WIND TURBINES AND FARMS

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1.0 SCOPE

This data sheet presents property loss prevention guidelines and recommendations for both land-based and offshore wind turbines, typically part of a wind farm or wind park, used to generate electrical power. Guidelines and recommendations are also provided for collector substations, cables, and other support equipment as part of a wind farm or wind park.

For offshore wind turbines, the scope of this data sheet is limited to locations with shallow water or transitional water depths; deep-water locations or floating offshore wind turbines are not covered.

This data sheet applies to commercial Horizontal Axis Wind Turbines (HAWTs).

1.1 Hazards

1.1.1 Natural Hazards

A. Wind

Excessive wind speed, and the resulting wind loads, can contribute to wind turbine losses. Wind speed, combined with erroneous wind measurements (such as wind speed or wind direction) or with wind turbine control or safety system malfunction (such as blade pitch, yaw, or rotor brake) can create a rotor overspeed condition resulting in damage. Windstorms can cause damage to components such as rotor blades or can topple a turbine due to excessive overturning forces, causing either buckling of the support tower or failure of the tower foundation. Damaged wind turbine rotor blades can create a hazard to surrounding property due to blade throws.

B. Hail

The impact of hail stones on wind turbines can cause damage to rotor blades, exposed wind-monitoring instrumentation (e.g., anemometers and vanes atop the nacelle), and possibly parts of the nacelle enclosure.

There is a potential that severe hail impacts could cause blade delamination over prolonged periods of time. The initial impact can cause damage deep in the inner layers of the blade material, which might eventually lead to delamination around the impact zone. This type of long-term damage is difficult to detect, and as wind farms become more widespread in hail-prone regions (e.g., in the United States, from Texas north to the central and high plains) hail could be a growing concern.

C. Ice

Ice accretion (buildup) on rotor blades can disrupt the balance of the rotor and cause vibrations and dynamic loads that can damage the blades as well as other mechanical components. There is a hazard associated with ice on rotor blades dislodging and becoming a projectile either while the rotor is spinning (ice throws) or while the rotor is parked (ice shedding). These ice projectiles can damage adjacent property.

Ice accumulation on anemometers and vanes can produce erroneous wind speed or wind direction readings, which can lead to a turbine remaining operational, or restarting, in wind speeds above cut-out speeds or with significant yaw error, which could damage the wind turbine.

D. Bushfire/Wildfire

Wildfires can cause thermal damage to land-based wind turbine farms, particularly the collector substations, rotor blades in use and in storage, which are typically made from fiber-reinforced plastic (FRP). Turbine support towers typically made of steel, or sometimes concrete have not been known to experience significant structural damage due to wildfire exposure.

E. Earthquake

Seismic shaking has the potential to cause widespread damage to wind farms. Weak foundation-bearing strata (i.e., soil or seabed) and the structural nature of wind turbines (a large, lumped mass [the nacelle and rotor] on a long vertical cantilevered member [the support tower]), including the inherent lack of structural redundancy, can contribute to the susceptibility of wind turbines to damage from seismic events. Catastrophic failure (e.g., collapse or overturning) can be the result of buckling of the support tower or failure of the tower foundation.

F. Flood

Land-based foundation footings may be susceptible to soil bearing failure due to saturation from flood exposure. This hazard is amplified when combined with wind exposure resulting in greater likelihood of overturning failure.

Flood damage is not known as a common hazard for land-based wind farms, but as wind farms become more widespread, flood may become more of a concern, particularly at coastal locations. Flood hazards include inundation (which could damage equipment in the collector substation, at the base of the tower or other aspects of the wind farm), wave action and surface flow (which could undermine the tower foundations), and flood-borne debris (which could cause impact damage to the tower and equipment).

G. Hydrodynamic Loads

Sea and lake waves and currents can impose loads on offshore wind turbine foundations, platforms, and towers, as well as on offshore substation support structures. In addition, wave loads can occur concurrently with substantial wind loads.

For land-based wind turbines located at or near the shoreline in regions potentially exposed to tsunami, damage is possible.

H. Lightning

Failure due to lightning strikes is a common cause of losses at wind farms. Lightning damage can occur to multiple wind turbines and to significant parts of the electrical system at a wind farm.

Direct lightning strikes can result in wind turbine blade damage (most common) and nacelle damage, and, occasionally, fire. Direct or indirect lightning strikes can also cause damage to electrical systems. Induced transients or surges due to nearby lightning strikes are more likely to cause incremental damage across the entire electrical system.

1.1.2 Fire

A fire in the collector substation involving combustible construction materials, and oil filled electrical equipment, cable insulation etc. could lead to a complete shutdown of the wind farm for extended periods of time.

For wind turbines, hot work, lubrication and hydraulic oil systems, and electrical equipment located in the nacelle present a fire hazard. A fire initiating in the nacelle, typically constructed of combustible materials, can spread to the combustible blades and lead to a complete loss of the wind turbine. Falling burning debris can ignite brush/wildfires leading to the spread of a fire with the potential of involving other structures and equipment in the wind farm.

Turbine transformers may be located in the nacelle, but also in the interior base of the tower, or outside of the wind turbine adjacent to the tower. Oil-filled transformers that are not FM Approved, present a greater fire hazard as an internal or an external electrical fault can result in overpressure of the transformer and an oil fire exposing the wind turbine. Substation transformers present similar fire hazards, with larger potential business interruption impact.

FM Global does not consider that adequate fire protection methods to protect a nacelle are currently available. In addition, fire service response can be limited due to the remote nature of wind farms. It is therefore critical to control ignition sources and implement other passive measures to prevent a fire from occurring within the nacelle.

1.1.3 Mechanical

Rotor overspeed is a key hazard that can result in complete destruction of the wind turbine, including the tower structure. Rotor overspeed can occur when the wind speed exceeds the cutoff speed and the overspeed protection systems fail to limit the rotor speed. For some generator designs, it can also occur upon the loss of grid power along with the failure of the protection system.

Blade failure is the most common hazard for wind turbines. Blade failure can be the result of manufacturing defects, inadequate design and/or operation, transportation damage, improper storage, improper installation, foreign object damage, windstorm damage, lightning damage, ice accumulations, leading edge erosion, water incursion, and temperature extremes.

Drivetrain failures can result from damaged bearings, couplings, and gearboxes. Rotor imbalance is a major contributor that can be caused by mass imbalances and/or aerodynamic imbalances. Causes of mass imbalances include foreign object damage and ice accumulation. Aerodynamic imbalances can be caused by inaccurate nacelle positioning (yaw), unequal pitch angles, or unmatched blade twist.

For wind turbines with gearboxes, gearbox failure has been a very common problem, including gear/tooth failures, shaft failures and bearing failures, etc. Contributing factors include high variable loads, improper lubrication, and lack of routine maintenance.

1.1.4 Electrical

Failure of electrical equipment in a wind farm will have different impact depending on type and location of that equipment. If electrical equipment located in the nacelle or the base of the tower fails, this could lead to the complete loss of power production from the wind turbine. Common places for electrical faults in nacelles are converter and capacitor cabinets. When an electrical fault produces an arc flash or sparks, a fire may result.

If electrical equipment located in the collector grid or substation fails, this could lead to a partial or complete shutdown of the wind farm for extended periods of time.

Offshore wind farms are subjected to harsh environments, equipment design and suitability are key factors in continued operation. In addition to the hazards identified above, offshore wind farms have an additional risk in the use of subsea cables. The loss of subsea cables can lead to the loss of power production from one tower up to the entire farm becoming disconnected from the grid for extended periods of time.

1.1.5 Collision

The combination of wind turbines towers and blades can reach combined heights over 785 ft (240 m). Collision of turbine blades with cranes and rigging during installation, maintenance, and repair activities have been common. Collision may also occur between blades and tower during operation. Collision or impact to the turbine from birds has been known to occur, while collision from aircraft is unlikely but possible.

Offshore wind farms can be subjected to impacts from debris and on occasions from marine vessels. Inter array cables and export cables can be damaged from ships anchors or other shipping activity.

1.1.6 Corrosion

Corrosion can cause damage to many components of a wind turbine, including structural, mechanical, and electrical components. This is of particular concern for nearshore and offshore wind turbines, where the corrosive environment can be severe.

1.2 Changes

July 2023. Interim revision. The following significant changes were made:

A. Updated recommendations for lightning protection and lightning detection systems.

B. Added recommendations for a blade damage tracking and rating system based on EPRI publicly available guide.

C. Updated recommendations for mechanical and electrical inspection, testing and maintenance frequencies.

2.0 LOSS PREVENTION RECOMMENDATIONS

The recommendations in this data sheet are intended to supplement and, in some cases, supersede local and/or national installation codes. For general reference, some of those codes and installation standards are listed in section 4 of this data sheet.

- Refer to Data Sheet 1-28, *Wind Design*, for additional information on wind speeds.
- Refer to Data Sheet 5-4, *Transformers*, for additional information.
- Refer to Data Sheet 5-19, *Switchgear and Circuit Breakers*, for additional information.
- Refer to Data Sheet 5-31, *Cables and Bus Bars*, for additional information.

Use FM Approved equipment, materials, and services whenever they are applicable and available. For a list of products and services that are FM Approved, see the *Approval Guide*, an online resource of FM Approvals.

2.1 Natural Hazards

2.1.1 Wind and Wind Combined with Other Environmental Hazards

2.1.1.1 Wind Speeds

Refer to Table 2.1.1.1.1-1 for descriptions and definitions of the various relevant wind speeds associated with the recommendations in this section.

Table 2.1.1.1.1-1. Some Relevant Wind Speeds for Wind Turbines

Symbol	*Description*	*Definition*	Typical Values (Note 1)
V	Basic wind speed	For land-based wind turbines: Extreme wind speed at 33 ft (10 m) above grade for terrain described as Ground Roughness C (Exposure C) (Note 2)	Location specific
		For offshore wind turbines: Extreme wind speed at 33 ft (10 m) above mean sea level	
$\mathbf{V_{hub}}$	Wind speed at hub height	Wind speed at the height of the wind turbine hub (accounts for vertical wind shear)	Roughly 15% to 30% greater than **V**, depending on the hub height, when $\mathbf{V_{hub}}$ is based on an extreme wind speed
$\mathbf{V_{ref}}$	Reference wind speed	Extreme wind speed at the hub height, typically used to define the standard wind turbine class; $\mathbf{V_{ref}}$ must not be less than $\mathbf{V_{hub}}$	Refer to Table 4
$\mathbf{V_{in}}$	Cut-in wind speed	Minimum wind speed at which the wind turbine operates	7 to 9 mph (3 to 4 m/s), based on 10-minute mean
			10 to13 mph (4.5 to 6 m/s), based on 3-second gust
$\mathbf{V_{out}}$	Cut-out wind speed	Maximum wind speed at which the wind turbine operates	45 to 55 mph (20 to 25 m/s), based on 10-minute mean
			64 to 78 mph (29 to 35 m/s), based on 3-second gust
$\mathbf{V_r}$	Rated wind speed	Minimum wind speed at which the wind turbine produces the rated power	25 to 30 mph (11 to 16 m/s), based on 10-minute mean

Note 1. These wind speeds are sample estimates of the typical values applicable to common sizes of new commercial land based and offshore HAWTs.
Note 2. See Appendix A of this data sheet for descriptions of ground roughness (also known as surface roughness, exposure, or terrain category).

