RISK ENGINEERING GUIDELINE

WIND FARMS AND WIND TURBINES (ONSHORE WIND ENERGY)
The first wind turbine that could generate electric power was built in 1887. Since then subsequent turbines arranged in series with an output power of several 10 KW’s has been available since around 1980. Since that time, the development towards more powerful wind turbines has been rapid, and involved larger rotor diameters (currently up to approx. 130 m) and higher hub heights (currently up to approx. 140 m).

The average rated power of a newly installed wind turbine e. g. in Germany is more than 2 MW and will increase further in the future. Series units with an output power above 6 MW are already available.

In Germany, the share of electricity generated by wind power and fed into the power supply grid has grown to around 10% (end of 2012) with an installed total capacity in excess of 30,000 MW. This has been achieved mostly by approximately 23,000 powerful onshore systems.

The present safety information relates to onshore units built or operated in European and especially in European locations. This document also focuses on the essential components of a wind farm such as export cable network and transformer substations from a machine protection and fire protection point of view.

Further growth of the share of wind turbines in electricity production is foreseeable and is the consequence of extending existing wind turbines and wind park locations; this frequently involves the substitution of old units by new and more powerful wind turbines (repowering) and the creation of wind parks in new locations.

Function, components and structure

There are a large number of different concepts and designs of wind turbines that have been and are being developed and tested. The three-blade rotor with a horizontal rotating axis and aerodynamically optimised profiles is the only
design that has gained wide acceptance today and is therefore found in most stations. In this configuration, the rotor blades run on the windward tower side (“Windward side rotor”).

Although system details may vary considerably between manufacturers, the basic design is mostly the one shown in figure 5:

The essential components of a wind turbine include:
- the supporting structure (foundations and tower),
- the nacelle on top if it, with an azimuth control system,
- the energy conversion section comprising the generator and possibly a gearbox inside the nacelle,
- the rotor that is connected with the energy conversion section and supported by the main bearing.

Other features include electric systems (especially transformers) in the tower base, on intermediate tower levels and in the nacelle.

These components may vary substantially between wind turbine manufacturers, type designations and as a function of location-specific requirements. Examples include differing gearbox concepts and designs without gearboxes, different generator concepts (e.g. double-fed asynchronous generators or separately excited synchronous generators, permanent magnet generators, different numbers of pole pairs), and different materials for different system components (e.g. epoxy resin, GRP or carbon fibre composite materials for rotor blades, concrete or steel for supporting structures).

Future developments are expected to indicate which designs are best suited to certain locations with respect to optimum performance with regard to economic profitability and reliability.

The interconnection of many wind turbines feeding the generated electricity through a single connection is a common feature that is essential for operation of a wind farm. A central or decentralised reactive-current compensation system must control, among others, the real power and if required the reactive power at the mains connecting point (see figure 6).

Basic differentiation is made between wind turbines in wind farms and island-type wind turbines. Wind turbines are mostly operated in wind farms and usually have a configuration as shown in figure 15. Island-type units are normally directly connected with the mains grid and are operated in parallel mains mode.

For connecting to the main grids and for financial compensation in Germany, the stations must be certified according to the German Erneuerbare Energien Gesetz (EEG – Renewable Energies Legislation). In this respect, they must meet the technical requirements for feeding into the mains grid of the network operator according to the Systemdienstleistungsverordnung (German abbr.: SDL Wind V - System Service Regulations).

1 Risk situation.

Complexity has grown as efficiency and power output of wind turbines and their components have been improved by new developments. The experience gathered from operating a high number of existing units and continuously...
improving design and calculation methods as well as optimised production processes have enabled higher operational reliability. Nevertheless if damage to a turbine were to occur, the consequences could be substantial and lead to significant repair costs or even total replacement of the unit. Similarly a lengthy business interruption period could also be expected that will affect power generation and revenue streams.

If central unit components such as the central switchgear fail, the entire wind farm may be affected by that failure, in which case this will lead to a long business interruption.

If central unit components such as the central switchgear fail, the entire wind farm may be affected by the failure.
The extent of many of these losses can be reduced or even be avoided altogether by using CMS (Condition Monitoring Systems) for remote monitoring of critical system components, and by undertaking regular and targeted maintenance and comprehensive revisions.

