the LKDS.

The specifications are listed below:

- 10MS/s sampling rate, 0.1µs resolution.
- 1.5s recording time, 100ms pre-trigger.
- 16bit vertical resolution, +/-240kA
- '-3dB' frontend bandwidth: 0.03Hz to 10MHz
- Simultaneous recording on all three blades.
- GPS or NTP synchronized time stamp.
- Remote access of full waveform and key data.
- Key data recorded per strike and per stroke:
    - Peak current, $I_{peak}$ [kA]
    - Specific energy, AI [kJ/Ω]
    - Charge, Q [C]
    - Current gradient, dI/dt [kA/µs]

The key data and waveform characteristics measured by the LKDS in the different locations are used to classify the lightning strikes with respect to polarity, direction of initiation, ICC pulses (Initial Continuous Current), etc. These are the information used to train the algorithms to suggest the consequence of the strikes experienced.

# FIELD EXPERIENCE AND DOCUMENTED OPEX SAVINGS

After more than 3 years of operation of the turbines with LMS installed, certain patterns are observed regarding damage mechanisms and lightning parameters.

It is evident that specific blade features react differently to the different lightning key parameters, and a careful and ongoing correlation between lightning exposure and observed lightning interaction with the blades, have led to an improved maintenance and repair strategy. Although blades are often certified to survive LPL1 impact, experience with specific blades shows that sometimes certain features of the lightning impact result in damages, both minor and catastrophic events.

The analysis conducted for the specific site, have led to both Qualitative and Quantitative learnings on lightning interaction with blades.

## 5.1. QUALITATIVE EXPERIENCE

For the particular blade design and specific lightning environment at site, the following tendencies are revealed [4]:

- Negative CG tends to be more damaging than Positive CG. It is also more frequent, but this is not the reason for being more destructive (highlighted below).
- Critical lightning parameters are the peak current and maximum current gradient (di/dt). Negative lightning strikes tend to have higher di/dt.
- High di/dt either on the first or the subsequent return stroke may cause significant flashover events.
- High Intensity Positive Lightning tends to be successfully conducted by the LPS, but it may damage the receptors. Also linked to CAT4 external damage near the tip. There was 1 serious flashover damage linked to a positive strike with high di/dt.
- Charge transfer could not be linked with critical or severe damages, but it may stress the receptors or enhance extent of damage given that I and di/dt are sufficiently high.
- We have recorded positive lightning strikes with energy transfer exceeding the LPLI threshold. Except some burning marks on the receptors or the blade root's conducting belt, no other damage was caused in the LPS or the blade.

## 5.2. QUANTITATIVE EXPERIENCE

The LKDS operator set-up an algorithm to assess lightning risk based on LKDS measurements. They came up with a decision tree algorithm which is set upon certain thresholds of the 4 key lightning parameters. Peak current and current gradient thresholds are the primary drivers which help distinguishing between different alarm levels. At a secondary level, the algorithm checks for energy transfer values and/or stroke count of strikes containing multiple strokes to decide about the alarm level triggered. Thresholds are dynamic, i.e. they were initially set according to IEC 61400-24, but they have been modified several times after gaining field experience from blade inspections.

For the particular blade design and specific lightning environment at site, the quantitative findings shown in Table 1, Table 2 and Table 3 are made [4].

Table 1 highlights the success in mitigating lightning damage risks. Of the total alarm triggers, 60% were linked to a blade damage or a cluster of blade damages. Early detection is crucial to avoid damage progression through cyclic loading. In the case of critical damages, LKDS assisted management led to the avoidance of 2 blade replacements. Instead, in each case, the wind turbine was immediately stopped and inspected, and the critical damage was repaired up tower preventing escalation.

**Table 1** Algorithm hit rate

| Algorithm hit rate (2022-2024) | | | |
|---|---|---|---|
| | Alarms | Damages | Hit rate |
| **Total** | 99 | 60 | **61%** |
| **Critical** | 10 | 5 | **50%** |

Table 2 provides some indicative lightning parameter thresholds for significant laminate damage, as inferred from the correlation of the LKDS measurements with the blade inspection findings. Each key parameter has been separately evaluated.

**Table 2** Lightning parameter thresholds for significant laminate damage

| Thresholds for >=CAT3 laminate damage | | |
|---|---|---|
| **Parameter** | Positive lightning | Negative lightning |
| **I(kA)** | 107 | **-45.3** |
| **W(MJ/ohm)** | 5.6 | 1.2 |
| **di/dt(kA/us)** | 21 | 14 |

In Table 3 an effort to quantify the correlation between various lightning parameters with the lateral, the longitudinal extent and the area of the damage has been made. The sample consists of 84 cases of lightning damages linked to actual lightning strikes measured by the LKDS. It was found that the square of the peak current displays a moderate linear correlation with the lateral length of the damage and a strong non-linear correlation (Spearman coefficient 0.46, p-value=0.05).

