Lightning and surge protection for wind turbines

Due to their vast exposed surface and height, wind turbines are frequently hit by direct lightning strikes. Comprehensive lightning and surge protection measures are essential to maximise the return on investment and prevent downtime.

Cloud-to-earth flashes, and earth-to-cloud flashes, so-called upward leaders, must be considered for objects with a height of more than 60 m in exposed locations. The high electrical charge of these upward leaders must be particularly taken into account for the protection of the rotor blades and when selecting suitable lightning current arresters.

Standardisation


Protection measures

The IEC 61400-24 standard recommends to select all sub-components of the lightning protection system of a wind turbine according to lightning protection level (LPL) unless a risk analysis demonstrates that a lower LPL is sufficient. A risk analysis may also reveal that different sub-components have different LPLs. The lightning protection system of a wind turbine consists of an external lightning protection system (LPS) and surge protection measures (SPM) to protect electrical and electronic equipment. In order to plan protection measures, it is advisable to subdivide the wind turbine into lightning protection zones (LPZ).

The lightning protection system of wind turbines protects two sub-systems, namely the rotor blades and the mechanical power train. The standard describes in detail how to protect these special parts of a wind turbine and how to prove the effectiveness of the lightning protection measures. According to this standard, it is advisable to carry out high-voltage tests to verify the lightning current withstand capability of the relevant systems with the first stroke and the long stroke, if possible, in a common discharge.

Lightning protection zone concept

The lightning protection zone concept is a structuring measure to create a defined electromagnetic compatibility (EMC) environment in an object. This defined EMC environment is specified by the immunity of the electrical equipment used. The lightning protection zone concept allows utilities to reduce conducted and radiated interference at the boundaries to defined values. For this reason, the object to be protected is subdivided into protection zones.

The rolling sphere method may be used to determine LPZ 0A, namely the parts of a wind turbine which may be subjected to direct lightning strikes, and LPZ 0B, namely the parts of a wind turbine which are protected from direct lightning strikes by air-termination systems, either external or integrated in parts of a wind turbine (for example in the rotor blade). According to the IEC standard, the rolling sphere method must not be used for rotor blades.

Fig. 1 shows a typical application of the rolling sphere method, and Fig. 4 shows the possible division of a wind turbine into different lightning protection zones, which depends on the design of the wind turbine. Therefore, the structure of the wind turbine should be observed. However, it is decisive that the lightning parameters injected from outside of the wind turbine into LPZ 0A are reduced by suitable shielding measures and surge protective devices at all zone boundaries so that the electrical and electronic devices and systems inside a wind turbine operate safely.

Shielding measures

The nacelle should be designed as an encapsulated metal shield. A tubular steel tower as predominantly used for large wind turbines can be considered an almost perfect Faraday cage, suitable for electromagnetic shielding. The switchgear and control cabinets in the nacelle and, if any, in the operation building should also be made of metal. The connecting cables should feature an external shield that is capable of carrying lightning currents. Shielded cables are only resistant to EMC interference if the shields are connected to the equipotential bonding on both ends. The shields must be contacted by means of fully (360°) contacting terminals without installing EMC incompatible long connecting cables on the wind turbine.

Magnetic shielding and cable routign should be performed as per section 4 of IEC 62305-4. For this reason, the general guidelines for an EMC-compatible installation practice according to IEC/TR 61000-5-2 should be used.

Shielding measures include:
- Installation of a metal braid on GRP-coated nacelles
- Metal tower
- Metal switchgear cabinets
- Metal control cabinets
- Lightning current carrying shielded connecting cables (metal cable duct, shielded pipe or the like)
- Cable shielding

![Fig. 1: Rolling sphere method.](image)

![Fig. 2: Example of an air-termination system for the weather station (anemometer) and the aircraft warning light.](image)
External lightning protection measures

These include:

- Air-termination and down-conductor systems in the rotor blades
- Air-termination systems for protecting nacelle superstructures, the nacelle and the hub
- Using the tower as the air-termination system and down conductor
- Earth-termination system consisting of a foundation earth electrode and a ring earth electrode

The function of the external lightning protection system (LPS) is to intercept direct lightning strikes, including lightning strikes into the tower of the wind turbine, and to discharge the lightning current from the point of strike to the ground. It is also used to distribute the lightning current in the ground without thermal or mechanical damage or dangerous sparking which may cause fire or explosion and endanger people.

