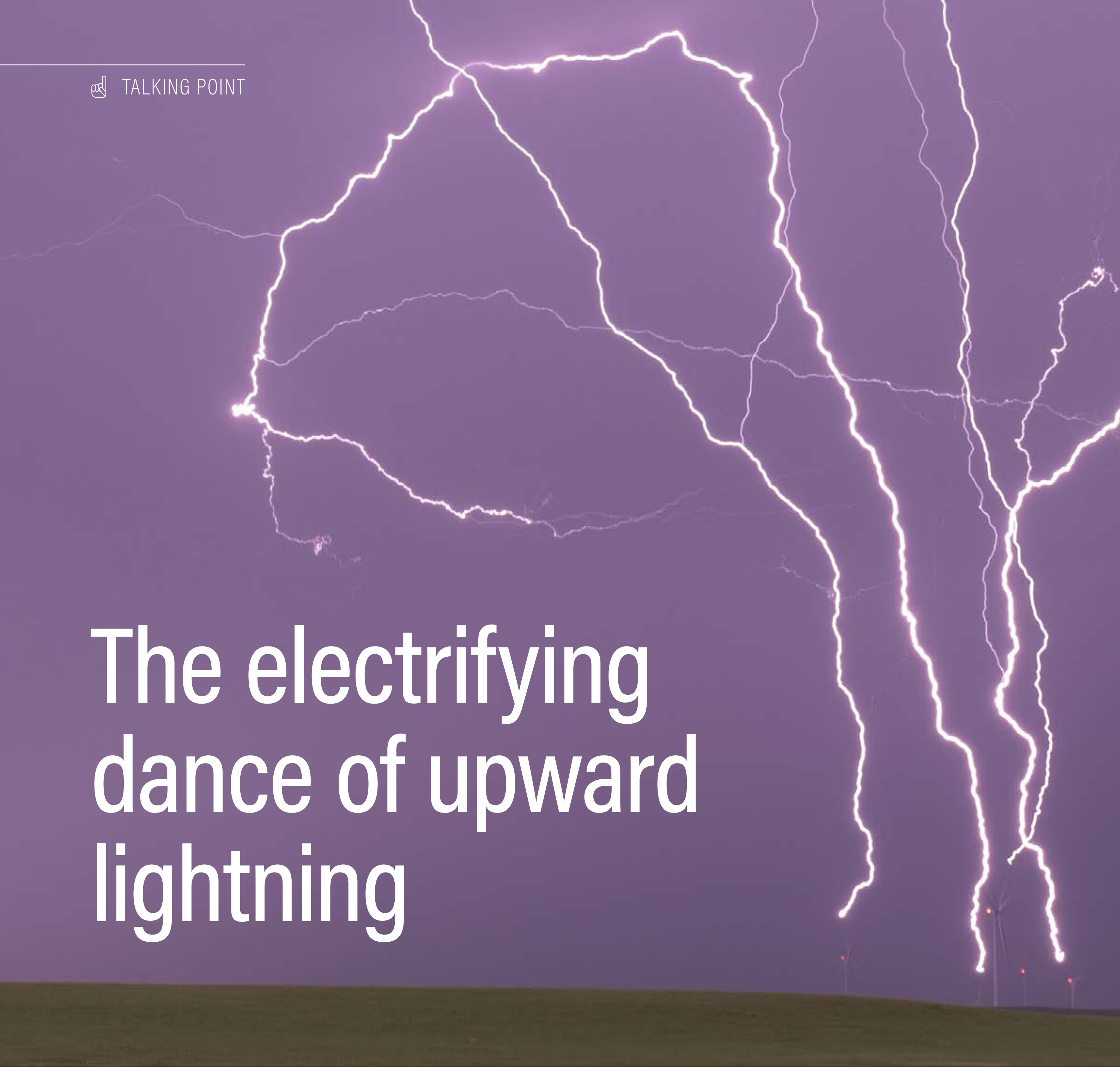

The electrifying dance of upward lightning

Blades certified before 2019 may be susceptible to damage from a destructive and anomalous type of lightning strike. Lightning protection systems (LPS) have been tested to an international standard since the early 2000s; however the focus was mainly on cloud-to-ground lightning and associated high energy levels. But there is another type of lightning that is less well-known. Difficult to detect and record, this elusive type of lightning can wreak havoc on wind turbine lightning protection systems.

This mysterious type of lightning is not normally seen, unless there is a really tall object nearby. Wind turbines are in that category; even 1 to 2 MW machines are relatively tall. Wind turbine designers are now pursuing 20 MW machines that will reach higher into the sky than ever before. Early estimates put 2 MW blade tips at over 300 m above the ground, taller than many buildings and even radio towers.

This creates a new level of lightning threat to wind turbines: the dreaded upward lightning.

What is upward lightning?

Most lightning strikes begin when massive quantities of electrical charge stored in thunderstorm clouds can no longer be contained. The charge exits the cloud and moves towards the earth, where it produces

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a massive display of light, heat, and thunder. These common cloud-to-ground strikes can be negative or positive.

Negative cloud-to-ground strikes are easily identified by their multiple bright flashes and illuminated branches, like an upside-down tree. Positive cloud-to-ground lightning strikes tend to be singular continuous charge transfers with a powerful beginning. Positive cloud-to-ground strikes are relatively rare but are noticeable by their lack of branching.

Upward lightning is very different from cloud-to-ground lightning. The lightning begins from the grounded object, typically a wind turbine, building, or tower, and travels at 100,000+ m/s to reach the charge in the clouds above.