**Table 3** Linear correlation between lightning parameters and internal damaged area

| Correlation matrix($R^2$) light. params vs internal damage extent | | | |
|---|---|---|---|
| **Variable** | lateral length | long. length | Damaged area |
| **$I^2$** | 0.83 | 0.79 | 0.78 |
| **di/dt** | 0.04 | 0.04 | 0.02 |
| **$a*di/dt+b*I+c*I^2+d*W$** | 0.89 | 0.89 | **0.8** |

There is also a weak linear correlation with the damaged area and a moderate non-linear correlation (Spearman coefficient 0.40, p-value=0.05). On the other hand, no direct correlation was found between current gradient and damage extent. If however, a linear relationship of di/dt, I , $I^2$ and W is formed by using polynomial regression, this linear relationship is strongly correlated with the damage extent and area.

The linear relationship seems to represent the voltage difference between the laminate and the LPS, leading to flashover events.

## 5.3. FINANCIAL IMPACT OF MITIGATION PLAN

Based on the thorough analysis of the lightning impact and the associated damages, the operator has managed to cut the cost for operational expenses significantly. The ability of detecting lighting events and having an adaptive algorithm to assist the decision on whether to continue operating the turbine, or stopping, inspecting and potentially repairing it before damages escalates, have proven very beneficial.

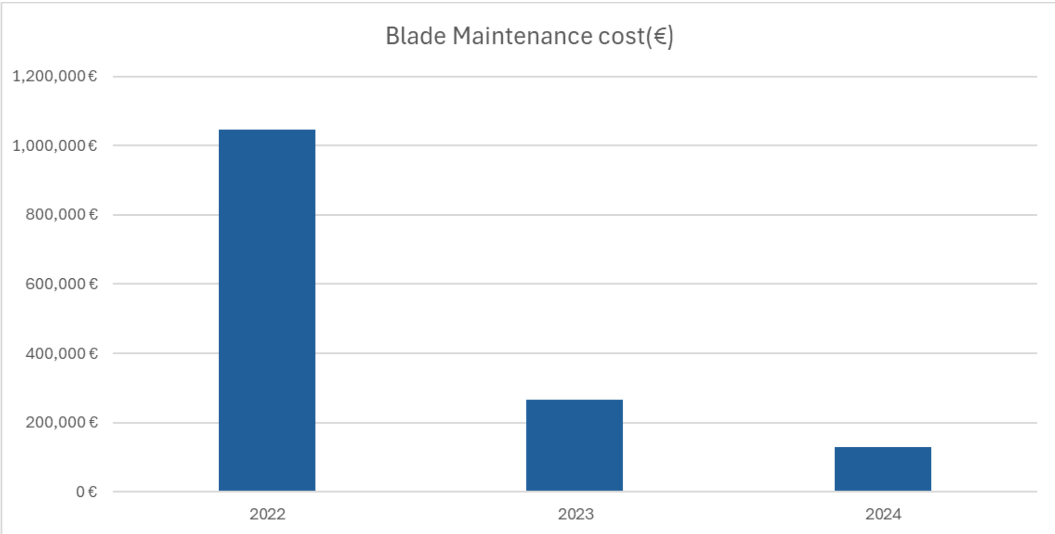
Below some highlights of our OPEX optimisation are provided:

- Online Lightning Monitoring prevented 3 blade replacements in the past 2 years.

- OPEX annual saving from Predictive Maintenance Activities is roughly 1.8€/MWh or 2000€ /MW.
- Annual energy yield gain is another 1.0EUR/MWh or 1500€/MW.

The evolution of the Maintenance cost over the past four years is provided in Figure 2.

**Figure 2** Evolution of maintenance costs by utilizing lightning measurement systems for driving turbine maintenance.




As seen in Figure 2, the total cost drops significantly (halved) by avoiding minor events developing into catastrophic events requiring blade replacements. This is a clear advantage for the turbine operator, since lower maintenance costs equals a larger ROI. Finally, having factual information available on lightning exposure and design performance, will also drive the development of future wind turbine blades to become more resistant towards lightning damages.