2.1.1.1.1 Determine basic (extreme) wind speed (V) for the wind turbine location.

A. For land-based wind turbines, refer to Data Sheet 1-28, *Wind Design*, to determine the basic wind speed (V) for the specific geographic location.

B. For locations where basic wind speeds are not provided by Data Sheet 1-28, including all offshore locations, refer to a nationally recognized local code or standard to determine the basic wind speed, or a site-specific wind study, and use a basic wind speed based on a return period (mean recurrence interval, or MRI) of at least 50 years.

Be sure the wind study includes the wind speed MRI (return period), the measured time basis (e.g., 3-second gust or 10-minute mean), the baseline height (e.g., 33 ft [10 m] above grade), and the surface roughness.

Note: Use consistent units of measurements, including time basis and MRI throughout the entire process of identifying the class for the wind turbine.

See Section 2.1.1.4 for recommendations regarding wind turbine class and basic wind speed.

2.1.1.1.2 Determine the wind speed at the wind turbine hub height (V_{hub}) for extreme wind conditions (survival conditions).

To account for the effects of vertical wind shear, increase the basic wind speed (V) to determine the wind speed at the height of the turbine hub (V_{hub}). Use Table 2.1.1.1.1-2 (mph) or Table 2.1.1.1.1-3 (m/s), or Equation 1.

Note that V_{hub} must not exceed V_{ref}, and V_{hub} and V_{ref} must have the same measured time basis (e.g., both must be 3-second gust, or both must be 10-minute mean).

Equation 1: V_{hub} = (V)x (Hub Height/33 ft [10 m])$^{0.11}$

Table 2.1.1.1.1-2. Wind Speed (mph) at Hub Heights (V_{hub}) for Basic Wind Speeds (V)

Wind Speed (mph) at Hub Height (V_{hub})												
Hub Height (ft)	Basic Wind Speed (mph)											
	50	55	60	65	70	75	80	85	90	95	100	105
100	57	62	68	73	79	85	90	96	102	107	113	119
140	59	65	70	76	82	88	94	100	106	111	117	123
180	60	66	72	78	84	90	96	103	109	115	121	127
220	62	68	74	80	86	92	99	105	111	117	123	129
260	63	69	75	82	88	94	100	107	113	119	126	132
300	64	70	77	83	89	96	102	108	115	121	128	134
340	65	71	78	84	91	97	103	110	116	123	129	136
380	65	72	79	85	92	98	105	111	118	124	131	137
420	66	73	79	86	93	99	106	113	119	126	132	139
460	67	74	80	87	94	100	107	114	120	127	134	140
500	67	74	81	88	94	101	108	115	121	128	135	142
Hub Height (ft)	Basic Wind Speed (mph)											
	110	115	120	125	130	135	140	145	150	155	160	165
100	124	130	136	141	147	153	158	164	170	175	181	187
140	129	135	141	147	153	158	164	170	176	182	188	194
180	133	139	145	151	157	163	169	175	181	187	193	199
220	136	142	148	154	160	166	173	179	185	191	197	203
260	138	144	151	157	163	170	176	182	188	195	201	207
300	140	147	153	159	166	172	179	185	191	198	204	210
340	142	149	155	162	168	175	181	188	194	200	207	213
380	144	151	157	164	170	177	183	190	196	203	209	216
420	146	152	159	165	172	179	185	192	199	205	212	218
460	147	154	160	167	174	181	187	194	201	207	214	221
500	148	155	162	169	175	182	189	196	202	209	216	223

Note 1. Wind speed variation over height for extreme wind speed models (EWM).
Note 2. Basic wind speed is measured at 33 ft (10 m) above grade.

Table 2.1.1.1.1-3. Wind Speed (m/s) at Hub Heights (V_{hub}) for Basic Wind Speeds (V)

Hub Height (m)	Wind Speed (m/s) at Hub Height (V_{hub}) – Basic Wind Speed (m/s)											
	20	23	25	28	30	33	35	38	40	43	45	48
30	22.6	26.0	28.2	31.6	33.9	37.2	39.5	42.9	45.1	48.5	50.8	54.2
40	23.3	26.8	29.1	32.6	34.9	38.4	40.8	44.3	46.6	50.1	52.4	55.9
50	23.9	27.5	29.8	33.4	35.8	39.4	41.8	45.4	47.7	51.3	53.7	57.3
60	24.4	28.0	30.4	34.1	36.5	40.2	42.6	46.3	48.7	52.4	54.8	58.5
70	24.8	28.5	31.0	34.7	37.2	40.9	43.4	47.1	49.5	53.3	55.7	59.5
80	25.1	28.9	31.4	35.2	37.7	41.5	44.0	47.8	50.3	54.1	56.6	60.3
90	25.5	29.3	31.8	35.7	38.2	42.0	44.6	48.4	50.9	54.8	57.3	61.1
100	25.8	29.6	32.2	36.1	38.6	42.5	45.1	49.0	51.5	55.4	58.0	61.8
110	26.0	29.9	32.5	36.5	39.1	43.0	45.6	49.5	52.1	56.0	58.6	62.5
130	26.5	30.5	33.1	37.1	39.8	43.8	46.4	50.4	53.0	57.0	59.7	63.6
150	26.9	31.0	33.7	37.7	40.4	44.5	47.1	51.2	53.9	57.9	60.6	64.7
Hub Height (m)	Basic Wind Speed (m/s)											
	50	53	55	58	60	63	65	68	70	73	75	78
30	56.4	59.8	62.1	65.5	67.7	71.1	73.3	76.7	79.0	82.4	84.6	88.0
40	58.2	61.7	64.1	67.6	69.9	73.4	75.7	79.2	81.5	85.0	87.4	90.8
50	59.7	63.3	65.7	69.2	71.6	75.2	77.6	81.2	83.6	87.1	89.5	93.1
60	60.9	64.5	67.0	70.6	73.1	76.7	79.2	82.8	85.3	88.9	91.3	95.0
70	61.9	65.7	68.1	71.8	74.3	78.0	80.5	84.2	86.7	90.4	92.9	96.6
80	62.9	66.6	69.1	72.9	75.4	79.2	81.7	85.5	88.0	91.8	94.3	98.0
90	63.7	67.5	70.0	73.9	76.4	80.2	82.8	86.6	89.1	93.0	95.5	99.3
100	64.4	68.3	70.9	74.7	77.3	81.2	83.7	87.6	90.2	94.0	96.6	100.5
110	65.1	69.0	71.6	75.5	78.1	82.0	84.6	88.5	91.1	95.0	97.6	101.5
130	66.3	70.3	72.9	76.9	79.6	83.5	86.2	90.2	92.8	96.8	99.4	103.4
150	67.4	71.4	74.1	78.1	80.8	84.9	87.6	91.6	94.3	98.3	101.0	105.1

Note 1. Wind speed variation over height for extreme wind speed models (EWM).
Note 2. Basic Wind Speed is measured at 10 m (33 ft) above grade.

2.1.1.2 Design Load Cases for Wind and Wind with Wave Action

Design wind load cases from IEC 61400-1 for land-based wind turbines, or IEC 61400-3 for offshore wind turbines, are acceptable, with the exclusions, additions, and revisions indicated in the following recommendations (note that these recommendations apply to all wind-exposed and structural components of the wind turbine, including the rotor blades, the nacelle housing, the nacelle-to-tower connections, the tower and connections, and the tower foundation).

For offshore substation support structures, do not apply the IEC 61400-3 load cases related to loss of electrical grid connections and yaw misalignment. Alternatively, substation support structures may be designed in accordance with a reputable industry standard for fixed offshore platforms provided that reliability and structural safety factors are documented to be no less than those based on IEC 61400-3 as modified in this section.

2.1.1.2.1 For extreme wind model (EWM) and reduced wind speed model (RWM) design load cases with ultimate strength analysis; and a normal partial safety factor (load factor [L_w]) for wind load (which represent Design Load Cases 6.1 and 6.3 from IEC 61400-1; and design load cases 6.1a, 6.1b, 6.1c, 6.3a and 6.3b from IEC 61400-3):

A. For cases where the 50-year or reduced 50-year wind speed is needed (design load case 6.1 from IEC 61400-1; and 6.1b and 6.1c from IEC 61400-3) use recommended basic wind speeds (V) as recommended in Section 2.1.1.1.1.

B. Use a partial safety factor (load factor [L_w]) for wind load of not less than 1.5, and do not reduce this factor for wind directionality or any other reason.

C. Use a wind load Importance Factor (I_w) of 1.15 for the following locations:

- Shoreline areas (as defined Data Sheet 1-28, *Wind Design*, Exposure Category D)
- Coastal areas (as defined by Eurocode EN 1991, Terrain Category 0)
- Lakefront areas, or areas without obstacles and with negligible vegetation (as defined by Eurocode EN 1991, Terrain Category I)
- Tropical cyclone-prone regions (as defined in Data Sheet 1-28).
- Offshore wind turbines

D. For all other locations, use a wind load Importance Factor (I_w) of 1.0.

2.1.1.2.2 For EWM and RWM Design Load Cases, ultimate strength analysis, and an abnormal partial safety factor (load factor [L_w]) for wind load of 1.10, which are intended to represent the situations where there is a loss of the wind turbine connection to the electrical power grid (which represent Design Load Cases 6.2, 7.1 and 8.2 from IEC 61400-1; and 6.2a, 6.2b, 7.1a, 7.1b, 7.1c, 8.2a, 8.2b, and 8.2c from IEC 61400-3):

A. Use basic wind speeds (V) as recommended in Section 2.1.1.1.1.

B. Use a wind load Importance Factor (I_w) as recommended in Section 2.1.1.2.1.c , or Section 2.1.1.2.1.d.

C. If there is not an independent emergency power supply for yaw control systems with at least 12 hours of capacity for land-based wind turbine locations in tropical cyclone-prone regions, or 6 hours of capacity for all other land-based wind turbine locations, then assume yaw misalignment up to +/- 180 degrees (180-degree wind direction change, or 180-degree yaw error) for wind turbines with active yaw systems. This will apply to Design Load Case 6.2 from IEC 61400-1.

D. For all offshore wind turbines with active yaw systems, assume yaw misalignment up to +/- 180 degrees (180-degree wind direction change, or 180-degree yaw error). This will apply to Design Load Cases 6.2a and 6.2b from IEC 61400-3.

2.1.1.3 Design Load Cases for Wind with Ice Accretion

This section applies to wind turbines in locations where ice accretion (due to atmospheric icing, freezing rain, sea spray, snow, or other means) is known to occur.

2.1.1.3.1 Ice Accretion on Nacelle and Support Tower

For design wind loads acting on ice-encrusted structures and components, refer to Section 2.1.1.2 except use a wind speed based on a 10-year MRI. If the 10-year wind speed is not known, then assume that the 10-year wind speed is equal to roughly 85% of the 50-year wind speed. The use of the 10-year wind speed acting concurrently with ice is based on the assumption that no substantial reductions are made to load factors (partial safety factors) in the appropriate design load cases and combinations.

