SAFETY OF WIND SYSTEMS

4/25/2021

INTRODUCTION

The reliable, safe and beneficial operation of wind turbines requires the use of a number of Engineered Safety Features (ESFs), much like any other engineered device. Identification of the possible failure modes under severe wind conditions, risks and hazards will lead to future even more reliable and safer wind turbine designs.

The design lifetime of wind turbines is about 20 years, over which they have to be operated reliably and safely even under hazardous stormy conditions. This presents a design challenge for present and future turbine designers. In comparison, automobile engines are designed to operate for about 5,000 hours, whereas wind turbines are expected to operate with a capacity or intermittence factor of 0.40 for:

$$20 \text{ years} \times 365.12 \ \frac{\text{days}}{\text{year}} \times 24 \frac{\text{hours}}{\text{day}} \times 0.40 = 70{,}103 \text{ hours.}$$

Figure 1. Maintenance at wind turbines nacelles involves work at about 100 meters height. Source: Getty, Nordex.

Figure 2. Maintenance access of a wind turbine's nacelle through the use of a helicopter.

Figure 3. Assembly of wind turbine components entails work at great heights and use of safety harness equipment.

Utility scale wind electrical power production is unequivocally an industrial process with inherent characteristic operational and environmental hazards and risks. They involve mechanical hazards characteristic of rotating machinery, as well as electrical hazards typical of electrical production equipment.

Turbine blades rotate at high speeds at their tips that can reach 90-180 mph. The possibility of ejection of ice chunks in large turbines and blade ejection in small turbines necessitates their emplacement away from human dwellings.

Like any other industrial process, the beneficial and environmentally desirable use of wind power production involves the professional and ethical issue of minimization and

informed consent and acceptance of its societal risks. To minimize such risks an offset from human dwellings and congregation areas such as school buildings and university campuses is adopted according to different local, national and international norms, regulations and laws.

WIND POWER PRODUCTION ACCIDENTS

The Department of Labor reported 75 wind turbine accidents involving injuries since 1972, including 8 in 2007. Accidents that do not involve death or injury are not reported. About 30,000 turbines were operating in the USA as of 2008, according to the American Wind Energy Association, and with the push to find alternative energy, more are being commissioned.

The safety policy of a wind farm must cover all stages of its development and should include the risks to its employees, contractors and members of the general public. A poor safety record, in addition to violating professional ethics issues, would eventually cost an operator its reputation as well as possible compensatory damages by law.

Reports of turbine failures in the USA include rotor blades throws, oil leaks, fires and tower collapses. While weather conditions and climate are taking a toll on the machines, reports from critics of the industry blame it on that the rush to erect industrial wind turbines was accomplished at the expense of quality assurance and safe installation practices.

Critics claim that some of the facilities may not be as reliable and durable as the producers would have them designed to be, with multiple mishaps, breakdowns and accidents having been reported in recent years. Turbine owners are committed to conducting regularly scheduled maintenance necessary to ensure the mechanical towers remain in good operating condition. An informal survey of approximately 75 wind farm operators in the USA found that 60 percent of them were behind in their maintenance procedures.

Wind turbine manufacturers recommend a safety zone with a radius of at least 1,300 feet from a wind turbine, and that children must be prohibited from standing or playing near the structures, particularly under icing or stormy conditions. Some wind parks operators responsibly expand that requirement by spreading wind turbines to the level of one turbine per 80 acres of land in the USA even though wind turbines have been erected more closely requiring a land area of 2-5 acres per turbine, including the access roads. Yet some wind turbines construction escaped careful scrutiny in their siting and were planned, based on well-meaning and romantic but uninformed considerations of clean and green power, to be erected near school buildings and adjacent to university structures close to human traffic and congregation areas.

Wind turbines are rated for 150 miles per hour (mph) winds. As wind speed picks up, there is a decoupling and the blades free-wheel to minimize damage. A sophisticated design easily changes the rotor pitch like a helicopter and spins it at a lower speed than the wind. In the case of a hurricane, 250 mph would cause worries far beyond a few turbines, since engineering structures are not generally rated for such high speeds. A Category 5 hurricane is associated with wind speeds over 150 mph. There are rare events; and there have been only three such hurricanes in the USA in the last century.

Safety regulations vary from one country to another, but they possess some

common features such as the requirement for testing the rotor blades before their installation for use, but not the whole turbine design.

Reliability is closely tied up to safety. Inadequate testing of components and lack of maintenance and servicing, in a rush to deliver components, could lead to frequent breakdowns and possible financial losses. Driving around a wind turbine farm in 2008, it was noticed that fully one third of the turbines were not in operation under favorable wind conditions, being shut down for repair or maintenance.

OFFSET SITING DISTANCES

Table 1. Offset distance of commercial and utility scale wind turbines from human structures.

Source	Distance [ft]
Manufacturer's recommendation	1,300
General Electric (GE) Energy Company	1.5 H, from property lines, H = turbine nacelle height
Cleveland, Ohio	1.1 H, from nearest property line, H = turbine nacelle height
Protection from ice shedding and blade throw	1,750
USA National Research Council	2,500
Shadow and strobe flicker effect	3,300-5,000
Germany	1 mile
France	1 mile
French Academy of Science	1.5 km, from residences
Canada, rural Manitoba	6,500
Riverside County, California, USA	2 miles
Michigan, USA	1,000
Wisconsin, USA	1,000
Illinois, USA	1,500
Ontario, Canada	550 m, residences, 120 m, roads, railway, property lot lines.
Conservation, planning and zoning commission, Woodford County, near Eureka, Illinois, USA	1,800 from residences

1 mile = 1.609 kilometer = 5,280 feet
1 meter = 3.28 feet

The offset distance of wind turbines from human dwellings differs from location to location. In Wisconsin and Michigan in the USA, licenses were reported to be granted by local licensing boards to build turbines as close as 1,000 feet from human dwellings.

In contrast to other forms of power plants which require federal review for their siting, wind farm in the USA are primarily subject to local siting rules. This has created a situation where a fossil power plant would require about a ten years planning, licensing

and construction period; whereas the construction and operation of a wind farm requires a more favorable and much shorter 2-3 years period of time from inception to construction and operation.

With more experience in wind power production, the more experienced Europeans require a one mile siting offset for utility-scale wind turbines from human dwellings, and the state of California in the USA requires an even larger 2 miles offset.

SOURCES OF RISK

The total number of accidents in the wind power industry in terms of deaths and serious injuries is remarkably small, but the percentage is high relative to other industries, due to its being a labor intensive option of energy production. The risks of disease from exposure to hazardous substances are minimal but wind power is characterized by unique industrial risks related to its workers operating under hazardous conditions involving:

1. Blade ejection,
2. Runaway turbine disintegration,
3. Tower Collapse,
4. Overheating of generators and transmission lubrication and cooling fluids and component fires,
5. Hazardous weather conditions,
6. Working at significant heights (about 100 m),
7. Use of rotating machinery,
8. Handling heavy equipment,
9. Use of high voltage electricity and cabling,
10. Vehicular access,
11. Lightning strikes causing fires,
12. Hazardous solvent chemicals exposure in rotors manufacture,
13. Oil spills,
14. Ice shedding.

Many of the involved accidents unnecessarily involve the adoption of shortcuts and ignoring the existing standard industrial and electrical practices.

Other risks can be caused by other low probability events such as a blade ejection or a runaway turbine. Mundane risks such as tripping also occur.

A good risk policy should involve limiting the public's access to a wind farm site much like any industrial site, particularly because of the presence of high voltage electricity cabling, and posting notices to that effect. Wind turbines as tourist attractions are best viewed from a distance without direct access.