The potential points of strike for a wind turbine (except the rotor blades) can be determined by means of the rolling sphere method (Fig. 1). For wind turbines, it is advisable to use class of LPS 1. Therefore, a rolling sphere with a radius \( r = 20 \) m is rolled over the wind turbine to determine the points of strike. Air-termination systems are required where the sphere contacts the wind turbine.

The nacelle construction should be integrated into the lightning protection system to ensure that lightning strikes in the nacelle hit either natural metal parts that are capable of withstanding this load or an air-termination system designed for this purpose. Nacelles with GRP coating or the like should be fitted with an air-termination system and down conductors forming a cage around the nacelle (metal braid). The air-termination system including the bare conductors in this cage should be capable of withstanding lightning strikes according to the lightning protection level selected. Further conductors in the Faraday cage should be designed in such a way that they withstand the level of lightning current to which they may be subjected. Natural components made of conductive materials which are permanently installed in/on a wind turbine and remain unchanged (e.g. lightning protection system of the rotor blades, bearings, mainframes, hybrid tower, etc.) may be integrated in the LPS. If wind turbines are of a metal construction, it can be assumed that they fulfill the requirements for an external lightning protection system of class of LPS 1 according to IEC 62305, which requires that the lightning strike is safely intercepted by the lightning protection system of the rotor blades so that it can be discharged to the earth-termination system via natural components such as bearings, mainframes, the tower and/or bypass systems (e.g. open spark gaps, carbon brushes).

Air-termination system/down conductor

As can be seen in Fig. 1, the rotor blades, nacelle including superstructures, rotor hub, and the tower may be hit by lightning. If they are capable of safely intercepting the maximum lightning impulse current of 200 kA and to discharge it to the earth-termination system, they can be used as ‘natural components’ of the air-termination system of the wind turbine’s external lightning protection system. Metallic receptors, which represent defined points of strike for lightning strikes, are frequently installed along the GRP blade to protect the rotor blades against damage due to lightning. A down conductor is routed from the receptor to the blade root. In case of a lightning strike, it can be assumed that the lightning strike hits the blade tip (receptor) and is then discharged via the down conductor inside the blade to the earth termination system via the nacelle and the tower.

Earth-termination system

An effective earth-termination system (Fig. 3) is essential to distribute lightning currents and to prevent the wind turbine from being destroyed. In the case of a lightning strike, the earth-termination system must discharge high lightning currents to the ground and distribute them in the ground without dangerous thermal and/or electrodynamic effects, thereby protecting humans and animals from electric shock.

Arrangement of earth electrodes

The IEC 62305-3 standard describes two basic types of earth electrode arrangements for wind turbines:

Type A: Annex I of IEC 61400-24 says that this arrangement must not be used for wind turbines, but it can be used for annexes (for example, buildings containing measurement equipment or office sheds in connection to a wind farm).

Type A earth electrode arrangements consist of horizontal or vertical earth electrodes connected by at least two down conductors on the building.
Type B: Annex I of IEC 61400-24 says this arrangement must be used for wind turbines. It either consists of an external ring earth electrode installed in the ground or a foundation earth electrode. Ring earth electrodes and metal parts in the foundation must be connected to the tower construction.

The reinforcement of the tower foundation should be integrated into the earthing concept of a wind turbine. The earth-termination system of the tower base and the operation building should be connected by means of a meshed network of earth electrodes to gain an earth-termination system ranging over as large an area as possible. To prevent excessive step voltages as a result of a lightning strike, potential controlling and corrosion-resistant ring earth electrodes (made of stainless steel) must be installed around the tower base to ensure protection of persons (Fig. 3).

**Foundation earth electrodes**

Foundation earth electrodes are part of the electrical installation and fulfill essential safety functions. For this reason, they must be installed by electrically skilled persons or under supervision of an electrically skilled person.