Base the thickness of encrusted ice on the nacelle and support tower on the 50-year MRI. For locations where ice accretion is known to occur, the ice thickness should be at least 0.5 in. (13 mm), but may be much greater.

2.1.1.3.2 Ice Accretion on Rotor Blades

Account for ice formation on all rotor blades (balanced), and ice formation on all rotor blades except one (unbalanced), for both of the following conditions:

A. For parked (non-rotating) rotor blades, and with $V_{hub} = V_{ref}$ and extreme wind direction change, assume ice formation with a thickness of at least 1.2 in. (30 mm) on all blade surfaces.

Condition A (above) represents design load case 6.5 from GL IV-1 and GL IV-2.

B. With the rotor rotating, and with wind speed at the hub between the cut-in and cut-out wind speeds (V_{in} V_{hub} V_{out}), assume ice mass distribution to be at the leading edge of the blade, and to vary linearly from zero at the rotor axis to full ice at one-half the radius and remain constant to the outer radius.

Condition B (above) represents design load case 1.10 from GL IV-1 and GL IV-2.

2.1.1.4 Wind Turbine Class

For land-based wind turbines, use the appropriate Wind Turbine Class (Class I, II, III, IV, or S) based on the Reference Wind Speed (V_{ref}) by ensuring that V_{ref} meets or exceeds V_{hub}, where V_{hub} is based on the basic wind speed (V).

For the offshore wind turbine nacelle and rotor (including rotor blades) only, use the appropriate Wind Turbine Class based on the Reference Wind Speed (V_{ref}) by ensuring that V_{ref} meets or exceeds V_{hub}, where V_{hub} is based on the basic wind speed (V).

For all offshore wind turbine support structures and foundations, use Wind Turbine Class S, designed for the appropriate case-specific and site-specific conditions and load cases.

Refer to Table 2.1.1.4, Reference Wind Speeds (V_{ref}) for Wind Turbine Classes.

Typically, reference wind speeds are based on 10-minute mean (average) wind speeds; however, many locations around the world, including the United States, use 3-second gust basic wind speeds rather than 10-minute mean basic wind speeds.

Table 2.1.1.4. Reference Wind Speeds (V_{ref}) for Wind Turbine Classes

Wind Turbine Class		*I*	*II*	*III*	*IV*	*S*
V_{ref}	10-minute mean	112 mph (50 m/s)	95 mph (42.5 m/s)	84 mph (37.5 m/s)	67 mph (30 m/s)	Case-specific
	Equivalent 3-sec gust	161 mph (72 m/s)	136 mph (61 m/s)	120 mph) (54 m/s)	96 mph (43 m/s)	Case-specific

2.1.1.4.1 Using or Specifying the Proper Standard Wind Turbine Class

2.1.1.4.1.1 Wind Turbine Class when Recommended L_w and I_w Values are Used

If the L_w and I_w values recommended in Section 2.1.1.2 of this data sheet are used in the appropriate design wind load cases; then use Equation 1, Table 2.1.1.1.1-2, or Table 2.1.1.1.1-3 when determining V_{hub} in order to compare it to, or specify, the proper standard wind turbine class based on V_{ref}.

2.1.1.4.1.2 Wind Turbine Class when the Recommended L_w and I_w Values are not Used

If the L_w and I_w values recommended in Section 2.1.1.2 of this data sheet are not used in the appropriate design wind load cases, but the typical values (per IEC 61400-1 or GL IV-1) of normal L_w = 1.35 and I_w = 1.0 are used, then use Equation 2 to determine the adjusted basic wind speed (VA), and use VA in place of V in Equation 1 when determining V_{hub} for the purpose of determining the proper standard wind turbine class based on V_{ref} as shown in Table 2.1.1.4.

Since L_w and I_w are applied to wind pressure or wind load, not wind speed, when adjusting wind speeds to account for L_w and I_w, the square roots of L_w and I_w must be used since wind pressure is a function of the square (2^{nd} power) of the wind speed.

Equation 2: Adjusted Basic Wind Speed (VA) = $[V] [(I_w)(L_{w2}/L_{w1})]^{0.5}$

where:

I_w = 1.15 or 1.0 (as recommended in Section 2.1.1.2.1)

L_{w1} = 1.35 (normal L_w used by typical industry standards and guides, e.g., IEC 61400-1, or GL IV-1)) L_{w2} = 1.5 (the normal L_w as recommended in Section 2.1.1.2.1)

Refer to Appendix A for examples of determining the proper standard wind turbine class.

2.1.1.4.2 Wind Turbulence Intensity Category

There are up to three wind turbulence intensity categories (A, B, and C) according to the most commonly used standards and guidelines, including IEC 61400-1 and GL IV-1.

For normal and extreme turbulence models (NTM and ETM), use Category A turbulence intensity unless a lesser category is justified.

2.1.1.5 Topographic Factors and Complex Terrain

For land-based wind turbines located on hills, ridges, or escarpments, additional topographic speed-up factors (K_{zt}) applied to extreme wind speeds or extreme wind loads may be appropriate. See Data Sheet 1-28, *Wind Design*, and consult an applicable local code or standard for additional guidance.

If the terrain is defined by IEC 61400-1 or GL IV-1 as “Complex Terrain”, then account for increased turbulence intensity as noted in these standards and guidelines, as well as extreme wind shear (i.e., wind speed-up factors for extreme wind speeds) as noted in the previous paragraph.

2.1.2 Hail

Refer to Data Sheet 1-34, *Hail Damage*, NatHaz toolkit and maps on FMGlobal.com for locations in the United States subject to hailstorm, and guidance regarding hailstone size, velocity, and impact energy.

For land-based locations outside the continental USA, and for all offshore locations consult local authorities, codes, or standards to determine hail-prone areas and the appropriate size of hailstones.

2.1.2.1 Provide adequate hailstorm protection to exposed wind turbine sensors and instrumentation, such as anemometers (for wind speed) and wind vanes (for wind direction).

2.1.2.2 Provide rotor blades that have been verified to withstand hailstorm exposure and hail stone impact without damage to the blades or adverse effects on blade performance.

2.1.2.3 Provide other exposed components, such as the rotor hub, nacelle enclosure, nacelle hatch and vents, etc., that have been verified to adequately withstand hailstorm exposure.

2.1.3 Ice and Snow

2.1.3.1 Atmospheric Ice Accretion and Snow

2.1.3.1.1 Ice Shedding and Ice Throws

In locations where ice accretion is not known to occur, a hazard may still exist due to rotor blade throws refer to Section 2.3.2 for additional guidance.

A. Ice Shedding (Rotor Stationary):

Horizontal Ice Shedding Radius (ft) = (V_{hub}) x (D/2 + H)/130 with V_{hub} in mph
Horizontal Ice Shedding Radius (m) = (V_{hub}) x (D/2 + H)/58 with V_{hub} in m/s

B. Ice Throws (Rotor Spinning):

Horizontal Ice Throw Radius = 1.5 x (D + H)

Where:
D = rotor blade diameter (ft or m)
H = hub height (ft or m)
V_{hub} = 3-second gust extreme wind speed at the hub height (mph or m/s) based on V

Example:

Rotor Diameter = 295 ft (90 m)
Hub Height = 262 ft (80 m)
V_{hub} = 112 mph (50 m/s), 3-second gust

Horizontal Ice Shedding Radius = (112) x (295/2 + 262)/130 = 353 ft (108 m)
Horizontal Ice Throw Radius = 1.5 x (262 + 295) = 836 ft (255 m)

Therefore, structures within 353 ft (108 m) of the wind turbine are exposed to damage from rotor blade ice shedding, and structures within 836 ft (255 m) of the wind turbine are exposed to damage from rotor blade ice throws.

2.1.3.1.1.1 For wind turbines with adequate ice shedding systems and active ice detection/monitoring, consider ice shedding exposure but not ice throw exposure for structures within the horizontal ice shedding radius.

2.1.3.1.1.2 For wind turbines without adequate ice shedding systems and active ice detection/monitoring, consider ice shedding and ice throw exposure for structures within the horizontal ice shedding and ice throw radii.

2.1.3.1.1.3 Locate new wind turbines or structures including substations, ground-mounted transformers, overhead conductors, etc., so the separation distance between them is not less than the horizontal ice shedding or ice throw radii (i.e., adequately setback from the exposing wind turbine). If adequate separation distance cannot be provided, then provide adequate protection from ice projectiles for the structure(s).

For buildings, protection from ice shedding and ice throws could include the use of a reinforced roof, such as a concrete roof slab or concrete on steel deck; or heavy steel grating or similar impact protection for lightweight roof construction, such as metal roofs, insulated steel deck, boards-on-joists, or plywood sheathing.

Ensure the weight and impact velocity of shed or thrown ice projectiles is based on a site-specific wind turbine risk assessment. Generally, the weight of the shed ice will exceed that of the thrown ice.

2.1.3.2 Pack Ice

For offshore wind farm locations where sea or lake ice (pack ice) is expected to occur based on a site-specific study, ensure the design is based on the provisions for ice loading from IEC 61400-3, where the design ice thickness represents the 50-year return period.

2.1.3.3 Snow Loads

Design nacelle housing to adequately support snow loads based on the guidance provided in Data Sheet 1-54, *Roof Loads and Drainage*.

2.1.3.4 Ice and Snow Interference with Sensors and Instrumentation

Provide adequate heating or other appropriate means to prevent ice accretion or snow accumulation on wind turbine sensors and instrumentation, including wind speed indicators (anemometers) and wind direction indicators (vanes), that may affect any control systems or safety (protection) systems.

2.1.4 Earthquake

See Section 2.1.7 for recommendations related to tsunami.

2.1.4.1 Location-Specific Recommendations

Section 2.1.4.2 also applies.

2.1.4.1.1 United States Locations

2.1.4.1.1.1 Land-based Wind Turbines

For locations in the United States and its territories (Puerto Rico, US Virgin Islands, and Guam) use design earthquake forces as provided in the latest edition of ASCE/SEI 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, or as provided in a model code based on ASCE 7, such as the ICC International Building Code (IBC).

2.1.4.1.1.2 Offshore Wind Turbines

For offshore locations in US territorial waters, follow the same recommendations for offshore locations outside the US as indicated in Section 2.1.4.1.2.

2.1.4.1.2 Locations Outside the United States

For land-based wind turbine locations outside the United States, and for all offshore wind farm locations, use nationally recognized codes and standards, as well as earthquake load parameters, appropriate for the location and based on a return period of at least 475 years for design earthquake loads.

If these codes, standards, or parameters are not available for land-based locations, refer to Section 2.1.4.1.2.1

If these codes, standards, or parameters are not available for offshore locations, provide a site-specific seismic study, based on an appropriate MRI, to serve as the basis for seismic design.

2.1.4.1.2.1 Mapped FM Global Earthquake Zones

For land-based wind turbine locations outside the United States where no nationally recognized codes or standards (nor earthquake load parameters) appropriate for the location are available, use the appropriate design spectral response acceleration values (S_{DS} or S_{D1}) for the appropriate FM Global earthquake zone as the basis for determining earthquake loads. Refer to Data Sheet 1-2, *Earthquakes*, for more information.