As fires cause enormous losses, fire protection measures for these systems are also essential.

These aspects must be taken into account as early in the wind turbine concept stage as possible, to ensure that countermeasures are included within the specifications and design. This will enable the units to achieve the intended service life of 20 to 25 years.

2 Typical causes of losses.

Losses may occur on all components of a wind turbine. Naturally, high losses result from total destruction of the unit. Total loss may result from the tower falling over due to an inadequate foundation or by a rotor braking system failure, resulting in excess rotor speed. A fire following a lightning strike or damage to mechanical or electric components is a more frequent cause of total loss of a wind turbine.

Even partial losses can reach high loss values that may even reach the cost of the entire unit in some cases. The following causes of losses must be emphasized in particular:

2.1 Gearbox damage

In addition to the forces generally occurring in gearboxes, many particular loads appear in wind turbines such as short-term forces due to gusts of wind, turbulences, azimuth and braking processes as well as periodic loads due to tower oscillations etc.. Premature material fatigue on gears, gearbox parts and on shaft and gearbox bearings cannot be excluded under these conditions. This may have consequences such as gear cog and shaft material stripping and chipping, entailing further gearbox damage.

2.2 Rotor damage

Rotor damage counts among the most expensive losses that can occur on a wind turbine. The high number of load changes to which a rotor blade is subject to during its calculated service life places extremely high demands on:

- Design and manufacturing: Small faults may grow bigger during operation due to fatigue and repetitive actions and finally cause substantial loss.
- Wear resistance: mechanical damage caused e. g. by abrasion and spreading during further operation can cause a loss.
- Rotor blade protection: in case of rotor blade icing-over in certain weather conditions, ice can form on rotor blades, and if it comes off a single blade, whilst remaining on the others high rotor imbalance may result, causing damage on the rotor itself and on other system components.
- Lightning protection: lightning strikes are one of the main causes of losses (see also 3.3).

The highest loss is suffered when the entire rotor is lost. This may occur e. g. following a braking failure or an imbalance.
2.3 Lightning damage

In view of their height, wind turbines are vulnerable to lightning strikes. It is true that rotor blades are usually equipped with lightning receivers that are intended to divert lightning in a controlled way in combination with metal conductors, slip rings and/or spark gaps. In practice however, shortcomings on these components can occur due to faulty installation and maintenance of the lightning protection system. In these cases, loss occurs on rotor blades, rotor blade bearings, on sensors, electronic switchgear etc.

Especially in wind farms, lightning losses e. g. on telecommunication lines and electric equipment such as transformers must be expected.

Not least, lightning strikes are one of the major causes of fires in wind farms (see also 3.4 below).

2.4 Fire loss

Fires cause most total losses of wind turbines. The avoidable fire loads that occur often include oil and grease escaping through leaks in lubrication systems. In addition, there are numerous components of a wind turbine which represent high fire loads due to their operational use, e. g. cable harnesses, control cabinets (electronic sub-assemblies) as well as plastic coverings and GRP rotor blades. The ignition sources involved include amongst others over-stressed brakes, hot bearings and also lightning strikes (see 2.3). Fires of electronic equipment/control systems/compen-sation units are also possible. If there is no structural fire compartmentalisation, a fire can spread and cause total destruction of the plant.

2.5 Converters and other electric equipment

Damage to electric components of a wind turbine usually is not different in terms of features from damage occurring in electrical systems used in other fields of application. However, electronic semiconductor components, especially insulated-Gate Bipolar Transistors (IGBTs) constitute an exception to this rule. These components are used in the power electronics section of wind turbines in order to make constant and mains-compatible electric power available for feeding into the mains grid from wind-oriented units with variable generator frequency and voltage through a converter. Failure of these semiconductor components results in a wide range of damage which rarely reaches the loss amounts e. g. of total losses as mentioned above at 2.1 to 2.4.
2.6 Damage to central electrical plants of a wind farm

Damage to the transformer substation, especially damage to transformers (failure of on-load tap changer, earth fault or transformer fire e. g. due to mains overvoltage) is possible and will put an entire wind farm out of operation if it occurs. The number of damaged cables in wind farms has increased recently and this occurrence will have the same effect, i. e. a temporary downtime of the entire wind farm.