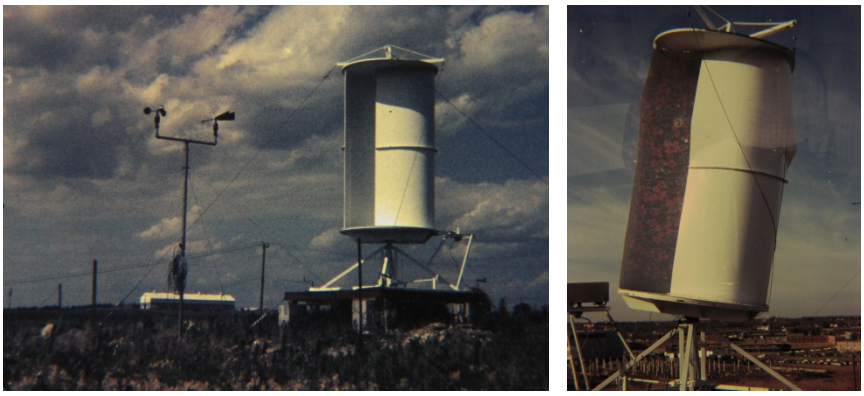

Figure 4. High winds damage effect on an experimental Savonius design wind turbine at Kansas State University, KSU.

LIGHTNING PROTECTION

INTRODUCTION

The lightning protection of wind turbines must consider the protection from the effects of direct and nearby lightning strikes, even though protection from lightning cannot be fully assured.

Lightning protection of wind turbines follows the international standard IEC 1024-1 and the Danish Standard DS 453.

Eleven out of 15 cases of turbine failures in the USA were caused by lightning strikes or another ignition source causing blazes that begin hundreds of feet in the air. One such event occurred in 2007 at the Twin Groves wind farm in eastern McLean County by Bloomington, Illinois. Despite countermeasures such as lightning rods meant to divert a strike from the turbines, one tower had to be shut down because of a lightning strike and a resulting fire.

Since wind turbines are sited on towers or pylons, often on hilltops, with their structural towers, they constitute a ready path for static electricity to the ground.

Figure 5. Wind turbine with ignited leaking lubrication oil near Uelzen, Lower Saxony, Germany, December 2, 2009. Other fire events. Source: DPA.

Figure 6. Wind turbine nacelle fire near Bloomingdale, Minnesota, USA, 2008.

Different layers of protection of the different wind turbine components exist:

ROTOR BLADES

The blades are protected with a dedicated protection system that is laboratory tested to currents of 200 kA without showing signs of damage other than superficial weld marks from the strike itself. Each blade has a lightning rod fitted close to the tip. The rod projects slightly above the blade surface on both sides. A flexible steel wire located inside the blade provides the conduction path from the rod to the rotor hub which in turn is used as a conductor to the main shaft.

For large composite blades, a full cord metal tip cap with an 8-10 cm skirt extending inboard from the tip is recommended. A trailing edge earth strap can be firmly attached to the tip cap and to the steel hub adapter to carry the lightning current to the ground.

Metal screening and conductive paint or other conductors must be placed along the blade to ground lightning strikes which miss the blade tip cap or the trailing edge. Similar provisions must be provided in areas that correspond to internal metallic parts to preclude lightning strikes penetration through the composite spar.

Figure 7. Lightning strike damage on a wind turbine in southern Minnesota, USA, resulted in the destruction of the nacelle and the rotor blades.

TURBINE NACELLE

Electrical and hydraulic equipment located inside the hub is completely shielded by the Faraday cage effect of the hub itself assuring that inside an electrical conductor, the electric field has a zero magnitude.

The nacelle canopy is usually fabricated from 5 mm thick steel plate, acting as a Faraday cage for the nacelle. The meteorological instruments at the rear of the canopy are protected by a separate lightning rod projecting above the instruments. All main components must be grounded, and metal oxide arrestors in the controller should provide transient protection from the effects of nearby strikes.

CONTROLLER PROTECTION

Metal oxide arrestors protect the turbine controller. The arrestors are installed with mechanical overload protection to prevent explosion in case of a direct lightning strike. The controller is fitted with three arrestors, one for each phase, all connected to the local grounding system. All metallic parts, such as cabinet doors, and components are efficiently grounded.

STRUCTURAL TOWER PROTECTION

The steel tower acts as a conductor from the nacelle and controller to the ground. Ground connection should be provided through several copper leads.

GROUNDING

Grounding is achieved to a resistance of less than 10 ohms, using two depth electrodes and a ring ground wire surrounding the foundation.

RISK ASSESSMENT METHODOLOGIES

Various methods of risk assessment exist to reduce the risk at the different stages of a wind farm development and operation to acceptable levels. Some of the approaches are:

1. Cost Effectiveness or Marginal Cost Analysis.
2. Fault Tree and Event Tree Analysis.

Some accidents may occur with low probabilities P_i but possess high consequences C_i. After estimating the accident sequence probabilities and their consequence, the overall risk is estimated as a summation over the number of accident sequences N as:

$$R = \sum_{i=1}^{N} R_i \tag{1}$$

With the individual accident sequences risk R_i described as the product of its probability of occurrence P_i and the consequence from it C_i:

$$R_i = P_i C_i \tag{2}$$

Substituting from Eqn, 2 into Eqn. 1, we get:

$$R = \sum_{i=1}^{N} P_i C_i \tag{3}$$

Wind power is characterized, and is accepted as a low consequence C_i but high probability of occurrence P_i energy option. From that perspective it shares a similar nature as car accidents, which have low consequences, but high probabilities of occurrence. That is in contrast to other sources of risk with low probabilities of occurrence but high consequences such as plane crashes or dam failures.

At any stage of the development of a wind farm the risks must be noted and assessed. Control measures must be implemented to reduce the risks to the acceptable levels suggested by the standard risk assessment methodologies. The risk assessment should be reviewed regularly such as on a yearly basis.

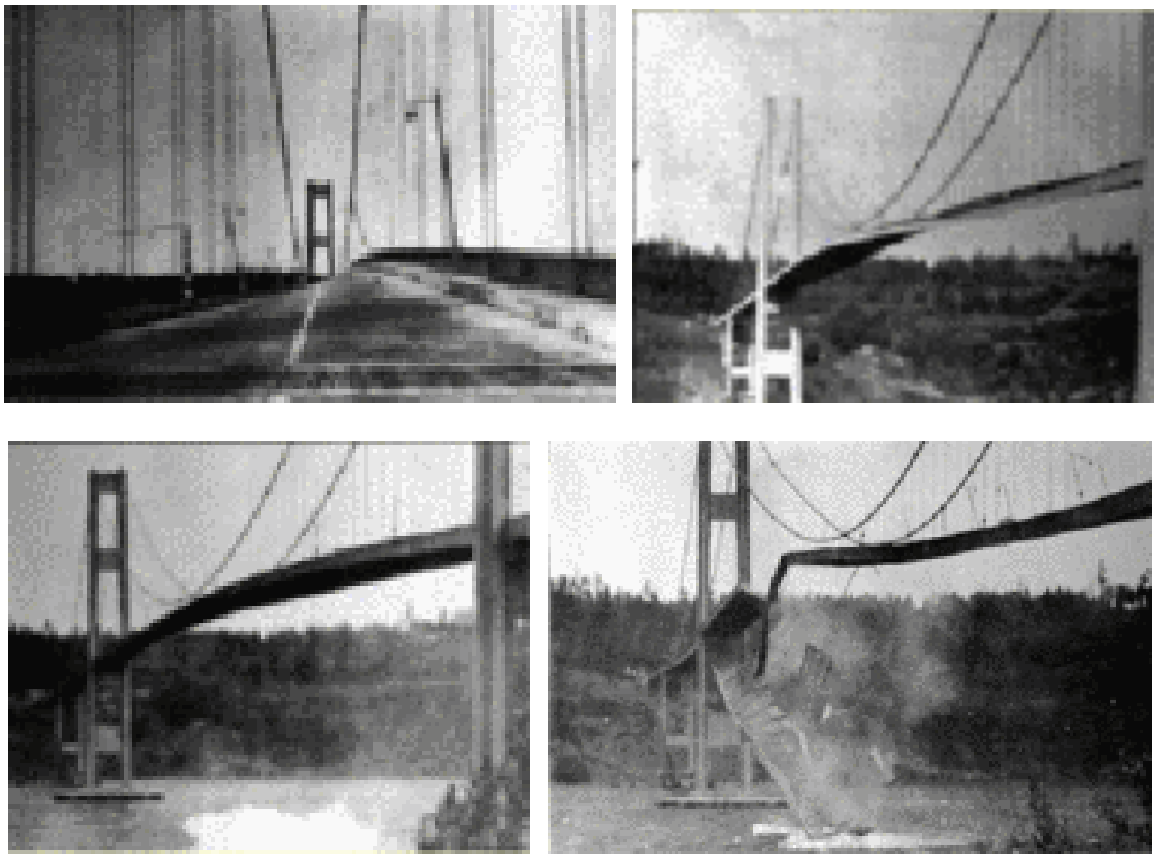

Figure 8. Torsional flutter aeroelasticity failure of the Tacoma Narrows Bridge, State of Washington, USA, 1940.