2.1.4.2 Recommendations for All Locations

2.1.4.2.1 Ensure the structural design is based on, and has accounted for, the following:

A. Local geotechnical conditions (e.g., soils, groundwater, liquefaction) and seabed conditions.

B. Structural damping (% critical) characteristics of the support tower. Use 1% of critical damping for steel support towers unless a larger structural damping value is justified by the structural engineer of record based on a rational analysis. Where 1% of critical damping is appropriate, increase the 5% damped design spectral response acceleration by 40% to account for the lower damping ratio; this need apply only to load combinations that do not include operational loads.

C. Use an ASCE 7 response modification factor [R] not exceeding 1.5 unless a larger value is justified by the structural engineer of record based on rational analysis.

2.1.4.2.2 Design Load Cases

Examine at least two general design load cases:

A. Earthquake forces acting on a parked or idle wind turbine (i.e., no operational loads acting) without any substantial concurrent wind speed ($V_{hub} < V_{in}$).

B. Earthquake forces acting on an operating wind turbine, with $V_{hub} = V_r$ or V_{out} (whichever places more demand on the various structural members and components), and an abnormal partial safety factor (load factor) not less than 1.1.

Earthquake forces are combined with the dynamic loads associated with an emergency stop of the rotor at the rated wind speed (V_r).

2.1.4.2.3 Use a partial safety factor (load factor) for earthquake loads, based on the design spectral response acceleration, of not less than 1.0 for ultimate limit states (strength design or LRFD) load cases.

2.1.5 Wildland Fire

2.1.5.1 Provide adequate space separation and protection in accordance with Data Sheet 9-19, *Wildland Fire*, and from combustible yard storage or inadequately protected adjacent buildings in accordance with Data Sheet 1-20, *Protection Against Exterior Fire Exposure*, with the following deviations:

A. Building design and construction, building sprinkler protection, and water supply apply only to buildings associated with wind farms, not to the wind turbines or support towers themselves.

B. For wind turbines exposed to forest/woodland fire, provide a minimum clearance zone of 500 ft (152 m).

C. For wind turbines exposed to brush/grassland fires, provide a base clearance zone of 195 ft (60 m) and add additional clearance as shown in Table 2.1.5.1-1.

Table 2.1.5.1-1. Adjustments to Vegetation Clearance Zones for Protection of Wind Turbines from Brush/Grassland Fires

Hub Height – Rotor Radius	*Add the following horizontal distance to the grassland clearance zone*
≥ 100 ft (30 m)	0
80 ft (24 m)	25 ft (8 m)
60 ft (18 m)	35 ft (11 m)
≤ 40 ft (12 m)	45 ft (14 m)

Note 1. Horizontal clearances are based on the distance from the wind turbine tower to the vegetation.
Note 2. Linear interpolation is acceptable.

Where wind turbines are situated on agricultural lands and the threat of wildland fire is based not on burning brush/grassland or forest/woodland vegetation but on burning crop fields refer to Table 2.1.5.1-2 for recommendations regarding vegetated clearance zones.

Table 2.1.5.1-2. Vegetation Clearance Zones for Protection of Wind Turbines from Crop Field Fires

Hub Height – Rotor Radius	*Horizontal Clearance to Crop Vegetation*
≥ 100 ft (30 m)	30 ft (9 m)
80 ft (24 m)	60 ft (18 m)
60 ft (18 m)	80 ft (24 m)
≤ 40 ft (12 m)	100 ft (30 m)

Note 1. Crop vegetation refers to crops such as wheat, corn, barley, soybeans, etc., that are: a) Actively cultivated (i.e., not abandoned, neglected, or substantially overgrown), and b) Located in regions/climates not generally susceptible to wildland fire; or irrigated regularly in regions/climates that are susceptible to wildland fire.
Note 2. Horizontal clearances are based on the assumption that crop fields surrounding wind turbines are healthy and are not more than roughly 25% cured; that is, not more than 25% of the vegetation is dried-out, dead, and brown, based on visual examination.
Note 3. Horizontal clearances are based on the distance from the wind turbine tower to the vegetation.
Note 4. Linear interpolation is acceptable.

2.1.6 Flood and Surface Water for Land-Based Wind Turbines

2.1.6.1 Locate wind turbines outside known flood zones. If this is not possible, ensure adequate measures have been taken to protect the tower foundation, tower, equipment, and associated utilities. Refer to Data Sheet 1-40, *Flood*, for additional guidance, and pay particular attention to the effects of surface water on geotechnical/foundation properties, including reduced soil bearing capacity, buoyant effects, foundation undermining and settlement, and loss of credited overburden.

During the design phase of the wind farm, develop a surface water drainage strategy that will be adhered to on site throughout all stages of construction and operation. Design the water drainage strategy to ensure surface water drainage does not negatively impact wind farm construction, access roads, staged materials, and any other critical construction areas. Lack of a surface water drainage strategy can lead to significant construction delays.

Refer to Section 2.2 of this data sheet for additional guidance regarding surface water and flood acting on tower foundations.

2.1.6.2 For conical steel or concrete support towers (monopole towers), assume the space within the tower base will subjected to flood inundation unless proper watertight design and construction can be verified and documented. Similarly, the access door at the tower base, although likely to be weather resistant, should not be assumed to be watertight and capable of adequately resisting hydrostatic flood pressure.

The concrete base on which the tower is supported often has penetrations for electrical conduit, drains, or other utilities that may allow flood water to enter the tower base.

2.1.7 Hydrodynamic Loads and other Marine Loads for Off-Shore Wind Turbines

2.1.7.1 Hydrodynamic Loads

Ensure offshore wind turbines (including foundations, transition sections, support towers, and exposed platforms and appurtenances) and support structures for offshore substations (including platform structure, exposed appurtenances, substructure, and foundations) are properly designed in accordance with Section 2.1.1.2 of this data sheet.

2.1.7.2 Tsunami Loads

Ensure offshore wind turbines (including foundations, transition sections, support towers, and exposed platforms and appurtenances) and support structures for offshore substations (including platform structure, exposed appurtenances, substructure, and foundations) are properly designed for tsunami related loads based on a site-specific study.

2.1.7.3 Marine Vessel Impact

Ensure the offshore wind turbine and substation support structures are designed to adequately resist the impact of a dedicated support, supply, or maintenance marine vessel (whichever has the greatest operating mass). Base the loads on the maximum anticipated vessel mass and impact speed but use not less than 1.1 mph (0.5 m/sec), and a mass coefficient of at least 1.1 for bow or stern collisions and 1.6 for sideways collisions.

2.1.8 Miscellaneous Natural Hazard, Environmental, and Siting Issues

2.1.8.1 Temperature and Humidity

Install wind turbines with temperature range and relative humidity ratings specified by the manufacturer that meet or exceed the normal temperature range and relative humidity for the installation location and humidity/water mediation/mitigation system. Consult the OEM for special precautions related to extreme environments and material behavior. Include the equipment installed within the base of the tower, the nacelle including the hub, and the design of the blades.

Ensure replacement blades are designed to withstand the normal temperature and relative humidity for the installation location and are provided with humidity/water mediation/mitigation system.

2.1.8.2 Wildlife Impact to Rotor Blades

Ensure blades are capable of withstanding bird strikes without damage to the blades. Use tactics to minimize bird strikes.

2.2 Substructure, Foundations, and Geotechnical

2.2.1 All Foundations

2.2.1.1 Provide foundations based on site-specific and turbine-specific criteria that have adequate strength, stiffness, stability, durability, and resistance to settlement.

2.2.1.2 Ensure adequate fatigue resistance has been included in the design in accordance with a reputable standard specific to wind turbines,

2.2.1.3 Ensure foundations conform to the wind turbine manufacturer’s performance specifications, including those for rotational and translational (horizontal) stiffness.

2.2.1.4 Geotechnical Study and Report

Base the foundation design on the findings and recommendations of a thorough geotechnical study.

2.2.1.5 Some land-based wind farms are located on a plateau, or on hills or escarpments, to take advantage of topographical wind speed-up effects. These locations may be subject to soil or bearing strata instability - including landslide or foundation undermining that could cause damage. Provide adequate foundation protection (see Sections 2.2.2 and 2.2.3)

2.2.1.6 Soil Liquefaction

Ensure the potential for liquefaction due to seismic ground shaking and/or wind turbine operational vibrations has been examined, is accounted for in the foundation design, and is included in the geotechnical study.

2.2.1.7 Erosion and Scour Protection

Provide adequate scour and erosion protection for wind turbines based on a case-specific study that includes the foundation geometry, topography, geotechnical conditions, and marine conditions (for offshore locations).

Refer to Section 2.7.1.3 for protection from scour and seabed movement for submarine cable for offshore locations.

2.2.2 Shallow Foundations

2.2.2.1 Frost Protection

For land-based wind turbines, place the bottom of spread footings sufficiently below grade to provide adequate protection from frost action. Check local building codes for the recommended depth of frost protection if not provided in the geotechnical report.

2.2.2.2 Soil Overburden and Undermining

In flood-prone regions or locations on sloped grades where surface water can erode the overburden, use armor stone, rip-rap, or other similar robust material to protect any credited overburden and also to prevent undermining of the foundation.

2.2.2.3 Soil Saturation and Ground Water Effects

Ensure the soil strength and resistance used in foundation design accounts for any deleterious effects due to soil saturation.

2.2.3 Deep Foundations

2.2.3.1 Due to the mechanical loads and vibrations associated with wind turbines, ensure specific recommendations regarding friction pile performance and wind turbine vibrations have been included in the geotechnical study, and have been accounted for in the foundation design.

2.2.3.2 Ensure the un-braced length of piles used for design capacity accounts for the potential effects of soil liquefaction, as well as the deleterious effects of saturated soils and buoyancy.

2.2.3.3 For offshore wind turbine steel monopile foundations, and offshore substation steel monopile foundations, provide an evaluation of the grouted connection (attaching the transition piece to the monopile) by a qualified independent engineering consultant or certifying agency to ensure the structural integrity of the grouted connection is adequate.

2.2.4 Shallow Foundations with Tension Anchors

2.2.4.1 Use a rock/soil anchor in-situ test load (proof load) equal to the least of the following:

a) 2 x Maximum Anchor Service Load
b) 0.8 x Anchor Yield Strength
c) 0.8 x Anchor Capacity

2.2.4.2 Provide adequate corrosion protection for rock/soil anchors, such as galvanizing, epoxy coating, or encasement in cement grout for steel anchor rods. Note that the performance of a galvanized coating on steel is usually satisfactory in soils unless they are poorly aerated, acidic, or highly contaminated by sulfates, chlorides, or other solutes.

2.2.5 Chloride Degradation (Corrosion)

2.2.5.1 For land-based wind turbines in coastal locations where concrete foundations may be exposed to salt-laden air, seawater mist, or brackish or salty groundwater or surface water; or for locations where road salt from surface run-off may reach turbine tower foundations, provide adequate measures to protect the concrete from chloride-based degradation and corrosion of embedded steel reinforcing.

There are several methods available to provide chloride protection, including corrosion-inhibiting concrete admixtures and durable coatings for reinforcing steel.

2.2.5.2 See Section 2.7.3 for offshore wind turbine corrosion protection recommendations.

2.2.6 Marine Growth

For offshore substructures and foundations, include an allowance for marine growth in the design loads based on a site-specific study.