Stolen cables are frequently the origin of such cases. In other cases, damage to cables occur, for example excavators often cut cables during excavation works in the vicinity of these wind farms.

3 Loss prevention.

3.1 Fire protection of wind turbines/wind farms

The probability of a large-scale loss due to a fire is increased by the fact that the fire brigade can not fight a fire in the nacelle. Rotary ladders do not reach the necessary height and climbing inside the tower during the fire is excluded because of the extreme risk to life involved for the fire-fighters.

For these reasons, effective fire protection is essential. This applies in particular to the central wind farm components located upstream of the joint mains feeding point. Their failure may cause business interruptions concerning the entire wind farm.

3.2 Fire alarms and fire protection systems

The hazards from electric system components and from the mains grid should be minimised by appropriate protection engineering which enables the selective detection of faults, immediate shut-down of faulty equipment, controlled system shut-down, disconnection from the mains and activation of fire-fighting systems.

Fig. 10: Fire detection system
Fire detection and fire-fighting means should be provided in a wind turbine and/or in a wind farm especially in joint electric systems (mains grid connecting point/switchgear/transformers) in line with the current standards (in Germany e. g. VdS standard). Reliable function of this equipment should be ensured by regular inspections and maintenance.

More detailed information can be found in VdS guidelines (also available in English see 5. Literature).

3.3 Lightning protection of wind turbines/ wind farms

Wind turbines are especially vulnerable to lightning strikes that may cause a fire, but also by overvoltage that can destroy certain electronic system components. In order to protect the sensitive electronic control systems of a wind turbine against hazardous overvoltage, the installation of an overvoltage protection system is recommended. This should be considered as early as possible when designing the unit and/or the wind farm, using the maximum hazard category according to IEC 62305 (lightning protection class 1) as standard.

All the same, this will not prevent losses due to improper installation/maintenance, and thus the following should be implemented:

- Regular inspections,
- Adhering to the manufacturer’s maintenance instructions
- Immediate removal of any detected faults

3.4 Condition Monitoring Systems (CMS), remote monitoring

Fires usually originate from technical defects on mechanical or electric components.

Fires attributable to mechanical system components may be caused by, for example a hot generator or gearbox bearings that have been improperly maintained. Mechanical or mechano-hydraulic brakes may reach high temperatures if the aerodynamic brakes fail during operation, and thus constitute another hazard that can cause ignition of combustible materials.

Modern wind turbines are equipped with online CMS (Condition Monitoring Systems) for comprehensive monitoring of the drive train and the rotor blades. Monitoring and analysis of oscillation spectra of bearings, gearbox (of the generator), rotor blades and other components are essential for enabling detection of developing damage at an early stage and can allow avoidance or limitation of potential damage with little effort.

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**Fig. 11:** Example of an operational data overview and CMS visualisation of wind farm monitoring system
This applies to precautions regarding both fire losses and machine damage. Usually wind farms are monitored from central control stations that can also control the essential functions.

### 3.5 Machinery protection in wind turbines

Machinery losses typically include losses on rotor blades, main bearings, gearboxes, generators and on control systems and general electronic equipment including power electronics. Loss prevention must be adapted to the specific unit.

- This can be achieved e. g. by using temperature, frequency, current and voltage monitoring in connection with safety circuits.
- Fail-safe mode functions for all and especially for safety-relevant components should be provided in a wind turbine. This applies e. g. to the azimuth brake which maintains an emergency function to safeguard the plant even in case of power failure.
- Another example of the fail-safe function is the standard protection against rotor overspeed which is usually monitored with multiple redundancy. Fail-safe functions can also be triggered e. g. by mechanical forces, hydraulic circuits or the central control system.
- A wide range of additional protective measures for gearboxes are available on the market. Online oil particle counting is useful, among others, in connection with the CMS mentioned in 3.4 above.

### 3.6 Supporting structures (tower and foundation)

Towers of wind turbines mostly consist of steel structures (cylindrical or conical steel tubes). Hybrid towers (steel on concrete) are less frequently used whereas steel lattice towers and concrete towers (in-situ concrete or prefabricated towers) are rare.