# GENERAL GUIDELINES

The benefit of utilizing LMS data for optimized OPEX is only increasing, as field experience on lightning interaction with the blades and lightning measurements are correlated and accumulated. Knowledge about the blade design, the blade design verification, and design rationale will ease the definition of an evaluation strategy. If only limited information is available, the fundamental mechanisms of lightning interaction with wind turbine blades suggest the following criteria.

## 6.1. CURRENT MAGNITUDE

Current magnitude drives the electromagnetic forces, such that conductors in proximity with each other will experience forces, known as Lorentz forces. If the current components are parallel, the two conductors will experience a force of attraction, whereas if the current components are antiparallel, the forces will repel one conductor from the other. The forces are proportional with the square of the magnitude and inversely proportional with the distance.

## 6.2. SPECIFIC ENERGY

The lightning strike is considered a very high impedance current generator, meaning that the current waveform is not affected by the blade which is struck. In that sense, the specific energy defines the energy release per unit of resistance, being the time integral of the current squared. For CFRP blade designs using internal down conductors, excessive current and specific energy is experienced in the equipotential bonding. Also, inadequately connection components on GFRP blade LPS, may observe damages for high specific energies.

## 6.3. CHARGE

The main effect of charge transfer is the erosion of air terminations, spark gaps, or other parts of the LPS constituting open arcs. In the IEC 62305-1 [5], an equation linking the transfer of charge with the volume removal of the affected component is provided, indicating a volume proportional with the time integral of the current. For the majority of blade LPS designs, the blade tip is fitted with a SMT (Solid Metal Tip), which is very immune to arc root erosion due to charge transfer. Only in very severe sites exposed to numerous upward strikes, and for blade designs with discrete lightning receptors, wear and tear due to charge transfer may be critical.

## 6.4. CURRENT GRADIENT

The current gradient affects the voltage drops during the lightning strikes, in the sense that both longitudinal voltages and differential voltages will be close to proportional with the current rate of rise. For blade designs with inadequate equipotential bonding, the consequence of the differential voltages will be frequent side flashes, where discharges within the blade design will seek to equipotentialise the different conductive components, down conductors, electrical sensors, carbon fibre spar cabs, etc.

## 6.5. TRIGGER THRESHOLDS

The four key parameters; current magnitude, specific energy, charge, and current gradient, each affect the blade designs differently.

Blades with discrete air terminations erected in intense lightning areas will suffer erosion at the air termination from the charge transfer, blades with limited lightning protection coordination may suffer side flashes at high current gradients, and blades with limited quality connection components may fail due to excessive specific energy.

The specific blade designer should evaluate how the blade is affected by each of the lightning key parameters, or a combination of them, based on simulations and verification tests conducted during the design and certification of the blade [3]. Secondly, field experience and correlations of blade damages and lightning key parameters can define the thresholds for inspections.

Until this evaluation is done sufficiently in the design phase, or acquired during field experience with the specific blade, a suggestion for inspection threshold levels could be as shown in Table 4.

**Table 4** Proposed threshold value for triggering inspection, until sufficient field experience is gained

| Lightning parameter | Glass blade | Carbon blade |
|---|---|---|
| Positive peak current | Ip < +10kA or Ip > +50kA | Ip < +10kA or Ip > +50kA |
| Negative peak current | Ip < -50kA | Ip < -50kA |
| Charge transfer | 50C | 50C |
| Specific Energy | 1000kJ/Ohm | 200kJ/Ohm |
| Current gradient | Not relevant | dI/dt > 15kA/us |

Although the threshold values suggested Table 4 are significant less than design values for LPL1 in IEC 61400-24 [3] used for the vast majority of wind turbine blades, experience have shown that a conservative level is advised for starting the iteration on "LKDS data vs. damage" correlation.

# CONCLUSIONS

The present paper has highlighted and documented the following facts:

- In situ Lightning Measurement Systems are commercially available, and comes in different performance ranges, and costs. Annex L of IEC 61400-24 Ed2.1 is written with the purpose of clarifying differences and benefits of the various types of system.
- If Class 1 systems are used, an impressive granularity of the lightning waveform can be achieved, enabling a careful evaluation of blade damage risk. The evaluation can rely on known blade design and general knowledge of lightning interaction with wind turbine blades, but should also be updated as field experience is accumulated
- From a specific onshore site, it is seen how savings in terms of reduced repair cost and reduced down time greatly improves the business case of operating a modern wind farm. Quantitatively, the case demonstrates how the annual OPEX savings due to predictive maintenance amounts to 1.8 EUR/MWh or 2000 EUR/MW installed capacity. Adding to this, the annual energy yield gain is another 1.0 EUR/MWh or 1500 EUR/MW.

# REFERENCES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