2.3 Support Towers and Rotor Blades

2.3.1 Support Towers

2.3.1.1 When determining any time-dependent effects of loading and resistance (e.g., fatigue loading or corrosion effects) for all structural elements and connections associated with the support tower and foundation, use a design life not less than that which is specified by the wind turbine manufacturer, and in no case less than 20 years. This includes, but is not limited to, tower shell walls, flanges, stiffeners, and gusset plates; anchor rods (anchor bolts), including rock anchors; and bolted or welded structural connections.

2.3.1.2 Provide a corrosion-protection system for all components of the support tower, including the tower shell and connection components (e.g., flange bolts and anchor bolts). Refer to Section 2.7.3, Corrosion-Related Protection, for additional guidance.

2.3.1.3 Provide a tower structure that has the strength, stiffness, and durability to adequately support the static, dynamic, and fatigue loads associated with wind turbine operational, emergency stop, parked, and temporary (e.g., assembly and erection) load cases and conditions.

2.3.1.4 Ensure the natural frequencies of the tower have been properly considered to avoid resonant behavior associated with rotor operation, including rotor rotational frequencies and blade-passing frequencies, and that calculated natural frequencies and damping are representative of the as-built condition.

2.3.1.5 Ensure adequate fatigue resistance has been included in the design in accordance with a nationally recognized standard specific to wind turbines, such as IEC 61400-1 and IEC 61400-3.

2.3.1.6 Ensure the tower conforms to the wind turbine manufacturer's performance specifications, including those for rotational and translational (horizontal) stiffness.

2.3.1.7 Structural Connections

For tubular steel tower sections with bolted flanges and other similar connections (such as nacelle yaw ring to tower flange connections), ensure bolts are properly designed to provide adequate resistance to all applicable load conditions, including fatigue resistance. Avoid using simple snug-fit (bearing) bolted connections at tower section flanges; instead, use pre-tensioned slip-critical (friction grip) bolted connections, which typically provide better fatigue resistance.

Do not mix hot-dip galvanized components with mechanical galvanized components in a single fastener assembly, and ensure dissimilar metals are not used in contact with each other, to avoid the potential deleterious effects of galvanic corrosion.

2.3.2 Rotor Blades

2.3.2.1 Use rotor blades that provide adequate strength, stiffness, fatigue resistance, and durability to function properly for intended design and operational conditions. Ensure sufficient understanding of all extreme load conditions, including severe environmental and natural hazards exposures and plans for risk mitigation. Exposures will include those listed in Section 2.1 and Section 2.8 of this data sheet, as well as temperature extremes, rain and humidity, solar radiation, atmospheric salinity, chemically active substances, and mechanically active particles, such as those from dust storms or sand storms that can cause leading edge erosion.

2.3.2.2 Ensure that rotor blades are designed in accordance with IEC 61400-1, IEC 61400-3, or a nationally recognized standard based on these IEC standards, with the exceptions, changes, and additions contained in Sections 2.1 and 2.8 of this data sheet regarding design wind load cases, wind loads combined with ice, earthquake loads, and lightning strikes, respectively.

2.3.2.3 Ensure the rotor blades are representative of full-scale blade samples tested in accordance with IEC 61400-23, or a nationally recognized test standard based on or similar to IEC 61400-23.

2.3.2.4 Use rotor blades with enough stiffness to ensure that the rotor blade tip deflection under extreme wind model conditions will provide adequate clearance from the support tower. Ensure that blade tip clearance is based on blade deflection calculations with partial safety factors (load factors) not less than those included in the standard design load cases from a nationally recognized standard, such as IEC 61400-1 or IEC 61400-3.

2.3.2.5 Blade Throws

Base rotor blade throw hazards on a wind turbine risk assessment specific to the site, as well as the type and size of the wind turbine. If such a risk assessment is not available, a reasonably conservative estimate of the horizontal blade throw radius (based on previous studies of blade throws) is:

Horizontal Blade Throw Radius = 2.5 x (D + H)

Where:

D = rotor blade diameter (ft or m)
H = hub height (ft or m)

2.4 Occupancy

2.4.1 Control and Lubrication Oil Piping

2.4.1.1 Design and install oil piping to minimize the chances of a break in a pipe or fitting.

2.4.1.2 Properly support and brace oil piping and protect instruments, controls, and associated fittings against mechanical damage.

2.4.1.3 Weld piping for lubricating and control-oil systems where possible.

2.4.1.4 Install supply piping inside drain or guard piping or inside steel welded enclosures designed to return oil leakage to a protected collection point.

2.4.1.5 Design and maintain rigid piping to account for potential vibration and deflection in the nacelle. Alternatively, provide flexible hose connectors in piping systems to prevent dangerous stresses due to vibration, settling, or thermal change. Provide the following material and installation features to ensure adequate hose strength/durability and protection against physical damage:

A. Construct flexible hose of high-strength, noncombustible materials that are resistant to decomposition or melting when exposed to fire, and are compatible with the liquid in use.

1. Use all-metal construction consisting of materials such as steel, Monel, stainless steel, brass, bronze, or an equivalent material.
2. Reinforced rubber hose with a synthetic liner and a metal-braid covering is acceptable when needed to meet operational requirements.
3. Do not use soft rubber, plastic, or other unreinforced or unprotected combustible tubing.

B. Allow the hose to be bent only in one plane, without subjecting it to tensile, torsional, or excessive bending stresses.

C. Protect the hose against mechanical damage.

2.4.2 Lubrication and Control-Oil Systems

2.4.2.1 Use FM Approved hydraulic (industrial) fluid in the turbine control system, rather than mineral oil. Consult the original equipment manufacturer (OEM) in selecting a suitable FM Approved fluid. Refer to Data Sheet 7-98, *Hydraulic Fluids*, for additional information regarding the use of FM Approved industrial fluids.

2.4.2.2 Limit quantities of oil to the minimum necessary to operate the lubrication and control-oil systems.

2.4.3 Grouped Cables

2.4.3.1 Locate and arrange grouped cable in accordance with Data Sheet 5-31, *Cables and Bus Bars*.

2.4.3.2 Route cables to minimize exposures from oil piping. If applicable, locate cables above adjacent oil piping.

2.4.3.3 Locate cables away from rotating or vibrating equipment.

2.4.3.4 Protect cable from fire exposure by enclosing it within noncombustible construction or providing an FM Approved fire wrap.

Wind turbine cables will twist as the nacelle rotates due to the yaw system. Therefore, it may not be practical to protect cables in this manner. Nevertheless, investigate the potential to reduce or eliminate the grouped cable fire hazard by providing the protection features listed above.

2.4.3.5 Seal penetrations between the tower and nacelle through which cables pass from one area to the other with an FM Approved fire-stop.

This will help prevent the spread of a fire initiating in the tower into the nacelle.

2.4.4 Housekeeping

Maintain high standards of housekeeping in all areas.

2.4.4.1 Conduct periodic recorded housekeeping inspections in all areas including the nacelle.

2.4.4.2 Ensure all areas are free of any combustibles including oil or grease spills.

2.4.4.3 Provide a management reporting channel for prompt correction of housekeeping deficiencies.

2.5 Fire-Related Construction Concerns

Refer to Section 2.1.5 for recommendations related to wildfire/bushfire.

2.5.1 Nacelle Construction Material

Use noncombustible or fire-resistant materials.

2.5.1.1 Separate the nacelle from the tower with noncombustible construction.

2.5.1.2 Provide noncombustible separation for openings that serve as access points between the tower and nacelle.

2.5.1.3 Containment

2.5.1.3.1 Where FM Approved industrial fluids are not provided in accordance with Section 2.4.2, provide containment features within the nacelle to achieve the following objectives:

A. Limit oil from spreading throughout the nacelle.

B. Prevent oil from spreading outside any equipment enclosures.

C. Prevent the possibility of oil flow into the tower.

2.5.1.3.2 Provide sufficient capacity to handle the safe containment of the total contents of the lubrication and/or control oil supply and, if applicable, the total fire protection system discharge quantity.

2.5.1.3.3 Design the containment systems in accordance with Data Sheet 7-83, *Drainage Systems for Ignitable Liquids*.

2.5.2 Where transformers are located outside the base of the tower, provide separation from the tower in accordance with Data Sheet 5-4, *Transformers*.

2.5.3 Where transformers are located inside the base of the tower or in the nacelle, provide dry type or FM Approved transformers and/or locate non-FM Approved transformers in enclosures of fire-rated construction, as specified in Data Sheet 5-4, *Transformers*.

2.5.4 Locate and arrange collector substations in accordance with Data Sheet 5-19, *Switchgear and Circuit Breakers*, Data Sheet 5-4, *Transformers*, and other applicable data sheets.

2.5.5 Provide arc-resistive switchgear within the nacelle. Alternatively, provide arc detection devices arranged to disconnect the electrical equipment from the network, in accordance with Section 2.6.1.2.

2.6 Fire Protection Systems

2.6.1 Fire Detection

2.6.1.1 Provide FM Approved detection devices in the nacelle, arranged in accordance with Data Sheet 5-48, *Automatic Fire Detection*.

All FM Approved smoke detectors have been tested for installation in areas with air velocities up to 300 ft/min (90 m/min), while some FM Approved detectors have been tested for permissible air velocities as high as 4000 ft/min (1220 m/min). Airflows within the nacelle should be examined prior to the selection of smoke detection devices, and the detector spacing may need to be reduced to account for ventilation.

In some cases, localized detection within the nacelle may be warranted, such as localized smoke detection in electrical enclosures, the hub of the wind turbine, generator enclosures, within the blades, and similar areas.

If it is determined that smoke detectors are not a viable option for the nacelle, provide heat detectors. Heat detectors will result in slower response times, especially in the presence of a smoldering electrical fire. If heat detectors are used, provide rate-of-rise or combination fixed-temperature and rate-of-rise heat detectors.

2.6.1.2 If arc-resistive switchgear is not used in the nacelle, provide arc detection devices.

2.6.1.3 Provide detection for collector substations in accordance with Data Sheet 5-4, *Transformers*, Data Sheet 5-19, *Switchgear and Circuit Breakers*, Data Sheet 5-32, *Electronic Data Processing Systems*, and other FM Global Property Loss Prevention Data Sheets as applicable.

2.6.1.4 Provide detection for indoor transformers in accordance with Data Sheet 5-4, *Transformers*.

2.6.1.5 Arrange detectors to automatically trip the wind turbine, de-energize electrical equipment and disconnect the equipment from the grid, shut off oil systems, and transmit an alarm to a constantly attended location.

2.6.1.6 Provide electronic supervision for fire-detection system trouble conditions and annunciate trouble alarms in a constantly attended location.

Generally, limited quantities of combustibles are located in the tower of a wind turbine, and detection devices in this area are not necessary. However, the presence of grouped cable that is not arranged as recommended in this standard, the use of oil-filled, non FM Approved transformers at the base of the tower, the presence of electrical cabinets, or other arrangements resulting in an increased hazard in the tower, may create the need for additional detection devices in this area.