Whereas units installed near coasts can use rather low towers due to the flat terrain profile and low wind turbulence intensities, current wind turbines installed inland meanwhile reach a total height of around 200 m. In onshore facilities, the towers are built to suit ground conditions, i. e. either on concrete block foundations or, if necessary, on special foundations (e. g. piled foundation). In some cases, the consequences of faulty dimensioning/design or of incorrect building execution have caused sub-
Substantial losses up to total unit loss. In practice, site investigation including boreholes and interpretive soils reports on ground conditions are prepared for the locations of individual wind turbines and serve for specific dimensioning of foundations and supporting structures. This procedure should ensure almost completely that foundations are sufficient.

Nevertheless, regular inspection of the supporting structure to confirm its integrity is essential due to the high amounts involved in case of total loss.

3.7 Rotor (rotor blades, hub, blade angle adjustment, rotor lightning protection)

Defects on rotor blades count among the most frequent and most expensive losses of wind turbines. Regular and professional inspections and repairs of rotor blades are indispensable.

Permanent monitoring of rotor blades by means of oscillation diagnoses as part of CMS is also considered vital. This feature can also be used for diagnosis of ice layers on the rotor blades that may occur in certain weather conditions. Should this ice fall down from a single rotor blade (“Falling ice”) while the other rotor blades still carry this load, a rotor imbalance results. This may cause mechanical damage on the wind turbine. When detecting this hazard, the turbine can be brought to a safe condition before any loss occurs.

Serious damage of a rotor blade can also result from lightning strike if the lightning protection system is faulty. Following such a strike, the resulting imbalance may also cause loss of the rotor. Regular testing of the earth resistance is therefore required to ensure the function of the lightning protection system along the entire distance from the blade tips to the earthing.

State-of-the-art units enable variable speeds and are pitch-controlled, i.e. the blade angle is adjusted. The pitch control system should therefore also be integrated into the inspection and maintenance schedules.

3.8 Drive train (gearbox, generator, clutches and brakes)

The recommended condition monitoring of wind turbines, generators etc. by condition monitoring systems (CMS), preferably with remote online monitoring, is already often employed in practice. Please see also section 3.4. As a supplement, it is recommended evaluating the recorded data using trend analyses as well in order to detect potential future failures that may lead to losses as early as possible.

Fig. 13: Assembling of a wind turbine gear box
The service life of a gearbox depends essentially on whether a gearbox is used in a static production environment or on a wind turbine tower oscillating in several axes. On wind turbine gearboxes of >1 MW, the phenomenon of “micro-pitting” occurs. In most cases, this is attributed to high-frequency resonant oscillations. Consequences of this progress from “micro-pitting” up to broken tooth flanks and finally gearbox failure.

When a CMS detects such oscillation patterns, the components concerned should be inspected without delay, if required using endoscopy.

Generator monitoring by CMS is also essential for safe wind turbine operation. Essential operational characteristics include among others:
- oscillations,
- bearing parameters (temperatures, pressure, gaps) and
- winding temperatures.

The current tendency of increasingly using systems without a gearbox and with permanent magnet synchronous generators avoids the possibility of gearbox damage. This is already the case for units without gearboxes and with a separately excited synchronous generator.

The condition of clutches and brakes should also form part of regular inspections.

3.9 Electric equipment (power electronics, sensors, condition monitoring)

Inspections of electric equipment by a recognized expert (state-approved and recognized electric equipment expert) are fundamental to safe system operation and loss prevention. Please refer to section 3.13, Maintenance below.

3.10 Other (azimuth control, air conditioning, …)

The reliable function of wind turbine peripheral components is also essential to the operational safety of the overall unit. Insufficient azimuth control in case of heavy winds may endanger the unit.

Appropriate security systems should be provided to prevent thefts and malicious damage; suitable security systems and the execution of access doors control systems (electric door monitoring) can prevent theft and sabotage. These types of events may cause significant losses.
Heating and ventilation systems, air conditioning and filter systems may also be essential, depending on the location. These components should accordingly be integrated into maintenance schedules and have the necessary redundancies if required.