Metals used for earth electrodes must comply with the materials listed in Table 7 of IEC 62305-3. The corrosion behaviour of metal in the ground must always be observed. Foundation earth electrodes must be made of galvanised or non-galvanised steel (round or strip steel). Round steel must have a minimum diameter of 10 mm. Strip steel must have minimum dimensions of 30 x 3.5 mm, must be covered with at least 5 cm of concrete for corrosion protection. The foundation earth electrode must be connected with the main equipotential bonding bar in the wind turbine. Corrosion-resistant connections must be established via fixed earthing points of terminal lugs made of stainless steel. Moreover, a ring earth electrode made of stainless steel must be installed in the ground.

**Internal lightning protection measures**

- Earthing and equipotential bonding measures
- Spatial shielding and separation distance
- Cable routing and cable shielding
- Installation of coordinated surge protective devices

**Protection of the lines at the transition from LPZ 0A to LPZ 1 and higher**

To ensure safe operation of electrical and electronic devices, the boundaries of the lightning protection zones (LPZ) must be shielded against radiated interference and protected against conducted interference (Figs. 4 and 5). Surge protective devices capable of discharging high lightning currents without destruction must be installed at the transition from LPZ 0A to LPZ 1 (also referred to as lightning equipotential bonding). These surge protective devices are referred to as class I lightning current arresters and are tested by means of impulse currents of 10/350 μs waveform. At the transition from LPZ 0B to LPZ 1 and LPZ 1 and higher only low-energy impulse currents caused by voltages induced outside the system or surges generated in the system must be coped with. These surge protective devices are referred to as class II surge arresters and are tested by means of impulse currents of 8/20 μs waveform.

According to the lightning protection zone concept, all incoming cables and lines must be integrated in the lightning equipotential bonding without exception by means of class I lightning current arresters at the boundary from LPZ 0A to LPZ 1 or from LPZ 0A to LPZ 2. Another local equipotential bonding, in which all cables and lines entering this boundary must be integrated, must be installed for every further zone boundary within the volume to be protected. Type 2 surge arresters must be installed at the transition from LPZ 0B to LPZ 1 and from LPZ 1 to LPZ 2, whereas class III surge arresters must be installed at the transition from LPZ 2 to LPZ 3. The function of class II and class III surge arresters is to reduce the residual interference of the upstream protection stages and to limit the surges induced or generated within the wind turbine.
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<td>BLITZDUCTOR XT BE 24 *</td>
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<td>DEHNguard M INC CI 275 FM</td>
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<td>&quot;Neptune&quot; arrester combination: 3 + 1</td>
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<td>(DG 1000 FM 3x, TFS SN1638 1x)</td>
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<td>952 309</td>
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<td>Main incoming supply, 400/690 V TN system</td>
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Table 1: Protection of a wind turbine (lightning protection zone concept according to Fig. 4)
*Associated base part: BXT BAS, No. 920 300.

Selection of SPDs based on the voltage protection level (Up) and the immunity of the equipment.

To describe the required voltage protection level Up in an LPZ, the immunity levels of the equipment within an LPZ must be defined, e.g. for power lines and connections of equipment according to IEC 61000-4-5 and IEC 60664-1, for telecommunication lines and connections of equipment according to IEC 61000-4-5, ITU-T K.20 and ITU-T K.21 and for other lines and connections of equipment according to manufacturer’s instructions. Manufacturers of electrical and electronic components or devices should be able to provide the required information on the immunity level according to the EMC standards.

Otherwise the wind turbine manufacturer...
Surge arresters used to protect 400/690 V power supply systems must have a minimum voltage protection level $U_{\text{Up}} \leq 2.5 \text{kV}$, whereas surge arrester used to protect 230/400 V power supply systems must have a voltage protection level $U_{\text{Up}} \leq 1.5 \text{kV}$ to ensure protection of sensitive electrical/electronic equipment. To fulfil this requirement, surge protective devices for 400/690 V power supply systems which are capable of conducting lightning currents of 10/350 μs waveform without destruction and ensure a voltage protection level $U_{\text{Up}} \leq 2.5 \text{kV}$ must be installed.

The voltage supply of the control cabinet in the tower base, the switchgear cabinet in the nacelle and the pitch system in the hub by means of a 230/400 V TN-C system (3PhY, 3W+G) should be protected by class II surge arresters, for example DEHNguard M TNC 275 FM (Fig. 6).