2.6.2 Fire Protection

2.6.2.1 Provide portable fire extinguishers in the nacelle and at the base of the tower, alternatively, provide portable fire extinguishers on a temporary basis when the tower and/or nacelle is accessed by personnel. If a portable fire extinguisher option is used ensure this is included in the organization's documented maintenance program (see Section 2.9). Refer to Data Sheet 4-5, *Portable Extinguishers*, for additional guidance.

2.6.2.2 Protect transformers in accordance with Data Sheet 5-4, *Transformers*.

2.6.2.3 Protect collector substations in accordance with Data Sheet 5-19, *Switchgear and Circuit Breakers*.

2.6.3 Ignition Source Control

Without reliable fire protection, and with difficult conditions for manual firefighting, the primary objective with regard to wind turbine fire protection is control of ignition sources and prevention of a fire within the nacelle.

2.6.3.1 Hot Work

2.6.3.1.1 Avoid hot work in the nacelle whenever possible, as this may result in ignition of an oily surface or other combustible materials. Investigate alternatives to hot work for all jobs.

2.6.3.1.2 Establish a hot work permit and supervision program in accordance with Data Sheet 10-3, *Hot Work Management*.

2.6.3.1.3 Require contractors to adhere to the rules of the hot work permit and supervision policy.

2.6.3.2 Braking Mechanisms

2.6.3.2.1 Provide shields to isolate sparks created by mechanical braking mechanisms from combustible materials.

2.6.3.2.2 Where dynamic braking of the wind turbine is achieved through the use of braking resistors, ensure the resistors are not located adjacent to any combustible construction or material.

2.7 Protection

Provide protection systems to maintain the wind turbine in a safe condition in all operating modes and to ensure the design limits are not exceeded. Design the protection systems to prevent manual or automatic intervention that compromises the protection functions. Also, protect the internal settings of the protection system to prevent unauthorized interference.

Arrange the protection to activate as a result of a control-function failure or as a result of the effects of an internal or external failure or a dangerous event.

Prioritize the protection systems to have higher priority than the control systems, but not higher than the emergency stop, to trigger the braking systems and equipment for network disconnection.

Protection systems should function so that no single failure or fault of a protection-related component, such as the braking system, a sensor or a power source, results in the failure of a protection function.

If two or more failures are interdependent or have a common cause, treat this event as a single failure.

As a minimum, provide protection functions to protect against the events identified in section 2.7.4.

2.7.1 Electrical Protection

2.7.1.1 Wind Turbine Generator

Provide electrical protection for the wind turbine generator to meet the intent as shown in Figure 2.7.1.1. See Table 2.7.1.1-1 for a description of the protective device. Provide additional protection for synchronous generators per Table 2.7.1.1-2.

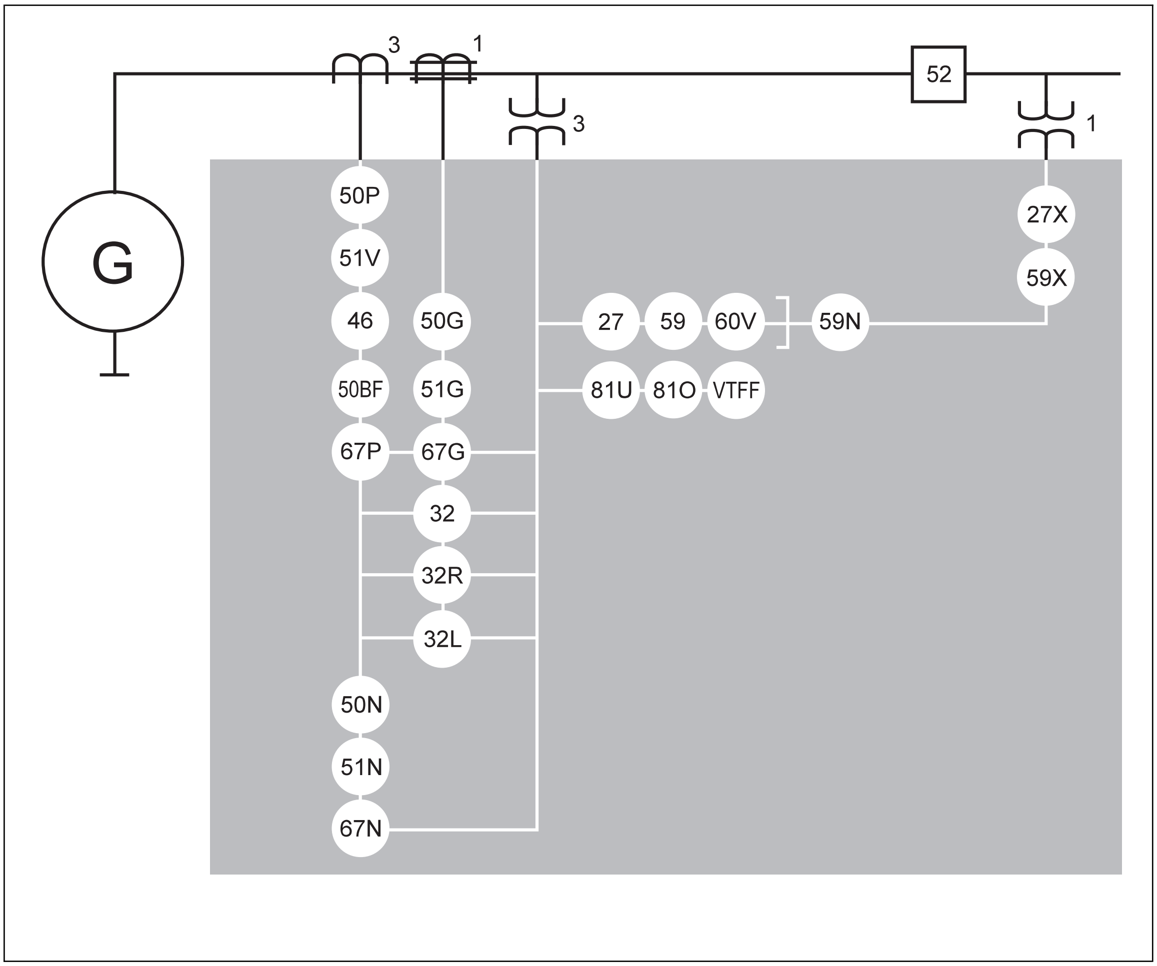


Fig. 2.7.1.1. Recommended protection scheme for wind turbine generators

Table 2.7.1.1-1. The Protective Devices in Figure 2.7.1.1. and their Purposes

IEEE Device No	Protective Relay	Purpose
27X	Auxiliary undervoltage	Protects against voltage dips or sags
27	Phase undervoltage	Protects against voltage dips or sags
32	Directional power	Anti-motoring protection
32R	Reverse power	Anti-motoring protection
32L	Low forward power	Anti-motoring protection
46	Negative sequence	Protection from single phasing faults and system faults causing current unbalance
47	Phase reversal	Protection from single phasing, unbalanced phase voltages and reverse phase sequence
50BF	Breaker failure	Protects against the condition where the circuit breaker does not open to clear a fault
50P	Phase instantaneous overcurrent	Short circuit protection
50N	Neutral instantaneous overcurrent	Ground fault protection
50G	Ground instantaneous overcurrent	Ground fault protection
51P	Phase time overcurrent	Overload protection
51N	Neutral time overcurrent	Ground fault protection
51G	Ground time overcurrent	Ground fault protection
51V	Voltage restrained time overcurrent	Backup for system faults beyond the generator
55	Power factor	Protection against out of step operation (loss of synchronism)
59P	Phase overvoltage	Protection against overvoltages
59X	Auxiliary overvoltage	Protection against overvoltages
59N	Neutral overvoltage	Protection against ground faults and single phasing
67P	Phase directional overcurrent	Directional protection for short circuits
67N	Neutral directional overcurrent	Directional protection for ground faults
67G	Ground directional overcurrent	Directional protection for ground faults
60V	Voltage unbalance	Protects the rotor of directly connected generators from overheating due to unbalanced voltages in the electrical system
81U/O	nder/over frequency	Protection against electrical grid frequency excursions
VTFF	VT fuse failure detection	Protection against failure of instrument transformers

Table 2.7.1.1-2. Additional Protection for Synchronous Generators

IEEE Device No	*Protective Relay*	*Purpose*
40	Loss of field	Protects against loss of excitation
55	Excitation Check	Protects against loss of excitation

2.7.1.2 Collector Substation Transformer

Provide electrical protection for the collector substation transformer in accordance with Data Sheet 5-4, *Transformers*.

For offshore substations, provide the following additional protection:

- An exterior coating for the entire enclosure of the electrical components, including mounting brackets and other peripheral components to resist water/salt corrosion, unless the components themselves are made of corrosion-resistant materials.
- A perforated capsule or bag containing a suitable vapor phase corrosion inhibitor for the interior of the enclosure.

2.7.1.3 Subsea Cable for Offshore Wind Farms

2.7.1.3.1 There are two types of subsea cables in offshore wind farms Inter-array cables and Export cables. Refer to Data Sheet 5-31, *Cables and Bus Bars*, for guidance

2.7.1.3.2 Install beach warning signs or posts where applicable to identify the position of the export cable route.

2.7.1.3.3 Register the subsea power export cable into the applicable sea chart.

2.7.1.3.4 Provide surge arrestor to protect the subsea cable against overvoltage caused by lightning or system disturbances.

2.7.1.3.5 Provide short circuit and ground fault protections for subsea inter-array cables. The protection can be directional (67), distance (21), or overcurrent (50/51).

2.7.1.3.6 Provide differential protection for export subsea cables. The differential protection can be line differential (87L), phase comparison (87PC), or directional comparison (21).

2.7.2 Collision Protection

Provide wind turbines and any related significant structures associated with wind farms (e.g., collector station platforms for offshore locations) with proper collision avoidance warning systems in accordance with local aviation and/or maritime authorities. These typically involve visual systems (such as signage and lighting) for land-based locations, and visual and audible systems for offshore locations.

2.7.3 Corrosion-Related Protection

2.7.3.1 Rotor and Nacelle

Provide corrosion protection for all parts, including internal equipment, that are exposed to the atmosphere. The protection should be suitable for the worst ambient conditions that can reasonably be expected.

Apply a coating system to all metal surfaces that is suitable for the atmospheric-corrosivity category of the environment in which the wind turbine is located. Determine the appropriate atmospheric-corrosivity category using ISO 12944, Paints and Varnishes - Corrosion Protection of Steel Structures by Protective Paint Systems – Part 2: Classification of Environments.

For offshore wind turbines, protect metal parts in accordance with ISO 12944 as follows:

A. Provide suitable corrosion protection of outside components, fittings, sensors, etc. in accordance with ISO corrosivity category CX (extreme - usually offshore).

B. Provide suitable corrosion protection of inside surfaces directly exposed to outside atmosphere in accordance with ISO atmospheric-corrosivity category C4 (high).

C. Provide suitable corrosion protection of inside surfaces not directly exposed to the outside atmosphere in accordance with atmospheric-corrosivity category C3 (medium).

2.7.3.2 Wind Turbine and Substation Support Structures

This section applies to wind turbine support structures, including support towers, tower connections, transition pieces (offshore), and foundation as well as other structures associated with wind farms (e.g., offshore substation support structures).

Provide corrosion protection that is suitable for the most severe service conditions that can be expected.