3.11 Transformer substations, transformers, reactive power correction systems and power switchgear

As the key component and bottleneck of a wind farm, a transformer substation requires particular attention with regard to loss prevention. The basis of loss prevention is efficient fire and machinery protection, see section 3.1.

The usual protective measure for transformers is the use of hydrodynamic relays (Buchholz relays). These relays detect gases generated from electric flashovers in the transformer and a warning can be transmitted. If gas generation continues, the transformer can be shut down using the second alarm from the Buchholz relay. In addition, Buchholz relays can also be used for detecting oil losses.

Taking oil samples and transformer oil analyses at regular intervals according to IEC DIN 60422 is also part of the loss prevention process.

Moreover, permanent remote monitoring of the transformer – see also DIN EN 60870 (Remote control systems) - is also recommended. Please see also section 3.13 below.

Overvoltage protection should be part of any transformer in a wind farm with a central transformer substation in order to protect the unit against overvoltage from the mains grid (e.g. due to lightning strike).

3.12 Wind farm cables

Thorough planning and execution of cabling systems is a basic condition for their reliable operation.

- When installing power and signal cables in the tower, not only resistance to chemicals must be ensured (in case hydraulic oil or gearbox oil leaks), but also temperature and temperature cycle resistance, vibration and torsion resistance as well as protection against mechanical damage e.g. by stress relief elements and easy installation/dismounting. FRNC (Flame-Retardant Non-Corrosive) and LSNH (Low-Smoke No Halogen) properties of cables in case of fire are recommended.

- In large wind farms, a suitable cable arrangement is to ensure that single point failure is avoided, for example, so that damage to one local cable will not result in failure of the entire wind farm.

Usually the cabling of onshore wind farms consists of single cable strands to which the wind turbines are connected serially, see figure 15.

Ring circuits are quite rare, but allow continuing operation through the remaining intact strand in case of cable damage and are therefore to be preferred, see figure 16. We also point out the explanations provided in sections 3.6 and 3.13.

![Fig. 15: Schematic structure of serially connected wind turbines](image1)

![Fig. 16: Schematic structure of ring circuit connected wind turbines](image2)
3.13 Maintenance

Defects of electrical system components are often the actual cause of a fire. They are due to overheating following overload, short-circuit or an electric arc. Defects in control electronics, power electronics, electrical connections and of capacitors in line filters and power factor correction units may also be the cause of a loss.

To enable detection and removal of mechanical and electrical defects the following actions are recommended:
- regular inspections and maintenance
- recurring inspections by a recognized expert
- regular thermographic inspections of the electrical installation carried out by an expert recognized in this field.

The central electric/electronic components of a wind farm also deserve particular attention (transformers, circuit-breakers of wind turbine and circuit-breakers of transformer station etc.).

3.14 Planning of wind turbines and farms

Planning of a wind farm should take all phases into account. This process starts with selecting a suitable location and the properly specified wind turbines and ends with the possible shut-down of the wind farm after the end of its service life.

To enable economic operation of wind parks, expert opinions of the place of installation regarding wind conditions and the associated wind yield are required. Expert ground reports are essential for sufficient foundation design and to ensure sufficient stability of the wind turbines and the transformer substation components. Conditions imposed by authorities and legal provisions must also be met.

Air conditioning, heating and filter systems must be provided depending on the location. This is more important in locations with a tropical climate. Animals and insects should also be considered, and the prevention of access by these into wind farm systems should be ensured at all times.

Corrosion protection must also be designed to suit the specific location, e.g. near coasts.

Fire protection and machinery protection equipment must be integrated as early as in the planning phase in order to prevent the above losses at an early stage. Please refer e.g. to German VdS Guideline 3523 for fire protection of wind turbines.

Components of wind turbines such as rotor blades are frequently very large, and due to their size and weight, will require special measures in respect of transportation and erection. This can include the use of abnormal load transport, and the assessment of roads or bridges used to get to the site. Actually, suitable consideration should be given to maneuvering, laydown, and assembly areas, as well as suitable and sufficient platforms for cranes or other lifting equipment.
The feasibility of the complete assembly sequence of the wind turbine, especially concerning the hub and rotor blades, should be examined and planned for each location in question in advance of the operation.