AEROELASTIC FLUTTER STABILITY

Aeroelasticity is the combination of elastic deformations with the aerodynamic loading. The dynamics of the deformations have a large influence on the aerodynamic forces and these forces in turn will influence the deformations.

Probably the most famous example of the importance of aeroelastic flutter properties is the Tacoma Narrows Bridge collapse in 1940. This bridge was destroyed due to torsional flutter.

Over the years wind turbines have increased in size. Larger wind turbines result in lower prices for the generated electricity due to the economies of scale. Larger turbines have however also shown aeroelastic instabilities; an effect that was unexpected.

This can lead to catastrophic failures and is the subject of current research involving the performance of fully nonlinear simulations of multi-body models under aerodynamic loading.

The aeroelastic analysis assesses the differences between the produced rotor blade and the original design as well as the differences between the different rotor blades. It also introduces possible guidelines for designers on what properties can be modified in order to obtain a more stable design. By correctly analyzing the stability properties of wind turbines their lifespan can be enhanced, particularly with respect to fatigue failure.

A related issue is the possible resonant frequency failure phenomenon observed in the failure of helicopter systems.

Figure 9. Resonance failure testing of helicopter blades.

WIND SITE SAFETY

At the time of site planning and design the safety aspects of the site including any existing hazards, as well as any possible future hazards resulting from the changes to the site and its usage. In addition the hazards resulting from the winds turbines and their auxiliary equipment must be accounted for.

The existing hazards include the aviation hazards, the local weather conditions, as well as the peculiar characteristics of the site.

AVIATION HAZARDS

The presence of wind turbines in the vicinity of airports does not pose a risk to high flying aircraft but would pose a hazard to low flying and landing aircraft. The allowed flight paths in the vicinity of wind farms is determined and adjusted in conjunction with the local aviation authorities.

Wind farms are highly visible in good weather conditions when recreational

aviation activities are normally conducted. However recreational activities such as ballooning, parachuting, hang gliding, and micro lights flying must be diverted away from the wind farm site. A parachutist hit a wind turbine upon landing in Europe and was killed.

Emergency evacuation air services are aware of the hazard, and avoid services and operation in wind farm areas due to the invisible turbulence created in the downwind wake from wind turbines. They worry also about the low visibility under low ceiling conditions, and judiciously bypass flying above wind farm sites.

WEATHER CONDITIONS

Wind turbines are normally designed to withstand the historically worst expected wind conditions over a 50 or 100 years time span depending on the available meteorological data. In the tornado alley in the USA's Midwest, particular attention should be directed towards the anticipation of weather conditions favorable to the development of tornadoes and shutting down operation of the turbines if their occurrence is predicted. The structural towers and rotors in these locations must be designed to withstand the maximum credible conditions at the particular site.

Turbine collapse occurred in high wind conditions at the Searsburg, Vermont wind facility on September 15, 2008. One of the rotor blades hit the base causing the tower to buckle and the nacelle and rotor assembly to crash to the ground.

Figure 10. Turbine collapse in high wind conditions at the Searsburg, Vermont wind facility, September 15, 2008.

Icing and the occurrence of freezing rain in a given location must be assessed. Freezing rain has been known to have collapsed truss type television towers in some locations. A large amount of ice forming on the rotors can cause a hazard through fall or ejection to the personnel, vehicular traffic and members of the public in the vicinity of the turbines.

Being normally placed on high locations, wind turbines attract lightning strikes and their nacelles and towers must be equipped with lightning rods and the electrical equipment protected with circuit breaking capabilities.

In low locations the probability of flooding and water logging affecting the foundations and the electrical cabling on the site must be supplemented with the addition of proper drainage facilities.

PECULIAR SITE CHARACTERISTICS

Wind farms must be sited away from seismically active zones and fault lines.

In the case of onshore and offshore wind farms, the effects of corrosion and from moisture and airborne particles such as sea salt must be accounted for.

In desert areas airborne dust in sand storms could cause damage to the equipment unless filtered out.

Ground stability influenced by water retention or flooding could weaken the towers foundations and affect the electrical cabling, as well as vehicular access on roads of heavy cranes and maintenance crews.

The history of the site must be assessed regarding subsidence as a result of previous mining or the presence of hazardous materials from previous usage as an industrial or a waste disposal site.

The location of buried services such as natural gas or oil pipelines must be assessed.

The agricultural use of a wind farm should be assessed from the perspective of the risks posed to conventional farming from the buried cabling and the rotating blades.

A wind farm must be considered as an industrial site restricting the public's right of way and recreational access for hunting, snowmobiling and bird watching. This would also minimize damage due to vandalism and the remote possibility of acts of sabotage.

FUTURE LAND USE

Future changes in land usage need to be considered in the process of safety assessment. The land owner may change the usage from plowing to cattle grazing impacting the design of the access routes.

Hazardous materials such as pesticides and herbicides may be introduced and the wind farm workers must be aware of those hazards and their associated access exclusion times.

Ancient cultures monuments or burial sites may be excavated at some time in the future.

The presence of the wind farm itself may generate changes in land usage by attracting visitors and tourists.

WIND TURBINES RISKS

As industrial equipment, wind turbines pose operational risks. The main sources of risks involve electrical, siting, as well as vehicular access risks.

ELECTRICAL RISKS

The electrical connections to the wind turbines and the transformer substations need to be designed within the safety specifications adopted by the local electrical utility

company.

The safe operation of the electrical cabling must take into consideration the soil acidity pH value and the electrical gradient, providing earth insulation and circuit breakers isolation and protection systems in case of corrosion and electrical leakage to the ground.

Provisions must be provided to warn the public about the presence at the site of high voltage electrical equipment and power lines and restrict access to their vicinity.

The underground power lines must be protected from exposure by flash flooding after heavy rain downpours and from wear from vehicular traffic.

The overhead power lines must be positioned so as to avoid any contact between them and maintenance vehicles and farm equipment is the site continues to be farmed.

There have been reports about the existence of stray currents at locations adjacent to wind farms such as dairy farms. The dairy cattle were claimed to be reluctant to drink their required daily amount of water for optimal milk production and that they suffered a lack of sleep.

SITING RISKS

The proximity of turbines to each other and their possible interaction resulting in fatigue loads must be considered in the risk assessment methodology.

The access roads and rights of way must be positioned at a distance from the turbines towers so as to prevent a rotor blade failure or ejection from affecting vehicular traffic.

The positioning of the transformers and the high voltage cabling on the ground must provide safety for the access crews and members of the public by enclosing them within fenced structures and restricting access to them by humans as well as animals such as grazing cows or deer.

Turbines rotation causes a humming sound, and the effect of noise pollution on the neighboring inhabited structures must be assessed. The noise caused by personnel movement and vehicles traffic, particularly at night, must also be assessed.