2.7.3.2.1 Steel Support Structures

For land-based wind turbine support structures, determine the appropriate atmospheric-corrosivity category using ISO 12944-2 and provide an appropriate corrosion protection system.

For offshore wind turbine and offshore substation support structures, protect steel members and components in accordance with ISO 12944-9, based on the exposure zone as follows:

- Atmospheric zone (above the splash zone): Provide corrosion protective coatings in accordance with ISO 12944 corrosivity category CX (extreme - usuallly offshore).
- Splash zone: Provide corrosion protective coatings in accordance with ISO 12944 atmospheric-corrosivity category CX (extreme - usually offshore) and use a corrosion allowance based on a case-specific study of the corrosive climate, but not less than a corrosion rate of 0.12 in. (0.3 mm) per year.

- Submerged zone (below the splash zone): Provide a cathodic corrosion protection system in conformance with a reputable industry standard such as DNVGL-RP-B401, and use a corrosion allowance based on a case-specific study of the corrosive climate, but not less than that calculated using a corrosion rate of 0.04 in. (0.1 mm) per year.

An acceptable case-specific corrosion study will include and consider the site-specific corrosion climate, structural materials, service stress levels, connections, and design life.

Base the total corrosion allowance on the intended design life of the wind turbine, but not less than 20 years.

Using the splash zone as defined in IEC 61400-3, GL IV-2, or DNV-OS-J101 is acceptable.

2.7.3.2.1 Concrete Support Structures

Provide a corrosion protection system based on a site-specific study of the corrosive climate, and appropriate for the construction materials.

2.7.4 Mechanical Protection

Table 2.7.4 lists the protective devices recommended for wind turbines.

Table 2.7.4. Protective Devices for Wind Turbines

Condition	*Alarm*	*Trip*
Rotor overspeed trip systems(Notes 1,2)		x
High vibration of shaft, bearing and gear	x	x
High vibration of nacelle and tower	x	x
High bearing temperature (main shaft and gear)	x	x
Low lube/hydraulic oil pressure(Note 3)	x	x
Low lube/hydraulic oil tank level(Note 3)	x	x
High lube/hydraulic temperature(Note 3)	x	x
Oil pump motor malfunction	x	x
Lightning detection or monitoring for tower and blades(Note 4) (See Section 2.8.1.1)	x	
Blade ice detection	x	x
Abnormal power control parameters(Note 5)	x	x
Excess of wind cutoff speed(Note 6)	x	x
Abnormal cable twist (due to nacelle yawing)	x	x
High temperature of electric power control components(Note 7)	x	x

Note 1. Measure the rotational speed using at least two independent systems.
Note 2. Design the braking system to have access to a least two mutually independent braking systems.
Note 3. Lubrication oil for bearings.
Note 4. Follow International Standard 61400-24:2010.
Note 5. Include loss of load, overvoltage, overcharge/overpower(instantaneous and average)
Note 6. Depend on design.
Note 7. Voltage clamp/regulator, diversion loads etc.

2.7.4.1 Provide an overspeed protection system. Verify the protection system has sufficient power source either emergency or UPS, to place the wind turbine in a safe state during high wind events.

Refer to Section 2.6.1.5 for trips associated with fire detection.

2.7.5 Control Systems

2.7.5.1 Ensure the wind turbine and wind farm controls meet the recommendations in Data Sheet 7-110, *Industrial Control Systems*.

2.8 Lightning Protection

2.8.1 Wind Turbine

2.8.1.1 Install a lightning detection system that can send notifications to operators to detect lightning strikes. Lightning detection minimum reported parameters should include peak current, charge transfer and specific energy.

2.8.1.2 Provide a lightning protection system for wind turbines that has been designed, certified and tested to Lightning Protection Level LPL 1 and in accordance with IEC 61400-24: Verify the following.

A. Provide the tower and nacelle with direct strike protection, including air terminals mounted on nacelle roof. Either a metallic nacelle or a metallic mesh or frame inside the non-metallic nacelle, bonded to the tower and grounded, can effectively establish Faraday Cage type of protection.

B. Provide blades with side and tip receptors, conductive coating or conductive mesh woven or laminated into the blade material. For two-piece blade designs, any pins or other components used to join the blades together should be connected to ground via down conductors.

C. Provide grounding electrodes to effectively disperse lightning currents to ground, per IEC 62305-3 Type B or equivalent local/national codes.

Electrical equipment and systems protection

2.8.1.3 Provide surge arrestors for the generator and transformer.

2.8.1.4 Provide transient voltage surge suppression for the power electronics, control, and communication systems.

2.8.1.5 Provide Faraday Cage-type protection for equipment located in the nacelle. A bonded metallic nacelle is considered equivalent to a Faraday Cage.

2.8.1.6 Provide a Faraday shield for communication and control cables running up the tower into the nacelle.

Gearbox and bearings

2.8.1.7 Provide lightning protection for the gearbox, drive shaft bearings, yaw bearings and generator bearings.

2.8.2 Collector Substation

2.8.2.1 Refer to Data Sheet 5-11, *Lightning and Surge Protection for Electrical Systems*, for recommendations regarding lightning protection and surge protection for electrical equipment and systems at the collector substation.

2.9 Operation and Maintenance

Establish and implement a wind turbine asset integrity program and inspection, testing, and maintenance program. See Data Sheet 9-0, *Asset Integrity*, for guidance on developing these programs. If a condition-based or predictive maintenance strategy is employed, use condition-monitoring systems as recommended in Section 2.10.

2.9.1 Fire

2.9.1.1 Identify operation and maintenance activities where errors could result in the accidental release of oil, such as maintenance work on lubrication and hydraulic oil systems. Include fire prevention warnings and precautions in the procedures for these activities.

2.9.1.2 Ensure equipment and devices that represent potential lubrication/hydraulic oil release sources are regularly maintained, inspected, and tested.

2.9.1.3 Periodically inspect all fire protection equipment, as applicable, in accordance with Data Sheet 2-81, *Fire Protection System Inspection, Testing and Maintenance*.

2.9.1.4 Inspect and test all fire detection devices in accordance with Data Sheet 5-48, *Automatic Fire Detection*.

2.9.2 Electrical

Figures 2.9.2-1 and 2.9.2-2 show the layout and electrical systems for a typical grid-connected wind farm. The terminology in this diagram will be used in the rest of this document.