During the operational phases, accessibility and local disassembly/reassembly options for components, e.g. removing a generator-rotor or rotor disassembly, must be taken into account during the design/feasibility stage, to ensure suitable access or arrangements are made during construction.

3.15 Delivery and installation

Erecting a wind turbine places increased requirements on installation personnel since components such as the nacelle and the rotor are installed at hub heights of around 100 m. These processes depend on weather conditions and require precise work execution, to mention but a few important factors.

The following loss prevention measures must be taken during delivery and installation:

- Before and after transportation, but prior to installation at the latest, the components should be inspected for damage, e.g. from lifting, or transportation.
- We proceed from the assumption that the components are transported and loaded professionally and in line with the manufacturer’s specifications (Method Statement).
- Logistics and transportation represent a particularly important aspect for wind turbines which, however, will not be dealt with in more detail here. All the same, we would at least like to point out that these services should be separately traced and integrated into the quality control schedule.
- Component storage on site should be protected against mechanical damage and theft.
- In addition, the components must be protected against corrosion and overvoltage.
- Regardless of the storage period, mechanical components such as gearboxes must be rotated/moved at regular intervals so that sufficient wetting with oil is ensured to avoid corrosion.
- In case of extended storage periods, components must be appropriately preserved and rotated/moved at regular intervals if required (gearboxes etc.).

Installation work should be carried out by qualified installation personnel only. Inspection of services regarding proper execution is indispensable. Suitable time windows relating, among others, to wind and weather conditions must be considered. The works schedule should have sufficient float to accommodate poor or unsuitable weather conditions during the erection phase.

3.16 Operation and maintenance

(Please see also section 3.13, Maintenance)

The features below are recommended for troublefree operation:

- Continuous and thorough maintenance including a stock of selected critical spare parts such as a converter is absolutely necessary for achieving a high level of plant availability. These maintenance services are frequently subcontracted to third parties, e.g. by concluding maintenance and spare parts service agreements between the wind farm operating companies and the manufacturers of wind turbines (OEMs, Original Equipment Manufacturer).
- As wind farms and wind turbines are frequently operated in rural areas and are therefore difficult to access, it must be ensured that service personnel are either permanently present on site or that the personnel can reach the wind farm within a sufficiently short period of time e.g. for troubleshooting. Usually remote control systems are provided for this purpose. This allows troubleshooting from a remote control station while the unit is in operation and disconnecting units from the mains in critical operating situations. Please see also section 3.4, CMS, Remote monitoring
- As described above, the use of a CMS online monitoring system is also of vital importance for safe operation of a wind farm. In this context, not only the wind turbines, but also components such as transformers should be monitored online 24 hours a day, e.g. from a central monitoring or engineering center.
- Auxiliary energy sources such as emergency generators or batteries must be provided in order to maintain emergency functions. These should also be tested at regular intervals and be part of a maintenance schedule.
4 References.

Local standards should be complied with.

**Internationally recognised standards:**
- IEC 61400 is a class of IEC (International Electrotechnical Commission) international standards regarding wind turbines
- NFPA 850, Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations
- NFPA 70, National Electrical Code
- NFPA780, Standard for the installation of lightning protection systems

**Specific standards (Best practice):**
- EN 61400-1 (VDE 0127-1) Wind Turbines
- DIBT: Guideline for wind turbines, draft of January 2012
- VdS 3523 Wind Turbines, fire protection information
- EN 50308 Wind Turbines: Protective measures – Requirements on design, operation and maintenance

5 Remark.

This information leaflet does not claim to be complete and does not relieve any party from the obligation of meeting legal or authority provisions. No liability will be accepted.
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HDI Risk Consulting GmbH supports major corporations, industrial and mid-size companies with loss prevention and in establishing risk management systems.

HDI Risk Consulting offers its’ customers access to some 180 engineers and experts from a wide range of technical disciplines. We aim to support companies with the management of risks and the development of individual risk-based concepts for insurance cover.

HDI Risk Consulting operates globally in the Property, Motor, Engineering and Marine markets, with particular focus on the identification and assessment of risks and the development of appropriate, individual protection concepts.

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