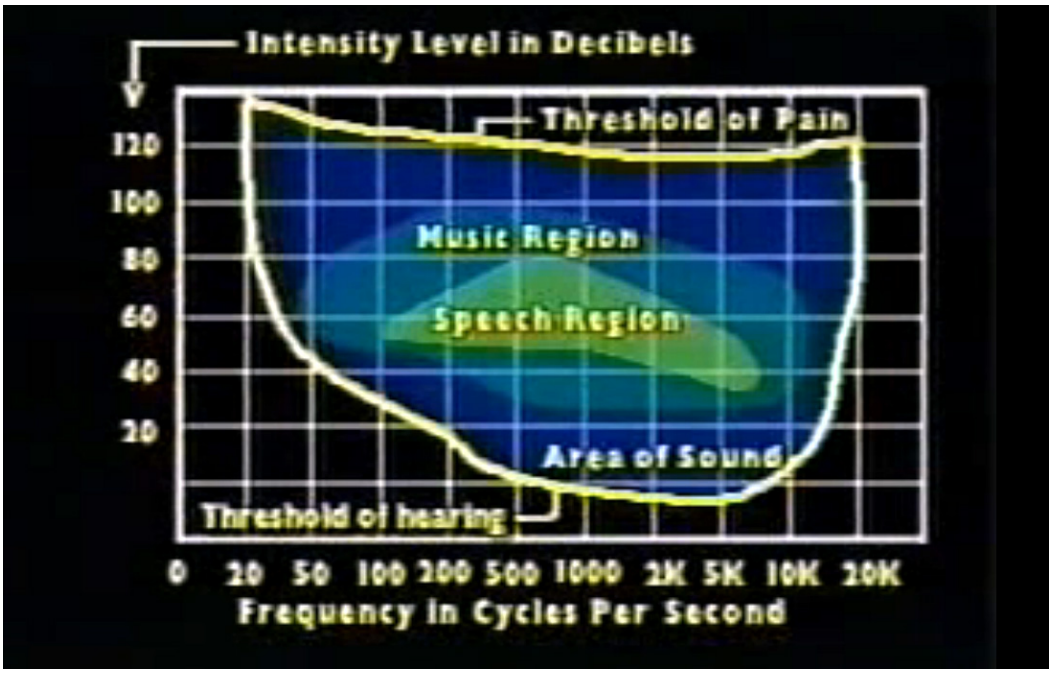

Figure 11. Sound audible region as a function of frequency in Hz and intensity.in decibels.

INFRASOUND GENERATION

The range of infrasound is generally accepted to be between 0-20 Hertz with a specific area of interest between 17 and 19 Hertz. Tests by NASA have revealed that the human eyeball resonates at around 18 Hz, to which infrasound exposure may cause a reaction and lead to hallucinations.

Infrasound occurs quite naturally at some locations and possible causes include storms, earthquakes, waterfalls, volcanoes, ocean waves, wind reacting with structures such as chimneys and even nuclear blasts. Some buildings or natural features can act as Helmholtz resonators and create infrasound at high levels. Ancient places of worship or ceremonial burial such as the Maeshowe mound in Orkney, have been shown to act in this way. Some animals are sensitive to these low frequency vibrations and may appear to foresee approaching storms and earthquakes. Elephants are known to use infrasound as a form of communication over long distances.

It is possible that any room with an open doorway or window can operate like a Helmhotz resonator, similar to blowing a column of air across an empty bottle. Subsonic sound can travel long distances, pass through walls and may be amplified in tunnel like structures. Standard hearing protection is of little use for subsonic sound as it often can pass straight through and may even be amplified. There have been links reported between supposedly haunted locations and the presence of infrasound.

Sound levels including infrasound are represented in pascals, micropascals or decibels. There is a huge variance in sound pressure ranging from the minimum that can be heard by the human ear, 20 micropascals, to the threshold of pain, 20 Pa (pascals).

Because of this huge range a logarithmic scale is used to represent the sound pressure level (SPL). A reference of 20 micropascals is commonly used, being the lowest level that can be heard by the human ear at a frequency of 1000 Hz. This is equal to .02 mPa (millipascals) or 0.00002 Pa (pascals). The unknown level is compared to the 20 micropascal threshold which is given a value of 0 dB (decibels) and the resulting level is expressed in decibels (dB). Because the human ear perceives sound intensity differently depending on its frequency, weightings may also be applied in attempt to match what the human ear experiences. "A-weighted" levels are the most common used, although a "G-weighting" is perhaps more suitable for infrasound.

The dB levels for some audible sounds are:

0-10dB Threshold of human hearing.

10-20dB Normal breathing, rustling leaves.

20-30dB Whispering at about 1.5 metres.

40-50dB Coffee maker, library, quiet office, quiet residential area.

50-60dB Dishwasher, electric shaver, office, rainfall, refrigerator, sewing machine.

60-70dB Air conditioner, alarm clock, background music, normal conversation, television.

70-80dB Coffee grinder, toilet flush, freeway traffic, hair dryer, vacuum cleaner.

80-90dB Blender, doorbell, heavy traffic, hand saw, lawn mower, ringing telephone, whistling kettle.

85dB Lower limit recommended for the wearing of hearing protection.

90-100dB Electric drill, shouted conversation, tractor, truck.

100-110dB Baby crying, boom box, factory machinery, motorcycle, subway train.

110-120dB Ambulance siren, car horn, leaf blower, walkman on high, power saw, shouting in the ear.

120-130dB Auto stereo, rock concert, chain saw, pneumatic drills, stock car races, thunder, power drill.

130-140dB Threshold of pain, air raid siren, jet airplane taking off, jackhammer.

150-160dB Artillery fire at 500 feet, balloon pop, cap gun.

160-170dB Fireworks, handgun, rifle.

170 -180dB Shotgun.

180 - 190dB Rocket launch, volcanic eruption.

The vibration of the sound alters the pressure of the medium it is traveling in - be it air, water or living cells. If the sound level is very high, the entire organism may vibrate. For instance the pressure of artillery with a few meters can exceed 200dB which is enough to cause blood vessels to tear and could even prove fatal. A level of 140dB is enough is to damage nerves of the inner ear which could lead to permanent deafness.

The sound we can hear (20-20,000Hz) gives us fair warning, but what of the sound frequencies we cannot hear? Such high levels of infrasound can easily pass through the skin and cause organs to vibrate which can lead to symptoms commonly associated with high infrasound exposure. As we cannot hear the sound the cause of the symptoms often remains unidentified - but may be just as intense and harmful as any audible sound exceeding 120dB.

FLICKER EFFECT

The rotation of the blades causes a visual light flicker, and must accordingly be located at a sufficient distance from areas of human dwelling and activities.

There are two types of flicker associated with wind turbines:

1. Shadow flicker arises as the shadow of the moving turbine blades moves across the ground.
2. Strobe occurs when turbine blades reflect the sun rays towards the viewer. For a 3 rotor blades turbine rotating at 10-20 rpm, the strobe flicker would have a frequency of 30-60 rpm or 0.5-1 Hz resembling a strobe light. The use of matted low reflectivity rotor blades would eliminate this effect.

VEHICULAR ACCESS RISKS

In case the access roads are not suitably designed to account for the maximum size heavy equipment such as cranes, as well as the possible water logging and retention, surface collapse could occur causing accidents. The access roads must also be planned for safe usage even in conditions of poor visibility at night or under fog or adverse weather conditions. They must be equipped with turning spots, passing lanes and warning signs.

On the access roads, pedestrian traffic must be kept separate from vehicular traffic or restricted altogether, particularly in the vicinity of inhabited areas in the vicinity, lest they get eventually turned with increased used into local roads presenting the traffic with undue risk.

OCCUPATIONAL SAFETY

Conical tubular steel towers predominate in modern wind turbines over lattice towers in spite of their higher cost. They offer a safe and comfortable environment for

service personnel to perform maintenance and repair. They are favored to the cheaper lattice towers which reportedly attracted birds nesting.

The primary occupational hazard in wind turbines is work at a substantial height above ground during installation and maintenance; a hazard shared with the construction business in general.

Fall protection devices in the form of work harnesses or straps are mandated in wind turbine maintenance work. The harnesses are connected with a steel wire to an anchor that follows the worker climbing or descending the turbine ladder inside the conical structural tower. The wire system is equipped with a shock absorber in case of an accidental fall.

Figure 12. The Netherlands, 2013. Maintenance workers caught in a wind turbine fire. Source: James Conca.

As a safety feature, the access ladders are placed at a distance from the structural tower wall allowing the service workers to climb the tower while resting their shoulders against the inside wall of the tower.

National and international standards govern the processes of fire protection and electrical insulation.

During service and maintenance operations the mechanical brakes are applied and a pin is used to lock the rotor to prevent any inadvertent motion of the mechanical parts.