Protection of the generator lines
Considering high voltage tolerances, class II surge arresters ("Neptune" arrester combination: 3+1, Fig. 8) for nominal voltages up to 1000 V must be installed to protect the rotor winding of the generator and the supply line of the inverter. An additional spark-gap-based arrester with a rated power frequency withstand voltage $U_{\text{Vac}} = 2.2 \text{kV} (50 \text{Hz})$ is used for potential isolation and to prevent that the varistor based arresters operate prematurely due to voltage fluctuations which may occur during the operation of the inverter.

A modular three-pole class II surge arrester, such as DEHNguard M WE 600 FM with an increased rated voltage of the varistor for 690 V systems is installed on each side of the stator of the generator (Fig. 9). These are specifically designed for wind turbines and have a rated voltage of the varistor ($U_{\text{Vac}}$) of 750 V AC, thus considering voltage fluctuations which may occur during operation.

Surge arresters for information technology systems
Surge arresters for protecting electronic equipment in telecommunication and signalling networks against the indirect and direct lightning strikes and other transient surges are described in IEC 61643-21 and are installed at the zone boundaries in conformity with the lightning protection zone concept (Fig. 4, Table 1). Multi-stage arresters must be designed without blind spots. This means that it must be ensured that the different protection stages are coordinated with one another. Otherwise not all protection stages will be activated, thus causing faults in the surge protective device. In the majority of cases, glass fibre cables are used for routing information technology lines into a wind turbine and for connecting the control cabinets from the tower base to the nacelle. The cabling between the actuators and sensors and the control cabinets is implemented by shielded copper cables.

Since interference by an electromagnetic environment is excluded, the glass fibre cables do not have to be protected by surge arresters unless the glass fibre cable has a metallic sheath which must be directly integrated into the equipotential bonding or by means of surge protective devices.

In general, the following shielded signal lines connecting the actuators and sensors with the control cabinets must be protected by surge protective devices:
- Signal lines of the weather station on the sensor mast
- Signal lines routed between the nacelle and the pitch system in the hub
- Signal lines for the pitch system
Signal lines of the weather station

The signal lines (4 – 20 mA interfaces) between the sensors of the weather station and the switchgear cabinet are routed from LPZ0B to LPZ2 and can be protected by means of combined arresters (Fig. 10). These space-saving devices protect two or four single lines with common reference potential as well as unbalanced interfaces and are available with direct or indirect shield earthing. Two flexible spring terminals for permanent low-impedance shield connection with the protected and unprotected side of the arrester are used for shield earthing.

Signal lines for the pitch system

If information between the nacelle and the pitch system is exchanged via industrial ethernet data lines, a universal arrester specifically designed for industrial ethernet and similar applications in structured cabling systems according to class E up to 250 MHz for all data services up to 48 V DC for protecting four pairs can be used (see Fig. 11).

The connection of the signal lines for the pitch system depends on the sensors used which may have different parameters depending on the manufacturer. These arresters can be installed in conformity with the lightning protection zone concept at the boundaries from LPZ 0A to LPZ 2 and higher.

Condition monitoring

The availability of output from wind turbines, especially offshore wind turbines, is increasingly important. This requires to monitor lightning current and surge arresters for signs of pre-damage (condition monitoring). The specific use of condition monitoring allows the utility to plan maintenance, thus reducing costs.

Laboratory tests according to IEC 61400-24

IEC 61400-24 describes two basic methods to perform system level immunity tests for wind turbines:

- During impulse current tests under operating conditions, impulse currents or partial lightning currents are injected into the individual lines of a control system while supply voltage is present. In doing so, the equipment to be protected, including all SPDs, is subjected to an impulse current test.

- The second test method simulates the electromagnetic effects of the lightning’s electromagnetic pulse. To this end, the full lightning current is injected into the structure which discharges the lightning current and the behaviour of the electrical system is analysed by means of simulating the cabling under operating conditions as realistically as possible. The rate of rise in lightning current is a decisive test parameter.

Contact Alexis Barwise, Dehn, Tel 011 704-1487, alexis.barwise@dehn-africa.com

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The new DEHN subsidiary in South Africa:
DEHN PROTECTION SOUTH AFRICA (Pty) Ltd
Unit B, Redek Place, Meadow Brook Business Estate
Jacaranda Avenue, Olivedale, Tel.: +27 11 704 1487
admin@dehn-africa.com, www.dehn-africa.com