There are two typical upward strike scenarios. As commonly documented in the United States, a large storm cloud creates a positive cloud-to-ground lightning strike which reverberates a negative discharge through the base of the cloud, referred to as crawling lightning. As the lightning traces along the clouds, the wind turbines react by reaching up with a filament of the opposite charge. This scenario leads to wonderful photographs of multiple wind turbines reaching towards the clouds simultaneously like the fingers of Zeus.

The second scenario is a bit rarer but just as important. There are no lightning strikes in the area but there is a significant amount of charge stored in the cloud. The presence of the wind turbine near the charge creates a rising filament of charge from the turbine which triggers a lightning flash.

During upward lightning, the clouds can't discharge fast enough. The charge transfer is relatively low to start, with occasional higher energy bursts, long pauses, and additional high energy pulses towards the end of the event.

The problems caused by upward lightning aren't caused by the strike itself, but instead result from the lightning pauses. A lightning channel is a fickle and temporary pathway of conductive plasma. A momentary pause around 1/1000th of a second, or 1 millisecond, can cause the lightning channel to collapse and become non-conductive. During upward lightning, there can be several current pauses greater than a millisecond. This forces lightning to re-use a degraded pathway or create new pathways for current to flow. A new pathway means a new blade connection point, and that connection can create an expensive blade puncture.

Blades designed before 2019 generally were not tested for the pause that occurs during an upward strike. With considerable industry feedback and scientific research, IEC 61400-24 Edition 2.0 (2019) includes additional tests such as the 'Subsequent Stroke Attachment Test', which recreates the high voltage breakdown that can occur between a blade and a lightning channel after a pause.

How do operators know if their turbine has been involved in an upward lightning event?

Detecting upward lightning can be quite challenging without specialised equipment. Lightning location systems (LLS) typically identify cloud-to-ground and cloud-to-cloud lightning accurately, but they may struggle with upward lightning. The slower-changing currents generated by upward lightning result in weaker electric and magnetic fields, making detection more difficult. Additionally, upward lightning often occurs simultaneously from multiple turbines, making it tricky to pinpoint a precise location.

More recent lightning detection systems from Sensoria, Phoenix Contact, and Polytech use magnetic field or current probes installed inside each blade which detect the current from an upward lightning strike. The benefit of these systems is that information is provided for each blade, which allows technicians to quickly investigate potential issues.

Tower-mounted lightning detectors are also capable of tracking upward lightning. Offerings from Jomitek and Ping sample the magnetic fields generated from lightning currents flowing in the turbine tower. Although these systems can't provide blade specific information, they tend to be less expensive and require less time to install.

In Japan, turbines are outfitted with large Rogowski coils wrapped around the base of the turbine tower. Rogowski coils sense the magnetic fields generated by currents flowing through the tower. These devices can be relatively low-cost and provide highly accurate data which researchers use to analyse the strong lightning strikes experienced in the region.

Are existing blade lightning protection systems designed for upward lightning?

Blades designed and certified after 2019 should be better prepared for upward lightning, due to the IEC 61400-24 2.0 update. Newer blades may have more receptors, metal mesh and/or segmented lightning diverters to keep lightning away from the composite structure. However, the vast majority of blades already in service, designed before 2019, are at risk.

Can the pre-2019 blade designs be upgraded to meet the newer IEC 61400-24 requirements?

Yes, most of the OEMs have tested or offer lightning upgrades to their older blade fleet. Unfortunately, operators who ask for lightning upgrades are presented with massive purchase prices and long lead times.

Operators can take matters into their own hands. Here are some simple steps to reduce lightning damage from upward strikes. Verify that the existing LPS is in working form; it's the backbone of your protection. Fix the leading-edge erosion around the receptors, because lightning prefers a clean air pathway to the receptors. Add segmented lightning diverters around the receptors to guide lightning to the existing LPS. Finally, install lightning detection on turbines and inspect blades after detected strikes.

Notably, Aerones offers innovative robotic solutions that can measure LPS resistance, identify down conductor breaks, and even repair leading-edge erosion for blades in service.

Looking ahead, blade designers must stay informed about lightning research to build better lightning protection systems. Tom Warner, Dr. Marcelo Saba and numerous others spent several years documenting upward lightning strikes via the Upward Lightning Triggering Study (UPLIGHTS) research campaign. The researchers used a combination of high-speed photography, electric field meters, and lightning mapping arrays to document strikes to tall towers in the US. The resulting data and insights provide critical information about upward lightning. Blade designers need to incorporate this research into the next generation of their work.

In Asia, Chinese researchers are investigating the influence of pressure gradients around the blade tip on receptor responsiveness to incoming lightning. Another set of Chinese researchers are modelling the flow of positively charged particles produced by receptors prior to a strike which directly impacts the receptor performance.

Powerful new CFD modeling by Denmark-based PowerCurve has explored aerodynamic effects on lightning. Their investigations include turbulence generated by leading edge erosion, vortex generators, trailing edge serrations, and blade pitch angles, which offer exciting new possibilities for research. Early CFD models have found the basic tip shape of most blades creates an impactful amount of turbulence that disrupts the receptors. Leading edge erosion adds to the turbulence, which makes lightning attachments to tip receptors much less likely.

Blades with carbon fiber spar caps can be at a disadvantage with regard to upward lightning. The proximity of the conductive carbon fiber to the surface of the blade increases the likelihood of damage. Blade manufacturers in some instances are adding metal mesh to the exterior of the blades to re-direct or reduce the lightning energy away from the carbon. The mesh is locally damaged by a strike, but the carbon remains generally unharmed.

Over the past two decades, the wind industry has made remarkable strides in lightning protection. However, with the anticipated growth of turbine blade lengths, we must rally together as a lightning community to safeguard the turbines of the future from the electrifying forces above.

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