The structural towers are designed to be flexible and not stiff in nature. The implication is that their access for maintenance should be avoided under windy conditions, since the presence of the personnel at the tower top would affect its bending moment in high winds. A tower collapse resulting in a fatality has in fact been reported while personnel were atop the tower under high wind conditions.

SAFETY SENSORS

Wind turbines are equipped with a vibration sensor located inside their structural tower. It consists of a ball bearing sitting on a ring. The ball bearing is connected to a disconnect switch through a chain that would turn the turbine off in case of excessive vibration. Fiber optics vibration sensors are used within the electrical components enclosures.

Other safety sensors include electronic temperature gauges checking for any undesirable temperature rises in the electrical generator and the mechanical gearbox or transmission.

Figure 13. Fiber optics vibration sensor. Source: VFT VibroFibre.

ROTOR BLADES

Safety regulations require that the rotor blades must be tested both statically and dynamically much like aircraft components. In static testing, static loads such as weights are applied to the blades. In dynamic testing repeated bending tests the resistance of the blades to fatigue failure. The bending test may reach more than 5 million cycles.

A wind turbine design had a blade failure and dropped a 6.5 ton blade into an Illinois corn field on October 22, 2008. Its manufacturing company promptly replaced the blades on more than 400 turbines, with most of them in the USA that could have similar problems. The manufacturer reported that its fiberglass turbine blades could develop cracks because of a design flaw, something the company said it could fix by adding more fiberglass. It spent about $25 million on the project, and initiated a retrofitting program for 1,251 blades that were determined to have the defect.

The turbine that shed the rotor blade in Wyanet, Illinois, about 55 miles north of Peoria, was set to be worked on the next week, was about 140 feet long and flew at least 150 feet away from the turbine and landed in a corn field. Similarly, a blade on a turbine in Minnesota broke loose.

OVERSPEED RUNAWAY TURBINE EVENT SEQUENCE

Wind turbines are required to stop automatically in case of the failure of some critical component that would cause it to overspeed with subsequent failure and even disintegration.

A possible initiating event for overspeed failure is a generator overheating or being disconnected from the grid. The accident sequence that follows involves the inability of the generator to brake the rotation of the rotor. The rotor would start accelerating in its rotation within seconds of the initiating event.

To prevent such an accident sequence an overspeed protection system is essential. Safety regulations specify that such a system must have two independent fail-safe brake mechanisms to stop the turbine.

Figure 14. Runaway turbine disintegration clip sequence from video caused by failure of brake system, 2008. Notice how an initiating event of a single blade failure evolved into a failure sequence where the unbalanced nacelle and hub caused another failed blade to hit the structural tower, slicing it and causing it to collapse while the disintegrated rotor blades were ejected away. Source: UTube.

AERODYNAMIC BRAKE SYSTEM

Aerodynamic braking is the primary braking system for most wind turbines. It involves turning the blades about 90 degrees around their longitudinal axis in the case of a pitch controlled turbine or an active stall controlled turbine. In the case of a stall controlled turbine, the rotor tips are rotated 90 degrees.

The Gedser wind turbine design was equipped with emergency rotor tip brakes.

Figure 15. Emergency rotor tip brakes for the Gedser stall controlled wind turbine.
Source: Danish Wind Turbine Manufacturers Association.

To make them fail-safe and operable in the case of electrical power failure, those devices are designed to be spring loaded and are automatically activated if the hydraulic system in the wind turbine loses its pressure. Once the hazardous situation is over, the hydraulic system would restore the blades tips or the whole blades to their original operational state.

The aerodynamic braking system is capable of stopping a wind turbine within two rotations. Under such circumstance no major stress is applied to the turbine components, and no tear and wear results in the structural tower and machinery.

MECHANICAL BRAKE SYSTEM

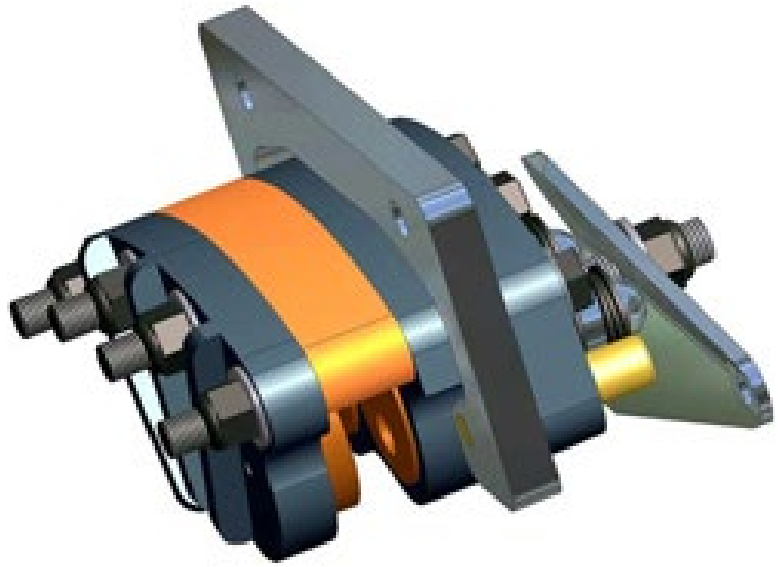

Figure 16. Wind turbine mechanical caliper disc brake. Source: WC Branham.

For reliability, a mechanical brake supplements the aerodynamic braking system in wind turbines. It also doubles as a parking brake when a stall controlled turbine is stopped. Its design draws on automobile brakes designs, but on a larger size scale.

In the case of a pitch controlled turbine, the mechanical brakes need to be used only during maintenance activities. They are rarely used since the rotor does not move much once the blades are pitched to a 90 degrees angle.

SAFETY AND ACCIDENTS

The blade system in a wind machine has incorporated in it mechanisms designed to avoid excessive rotational speeds, including blade feathering and hydraulic and friction braking. Blade failure could still occur ejecting the blade away for a distance from the machine. Stress and vibration could cause tower failure. Failure mode analysis and safety zones around wind machines must be used at the design and site selection stage.

Several potential major types of accidents can be considered for wind machines:

1. **Structural tower failure**.

This would involve a possible circular area around the base of the tower with a maximum hazard zone radius equal to the height of the tower plus the radius of the disc formed by the rotor blades.

Figure 17. Tower collapse of a wind turbine. Wasco, Oregon, August 27, 2007.

A tower collapse in Eastern Oregon caused a person to fall to his death and another to be injured in August of 2007. The worker killed in the incident was at the top of a turbine tower when the turbine tower buckled about halfway up and toppled over. The injured person was inside of the tower at the time while the third worker, who escaped injury, was at the base. The turbine had been in operation for 500 hours and the workers were doing a routine inspection. The turbine was part of the Klondike III wind project, located near Wasco which generates 221 MW of electricity. It was using a mix of 44 Siemens 2.3 MW wind turbines and 80 General Electric 1.5 MW wind turbines.

Figure 18. A 70-meter or 230-feet high tower collapsed in inclement weather at Goldenstedt, Germany, on October 28, 2002.

Figure 19. Tower collapse in high winds.

2. Blade failure and ejection.

A blade failure did actually happen and led to the decommissioning of the 1,250 kW Smith-Putman machine built at Grandpa's Knob in 1941.

In November 2006, a sudden wind gust ripped off the tip of a rotor blade from a 100 meters or 328 feet high in Oldenberg in Northern Germany. The 10 meters or 32 foot long fragment landed 200 meters away. Examination of 6 other turbines of the same model revealed possible manufacturing defects and irregularities.

Figure 20. Blade failure at the stem on a 140 feet radius wind turbine at Wyanet, Bureau County, Illinois, October 22, 2008. The blade landed 150 feet from the base of the structural tower.

Figure 21. Turbine failure at Lake Wison, Minnesota, November 2007.

A turbine at the Searsburg wind energy facility in Searsburg, Vermont experienced a catastrophic failure when one of the blades came in contact with the turbine's tower causing it to buckle during high winds. This turbine's 28 ton nacelle and 3-blade rotor assembly crashed to the ground scattering debris several hundred feet from the structure. About 20 gallons of heavy oil spilled from the unit when its fluid reservoirs were damaged. The 11 turbines Searsburg facility was brought online in 1997 and according to preconstruction documents, its turbines had an expected lifespan of 30 years, yet they were reaching their end of useful lifetime at about 11 years.

An important consideration is the maximum distance that an ejected rotor blade from a wind machine can reach. An exclusion zone should be provided within that range during wind machine operation.

For a 1.5 MW rated power wind machine, and based on the following assumptions:

1. Rotor tip speed of 64 m/sec (208 ft/sec.
2. Tower height of 46 meters (159 ft).
3. A rotational speed of 40 revolutions per minute (rpm).
4. A blade radius of 30.5 meters (100 ft).
5. No air resistance.
6. Simple projectile behavior for the ejected blade.
7. Blade ejection at a 45 degrees angle from the horizontal.
8. Center of gravity of blade at its midpoint.

The blade tip under these assumptions is expected to land at about 470 meters (1,540 feet) from the tower. There is a need for the more detailed analysis of not just individual occurrences, but the more complex occurrence of initiating events leading to accidents sequences and their associated probabilities and consequences. For instance one can envision tornado strength winds as an initiating event, breaking a wind blade, and then hurling it as a missile at 40-100 miles per hours. The methodologies of Fault Tree, Event Trees and Consequence Analysis could be used.

A fail-safe belt, cable or spring system inside the blade cross section could be used to prevent a failed blade from traveling a hazardous distance.

Failures to wind generators normally occur during extreme wind conditions, but the structural weaknesses may have been inherent in the original design or may have accumulated during operation under vibration, corrosion or fatigue loading conditions.

After they were exposed to two gales conditions in Denmark in 1981 generating wind speeds exceeding 35 m/s for a duration of 10 minutes on average, extensive damage was caused among 250 multi blade wind generators: 9 totally failed, and 30 percent of them were seriously damaged. For comparison among another 500 wind turbines less than 1 percent failed completely and the rate of serious failure was 5 percent. In the gale exposed machines, the failure types are shown in Table 2. The causes of failure or failure mechanisms are shown in Table 3.

Table 2. Failure distribution in 250 wind generators for a 10 minutes exposure to 35 m/s gale winds.

Failure Type	Occurrence [percent]
Total tower and nacelle collapse	15
Blade root failure	3
Blade tip failure	12
Blade buckling	6
Blade stay failure	3
Bearing and gearbox failure	10
Hub failure	15
Yaw control failure	36
Total	100

Table 3. Failure mechanisms in 250 wind generators for a 10 minutes exposure to 35 m/s gale winds.

Failure Mechanism	Occurrence [percent]
Fatigue loadings	21
Static loads	28
Under designed mechanical/aerodynamic brakes	11
Insufficient power regulation	21
Miscellaneous causes	19
Total	100

Fatigue failure of the rotor blades limits the safe operation period to 20 years. To avoid catastrophic failures the following preventative measures are normally adopted:

1. Reliable maintenance, service and repair by specially trained crews.
2. Assuring quality, reliability, easy service, and repair of manufactured components.

Many catastrophic failures of wind generators in all size ranges are caused by imperfect safety devices; which makes them the most important components of wind generators.

In December of 2006, fragments of a broken rotor blade landed on a road shortly before rush hour traffic at the city of Trier, Germany.

In January 2007, two wind turbines caught fire at Osnabrück and in the Havelland region in Germany. Lacking tall ladders, the firefighters could not intervene.

The rotor blades of a turbine at Brandenburg in January 2007 ripped off at a height of 100 meters or 328 feet, landing in a grain field next to a road.

Figure 22. Structural collapse of a wind turbine in a 2002 storm. Source: Der Spiegel, DPA.

RELIABILITY AND DURABILITY OF WIND TURBINES

Mishaps, breakdowns and accidents seem to be associated in the latest expansion wave of wind turbines construction.

Gearboxes or transmissions have proven to be the weakest link in the chain having short lives breaking down before 5 years, well ahead of the assumed 20 years design goal of wind turbines. They had to be replaced in large numbers. A questionnaire to the German Wind Energy Association only favorably ranked a German Company which manufactures gearless turbines without gearboxes eliminating the weakest link in the chain.

Fractures have formed along the rotors and the foundation after a short operational life.

Short circuits, overheated alternators or gearboxes oil have caused fires.

Figure 23. Fire caused by a short circuit, frictional overheating or lightning in 2004 in Germany. Source: Der Spiegel, DPA.

Figure 24. Structural crack near the hub of a wind turbine.

Figure 25. Structural crack caused by manufacturing defect in a rotor blade.

Figure 26. Recall and replacement of rotor blades in a wind farm due to a manufacturing defect, USA.

INSURANCE ISSUES

The insurance companies have complained about problems caused by improper storage of components and cracks and fractures caused by faulty manufacturing. They consider wind power as a risky sector. The insurance company Allianz in Germany handled about a thousand damage claims in 2006. On average, an operator had to expect damage to his facility, excluding malfunctions and uninsured breakdowns, with a frequency of once every four years.

Insurance companies now require the writing of maintenance agreements directly into their contracts, requiring wind farmers to replace the vulnerable components such the gearboxes once every five years.

The problem is that the replacement of a gear box could cost about 10 percent of the original turbine cost, reducing the anticipated economical return on the investment.

Many companies have sold a large number of units after testing the blades but not full system prototypes. A large worldwide demand for the rotors and the replacement parts take a long time to be delivered causing a supply crunch and a delivery time of about 18 months for a rotor mount.

Post mortem analysis of failed components revealed that the forces that come to bear on the rotors are much larger than originally anticipated. The reason is that wind speed is governed by random direction changes and by wind gusts of larger magnitudes

than the design values. Some manufacturers have built larger rotor blades for machines with larger capacity, hence better economies of scale, but with stresses and strains that are harder to control.

Figure 27. The gear boxes of wind turbines need replacement every five years, as they are the component that is most prone to failure from wind gusts causing misalignment of the drive train. Source: Der Spiegel, DPA.

Construction errors have occurred. With the turbines rated power getting larger, the diameter of the tower was kept constant because of the difficulty of transporting larger towers on highway systems. With the trend to build larger machines the concrete foundations are suffering from vibrations and load variations generating fractures. Water then seeps through the cracks causing the reinforcement steel bars to rust.

Figure 28. Difficulty in moving turbine components on existing rural roads.

GEARBOX DESIGN OPTIONS

The weakest link of a wind turbine has been its gearbox. As turbine sizes increased, the design gearboxes able to handle the torque generated by longer and heavier blades has become a major problem. In addition, turbine loading is variable and hard to predict. Some gearboxes have failed in less than two years of operation.

Most of these failures have been attributed to the movement of the machine chassis, which causes misalignment of the gearbox with the generator shafts and leads to failure. Such failure occurs in the high speed rear gearing portion of the gearbox when the bearings become faulty.

The frequency of failures can be reduced by regular turbine realignments.

Manufacturers have made their turbines more reliable by improving the oil lubrication filtration system in the gearbox so it can remove all particles larger than seven microns across. If a particle of that size breaks free of the meshing gears, it can damage other gears and bearings.

Manufacturers in Germany and under license in Japan have increased the number of generator poles in their machines, eliminating the gearbox. Most electrical generators have 4 or 6 magnetic pole pairs in their windings and must use a gearbox. With the generator built with 50-100 pole pairs, the use of electronic control can eliminate the need for a gearbox.

The coupling of the blades directly to the generator in machines without a gearbox also eliminates the mechanical or tonal noise produced by conventional turbines.

A California based wind turbine manufacturer in the USA, improved reliability by using distributed gearing using multiple paths and 4 generators to ensure continued turbine operation even if one of the generators fails.

It encountered a problem with its 2.5 MW turbine design, which experienced quality control and an apparent design problem, affecting the company's financial performance.

The 20 MW Steel Winds wind farm in upstate New York, using eight of the turbines, has been shut down because of a gearbox problem in the turbines. All eight turbines suffered from a manufacturing problem and repairing the problem required several months.

The Steel Winds project, on a former Bethlehem Steel site that is also a listed Superfund toxic waste site, was the first to use the 2.5 MW machines. The eight wind turbines rolled off the company's assembly line in Cedar Rapids, Iowa, in late 2006, and went into service at the site on Lake Erie in April 2007.

The operators of the project, UPC Wind and BQ Energy, first noticed the problems with the wind machines in August 2007. Upon inspection, engineers discovered that a tooth on one of the four gears in the box had broken. Inspections found the problem on all of the turbines on the site.

Similar turbines at projects in Iowa and Minnesota had the same problem and required repairs. SNL Financial, a trade news service, reported that 50 turbines required repair. The Steel Wind turbines were all under warranty, according to a UPC Wind official, so the manufacturer covered the costs of repair.

The turbines use a unique approach in their gearboxes to cope with the large torque generated by the turbine blades that are longer than the wing of a Boeing 747 airplane on

the gear box. The drive train of the wind turbine uses torque splitting and feed it into four turbo generators operating in parallel. An advantage is that the turbine can continue operation with one generator out of service and waiting for repair.

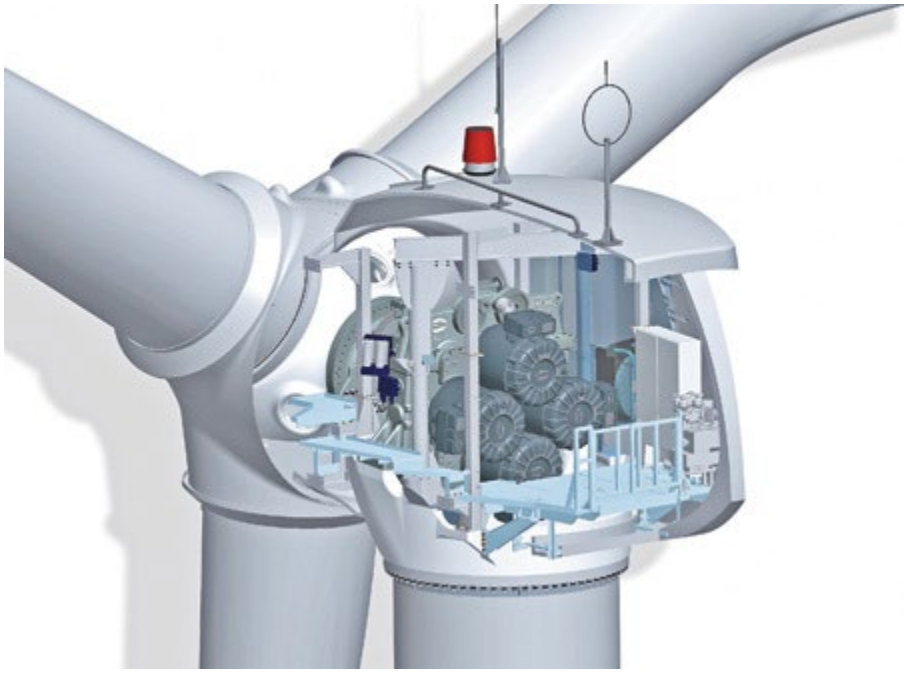

Figure 29. Torque splitting between four electrical generators operated in parallel. The turbine can continue operation with one generator out of service. Source: Clipper Wind Power Inc.

Figure 30. Backlog of wind turbine parts awaiting delivery for replacement. Source: DDP.

OFFSHORE FACILITIES

Offshore facilities have run into difficulties. The market leader Vestas company had to remove the turbines from an entire wind park along the Denmark's coast in 2004. The turbines were not resilient enough to withstand the dominant sea and weather conditions. A similar situation was encountered off the coast of the UK in 2005.

The German manufacturer Enercon, despite the growth potential, considers the risks of offshore wind power too great, opting to stay out of the field since according to its spokesperson Andreas Düser: "The Company does not want to lose its good standing on the high seas."

ICE SHEDDING

Icing of wind turbines is a common occurrence with some turbines equipped with icing prevention systems.

Icing would slow down the rotation of a wind turbine, which could be sensed by its control system that would shut it down.

Turbine blades rotate at high speeds at their tips that can reach 90-180 mph. The possibility of ejection of ice chunks necessitates their emplacement away from human dwellings.

EXAMPLE

The Suzlon S.66/1250, 1.25 MW rated power at 12 m/s rated wind speed wind turbine design has a rotor diameter of 66 meters and a rotational speed of 13.9-20.8 rpm. Its angular speed range is:

$$\begin{aligned}\omega &= 2\pi f \\ &= 2\pi \frac{13.9-20.8}{60} \\ &= 1.46-2.18[\frac{\text{radian}}{\text{sec}}]\end{aligned}$$

The range of its rotor's tip speed can be estimated as:

$$
\begin{aligned}
v &= \omega r \\
&= (1.46 - 2.18)\frac{66}{2} \\
&= 48.18 - 71.94[\frac{\text{m}}{\text{sec}}] \\
&= (48.18 - 71.94)x10^{-3}x60x60[\frac{\text{km}}{\text{hr}}] \\
&= (173.45 - 258.98)[\frac{\text{km}}{\text{hr}}] \\
&= \frac{(173.45 - 258.98)}{1.61}[\frac{\text{mile}}{\text{hr}}] \\
&= (107.73 - 160.86)[\frac{\text{mile}}{\text{hr}}]
\end{aligned}
$$

Figure 31. Blade failure due to possible ice shedding from one blade unto another or a manufacturing defect, Conisholme, Lincolnshire, UK.

Refusing to recognize ice shedding or structural manufacturing defects as causes of failure, UFO enthusiasts had their fun claiming that the damage to a Lincolnshire wind farm turbine was caused by a mystery aircraft. The turbine at Conisholme lost one 66 ft or 20 meters blade and another was badly damaged. The turbine was one of 20 at the Conisholme site, which has been fully operational since April 2008.

If the turbine blade were still, it would take the equivalent of a 10 tonne load to cause such damage, but if it were rotating, or hit by a moving object, the force could be significantly less. It definitely was not a bird hit, but it could be ice thrown from a neighboring rotor blade that struck it. Most turbines have an anti icing system on the blades and maybe it failed to prevent the ice build-up."

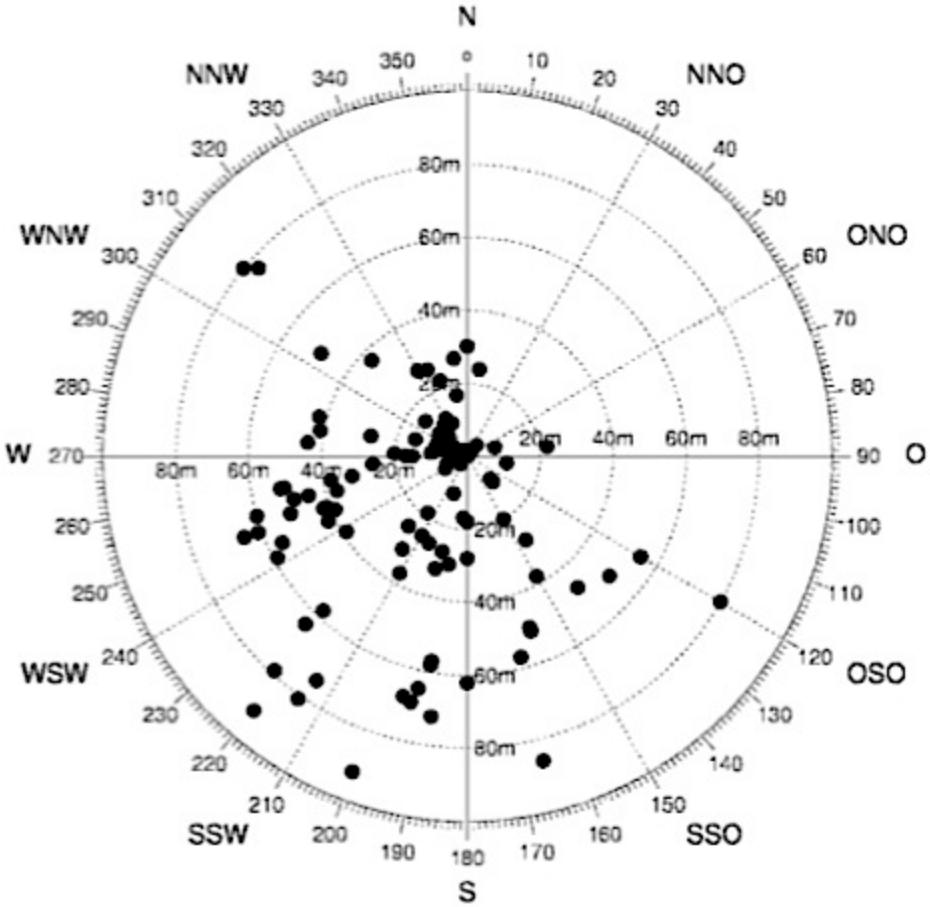

Figure 32. Frequency of an ice throw study in the Swiss Alps. Ice throws depend on the prevailing wind conditions and can reach a distance of 100 meters from the base of the wind turbine.

Figure 32. Judicious warning about ice shedding and limited access at a wind turbine site, USA.

MAINTENANCE AND REPAIR

Utility scale wind turbines are developing enough operational history to develop a picture of their maintenance needs.

Most of the repairs in occur in the electrical and electronic controls and the sensors units. The mechanical breakdowns are smaller in incidence but have more serious effects affecting the downtime of turbines.

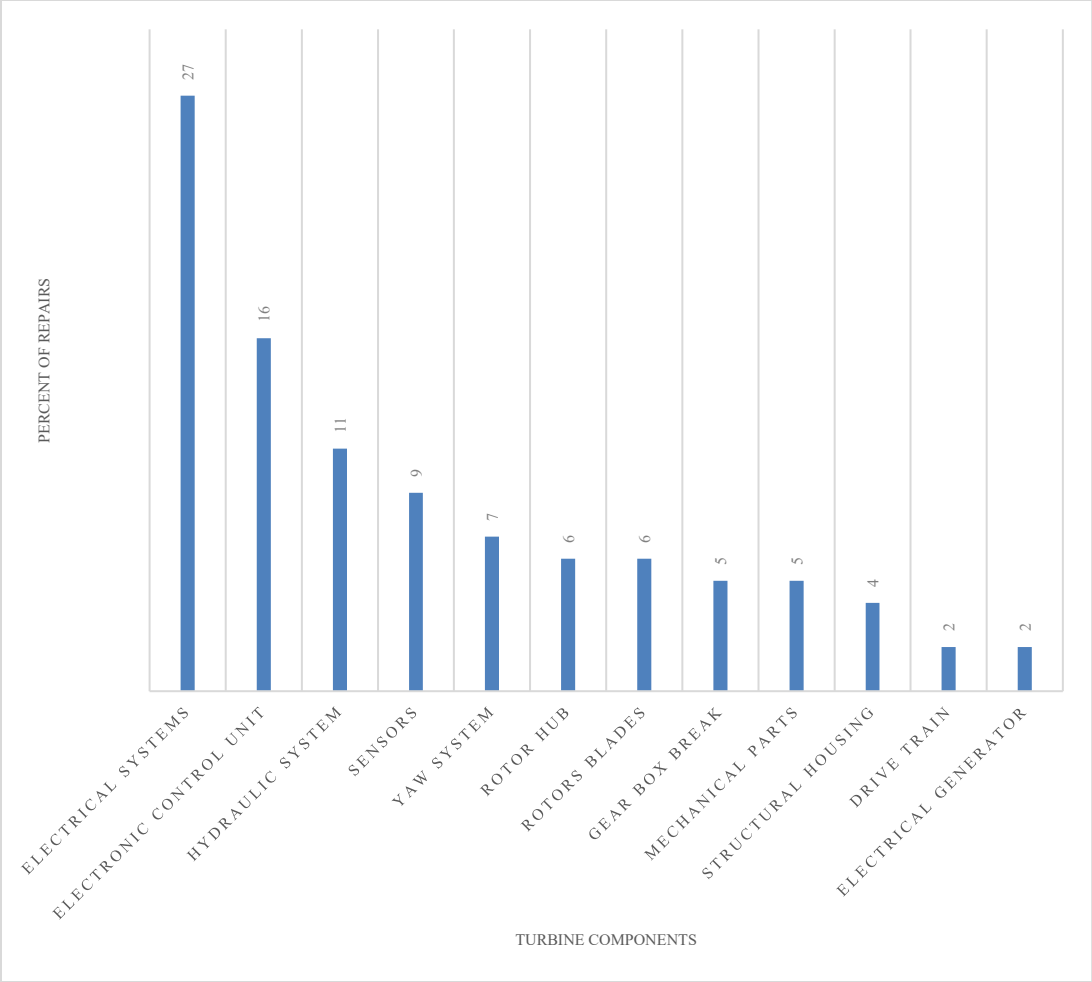

Figure 34. Percentage of needed repairs and maintenance on utility scale wind turbines. Data: AWEA.

DISCUSSION

Even though there are testing programs for the components of wind turbines such as the rotor blades, there exists a need for testing complete prototype wind turbines at the prevailing environmental conditions under which they are meant to operate at university or national laboratories before being fully deployed on a large scale.

A licensing process for reliable and safe designs needs to be offered for those wind turbines that would have undergone the testing process. The professional engineering societies need to provide their input in this regard.

Untested prototype designs operate differently under different conditions. Some turbine designs that may have operated satisfactorily under European or California conditions may not perform in the same way in the continental USA, American Midwest or East Coast; for instance under icing or storm conditions.

Unforeseen problems can be identified during the testing process and remedied. For instance, the early MOD-1 USA wind turbine design produced sub-audible vibrations which rattled the windows of houses nearby. They were caused by the

interaction between the rotor and the tower producing 2 pulses per revolution with a vibration frequency of 1.2 Hz. To reduce the effect, slower blade speeds were used, and the steel blades were replaced with fiberglass blades.

Utility scale wind power production is recognized by the industry professionals as an industrial process with inherent hazards and risks that the general public. as well as operators, must be protected from. They have emphasized the minimization of these risks in their designs and their acceptance by the public through informed consent. The use of wind in uneconomically wind resource and high population density areas and siting them close to human dwellings and congregation sites has been professionally avoided, primarily based on professional ethics considerations, and secondarily since this threatens the whole industry with demise through the organization of dedicated groups that would oppose their unsafe or unreliable implementation.

The benefits to be accrued to society and humanity at large from the widespread adoption of wind energy as an abundant, renewable and environmentally desirable energy source currently depends on the wide informed consent and acceptance of its risks and its acceptance as a good neighbor and a reliable and safe form of power production.

REFERENCE

1. Simone Kaiser and Michael Fröhlingsdorf, "Wüthering Height. The Dangers of Wind Power," Der Spiegel, 34/2007, August 20, 2007.

APPENDIX

THE WINDS IN HOMER'S ODYSSEY

Poseidon supported the Greeks out of hatred of the Trojans in the Trojan wars. However he was offended when Odysseus forgot to honor him after his victory using the stratagem of the Trojan Horse.

As a punishment, he imposed a curse on him to never return home to Ithaca as Odysseus wandered over the Mediterranean Sea for over ten years. He was kept at sea by storms and winds.

Poseidon's curse on Odysseus had a dual nature. When Odysseus landed on the island home of Poseidon's son, Polyphemus, a cyclop, Odysseus was forced to blind him so that he can escape. Odysseus returned to his ship as storms continually kept him off course and forced him to encounter such mythological beasts such as the Scylla, the Charybdis, the Sirens and the Laestrygonians.

Odysseus met King Aeolus of Aeolia who controlled the winds and implored him for help. Aeolus calmed all the winds, except for the east wind, Eurus, to blow Odysseus home. He contained the other winds in a flask, and instructed Odysseus to free the other winds only once he returned home.

As his ship finally neared home, Odysseus was asleep and his men wondering what he was keeping in the flask opened it and freed the winds, which then blew Odysseus and his ship and crew away from Ithaca once more.