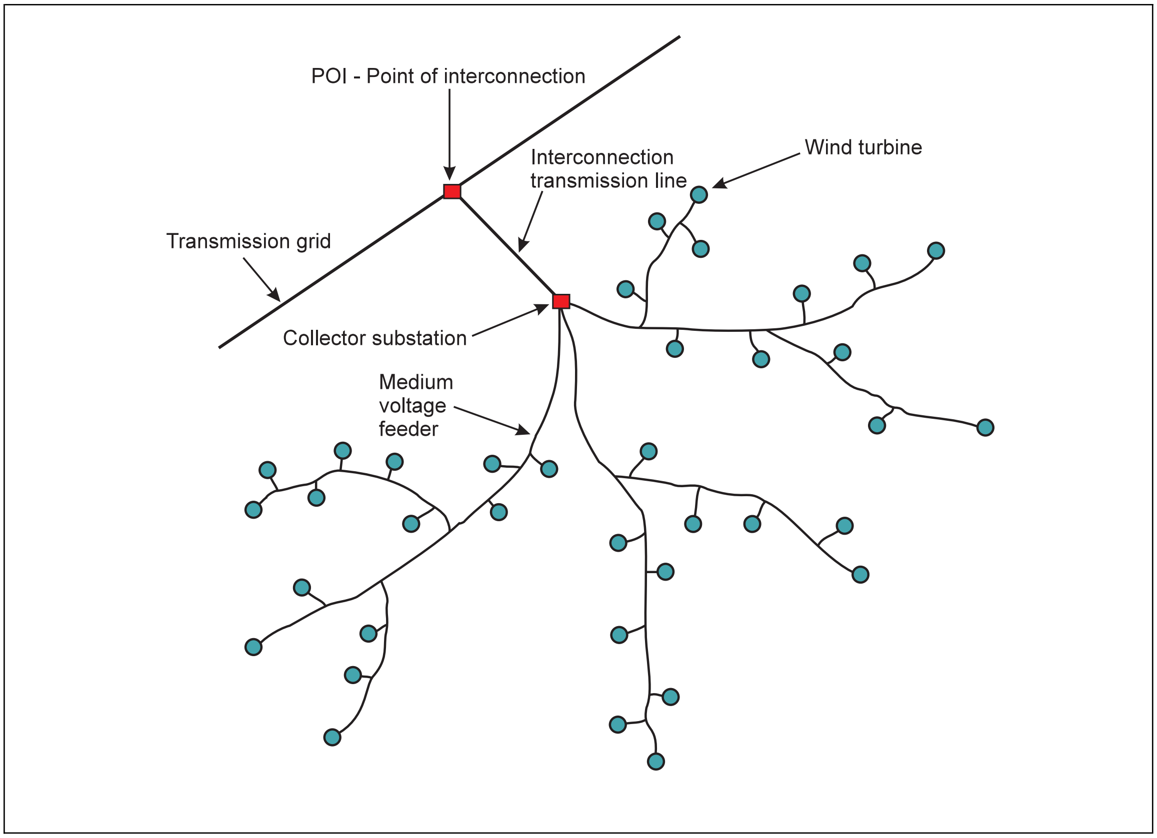


Fig. 2.9.2-1. Layout of a typical wind farm

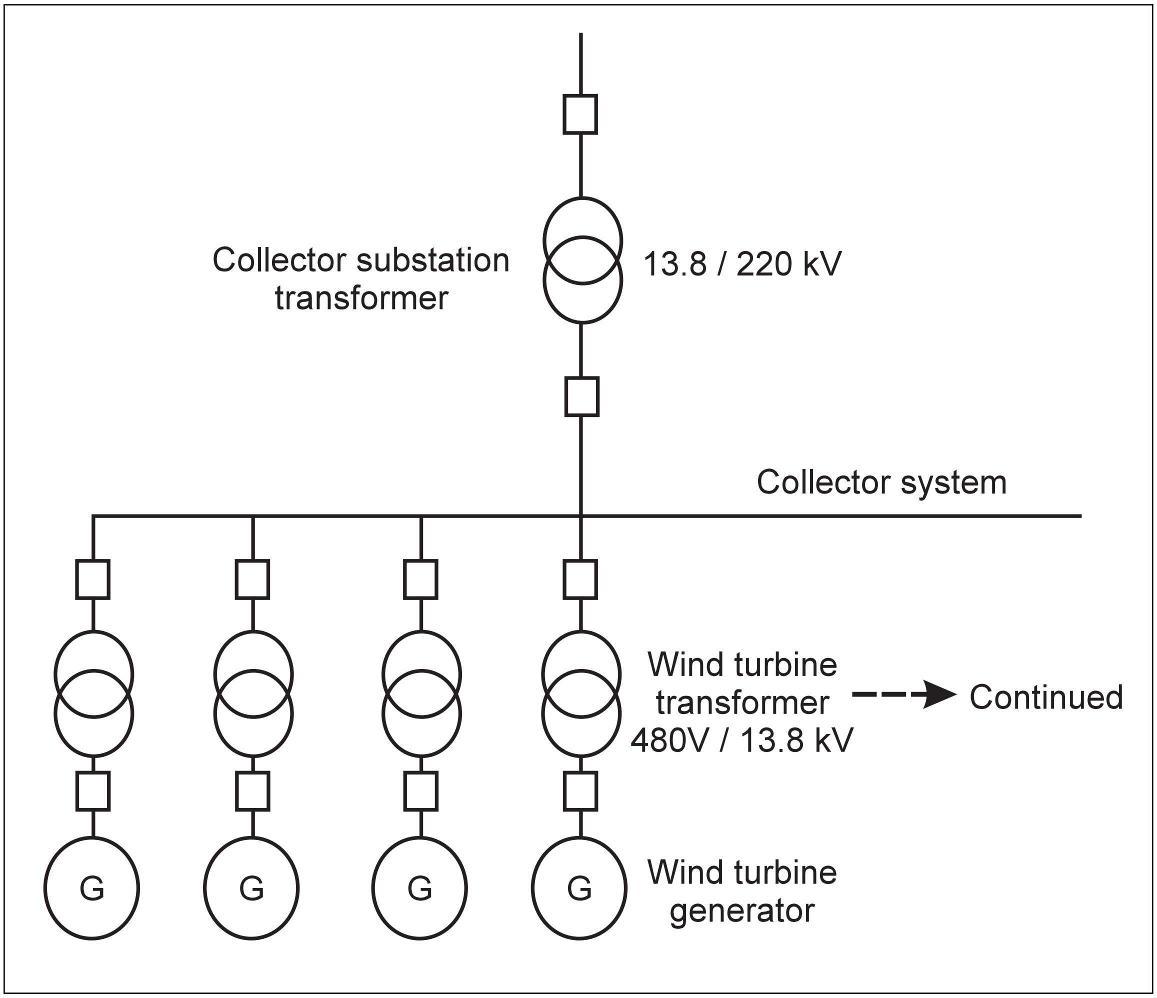


Fig. 2.9.2-2. Electrical systems of a typical wind farm (newer wind farms typically use 34.5 kV from tower to collector station)

2.9.2.1 Wind Turbines Generators

Squirrel Cage Induction Generators

2.9.2.1.1 In addition to the tests recommended in Data Sheet 5-17, *Motors and Adjustable Speed Drives*, perform the following (apply only those tests relevant to squirrel cage rotors):

- Measure the insulation resistance between the shunt capacitor terminals and the case.
- Measure the capacitance of the switched capacitor bank (all terminals).
- Measure the resistance of the internal discharge resistor for each capacitor.
- Functionally test the switches for the capacitor bank.
- Functionally test the soft starter for the induction generator.

Wound Rotor Induction Generators and Doubly Fed Asynchronous Generators

2.9.2.1.2 Refer to Data Sheet 5-12, *Electric AC Generators*, for operation, maintenance, and testing recommendations. (Apply only those tests relevant to wound rotors.)

2.9.2.1.3 In addition to the tests recommended in DS 5-12, perform the following:

- Measure the resistance of the variable rotor resistor (wound rotor induction generator only).
- Functionally test the soft starter for the induction generator (wound rotor induction generator only).

Synchronous Round Rotor and Salient Pole Generators

2.9.2.1.4 Refer to DS 5-12 for operation, maintenance, and testing recommendations. (Apply only those tests relevant to synchronous round rotor and salient pole generators).

Note: Some synchronous generators do not have rotor windings or slip rings and are instead provided with permanent magnets. Inspect these magnets to ensure they are securely fixed to the rotor.

2.9.2.2 Transformers and Switchgear

2.9.2.2.1 For dry-type transformers and associated low-voltage switchgear, refer to Data Sheet 5-20, *Electrical Testing*, for operation, maintenance, and testing recommendations.

2.9.2.2.2 For oil-filled transformers, refer to Data Sheet 5-4, *Electrical Testing*, for operation, maintenance, and testing recommendations.

2.9.2.2.3 For medium-voltage switchgear, refer to Data Sheet 5-19, *Switchgear and Circuit Breakers*, for operation, maintenance, and testing recommendations.

2.9.2.3 Power Electronics

2.9.2.3.1 Perform a functional test of the power electronics, including a test of individual components (fuses and DC link capacitors, as well as the diodes, silicon controlled rectifier (SCR) thyristors, gate turn off (GTO) thyristors or insulated gate bipolar transistors [IGBT]) to verify proper operation.

2.9.2.3.2 Measure the contact resistance of all bolted connections and compare to values of similar connections.

2.9.2.3.3 Verify all power electronics cooling systems are performing as intended.

2.9.2.3.4 Verify the high-temperature protection/monitoring system is performing as intended.

2.9.2.3.5 Perform functional testing of power electronics on the same frequency as other electrical testing recommended above.

2.9.2.4 Lightning Protection and Grounding Systems

Tower Connection to Grounding Electrode

2.9.2.4.1 Test surge arrestors according to Data Sheet 5-19, *Switchgear and Circuit Breakers*.

2.9.2.4.2 Inspect and test grounding and bonding systems in accordance with Data Sheet 5-20, *Electrical Testing*, on a routine basis and after severe lightning impacts as indicated by lightning detection equipment or third-party monitoring solutions.

Blades and Hub

2.9.2.4.3 Inspect the blade and hub lightning protection system yearly and after lightning strikes.

2.9.2.4.3.1 Based on lightning strike monitoring data, visually inspect wind turbine blades, nacelles and towers for damage after a lightning storm has passed through the wind farm.

2.9.2.4.3.2 Verify all lightning attachment points (air terminations, and diverter strips or coatings if applicable) at the tip and along the side of the blade are intact and undamaged.

2.9.2.4.3.3 Inspect LPS components, including mechanical sliding contacts (slip rings), spark gaps, surge protection devices, lightning measurement devices, etc., for visual wear or damage.

2.9.2.4.3.4 Inspect connections and mechanical supports for down-conductors and other LPS components, including conductive parts such as carbon fiber in the blade. For two-piece blade designs, inspect any pins or other components used to join the blades together.

2.9.2.4.3.5 If visual damage to the lightning protection system is identified, repair or replace damaged components; and conduct testing as identified in Section 2.9.2.4.4.

2.9.2.4.3.6 Inspect for water and moisture infiltration in the blade.

2.9.2.4.3.7 Confirm if the blade drain and air heating system are working properly to remove accumulated water and moisture.

Lightning Attachment Points to Grounding Electrode

2.9.2.4.4 Perform resistance testing every two years for the entire lightning protection system, from blade lightning attachment points to the grounding point at the base of the tower. Verify the measured impedance is within the limits specified by the OEM.

2.9.2.5 Wind Farm Collector Substation

2.9.2.5.1 Transformers

Refer to Data Sheet 5-4, *Transformers*, for electrical testing, operation, and maintenance recommendations regarding the transformers at the collector substation.

2.9.2.5.2 Switchgear and Protection Relay

Refer to Data Sheet 5-19, *Switchgear and Circuit Breakers*, for electrical testing recommendations regarding the switchgear and protection relays at the collector substation.

2.9.2.6 Cables for Onshore and Offshore Wind Farms

2.9.2.6.1 Refer to Data Sheet 5-31, *Cables and Bus Bars*, for inspection, testing, and maintenance recommendations.

2.9.3 Mechanical

2.9.3.1 Maintenance

2.9.3.1.1 Implement an outage and maintenance program based on the OEM's recommendations as contained in the Operation and Maintenance Manual and Service Bulletins.

2.9.3.1.2 For gearbox reliability, adhere to the recommendations in Data Sheet 13-7, *Gears*, in addition to the OEM's recommended operation and maintenance.

2.9.3.1.3 Establish an effective Lube-Oil monitoring program, see Data Sheet 13-7, *Gears*.

2.9.3.2 Inspections

2.9.3.2.1 Implement an inspection program based on the wind turbine manufacturer's documentation and recommendations. Table 2.9.3.2 lists wind turbine assemblies that require inspections.

2.9.3.2.2 Inspect blades following a major upset condition, such as lightning strikes severe windstorm, hail, and impacts from other foreign objects.

2.9.3.2.2.1 When damage to a blade(s) is identified, stop the wind turbine and repair or replace (if warranted) the damaged blade(s) as soon as possible.

2.9.3.2.2.2 Track and rate damage to blades, using the following publicly available EPRI report as a guide: 3002019669 *A White Paper on Wind Turbine Blade Defect and Damage Categorization*.

Table 2.9.3.2. Turbine Assemblies that Require Periodic Inspections

Assembly	Inspect for/Possible Defects[2]	Frequency of inspection[1]
Rotor blades	• Surface damage, cracks, and structural discontinuities • Weep/drain holes are clear • Damage to lightning protection system • Proper tensioning of bolts, every 10th bolt or as specified by the OEM	• Annually • Annually • Annually and after major lightning strikes • Break in period 6 months, follow by annual intervals
Drive train	• Lubrication • Condition of gearing (lube oil laboratory testing, if applicable) • Leakage • Unusual noises • Corrosion protection system • Proper tensioning of bolts, every 3rd bolt or as specified by the OEM	• Annually • 6 months. If continuous online monitoring, then annually • 6 months • N/A • Annually • Break in period 6 months, follow by annual intervals
Hydraulic and/or pneumatic systems	• Damage • Leakage • Corrosion	• Annually • 6 months • Annually
Safety devices, sensors and braking systems	• Function • Compliance with design limits • Damage • Wear	• Annually • Annually • Annually • Annually

Note 1. The frequency of inspections and maintenance is normally defined within the OEM's maintenance manuals. If OEM manuals are not available, follow the guidance in this table.
Note 2. All inspections are performed by qualified personnel. Results are properly and thoroughly documented with reports and photos where applicable.

2.9.4 Structural

2.9.4.1 Conduct periodic inspections of the structural support systems.

For land-based wind turbines, conduct inspections in accordance with the manufacturer's recommendations.

For offshore wind turbines:

A. Conduct an inspection in accordance with the manufacturer's recommendations, but at least once per year on a representative sample of components above-water, paying particular attention to the support structure and components within the splash zone.

B. Conduct inspection on representative samples of structural support system components below water, including foundations and scour protection, at least once every five years. The exception is grouted connections, such as those that attach a transition pieces to a pile, for which a representative sample should be inspected once a year.

2.9.4.2 Steel Towers

2.9.4.2.1 Check for corrosion or other damage to steel components, particularly the anchor bolts, the base of the tower shell (for land-based towers), the exposed tower section flange bolts, and any welded tower connections. For offshore towers, pay particular attention to corrosion of components within the splash zone.

2.9.4.2.2 At steel tower ring flanges (where tower sections are bolted together), check for deformed flanges, flange gaps, and loose bolts. Most flanges are on the interior of the tower shell, so access to the tower is needed. If interior access is unavailable, check for tower flange gaps from exterior grade level using binoculars or other means. Any visible deformation or gaps at the flanges is relevant and indicates the connection has been structurally impaired and should be repaired or strengthened (e.g., replace the bolts).

2.9.4.2.3 Check for any impact or other physical damage to the steel tower shell or steel lattice members. Members with visible damage have reduced structural capacity; have them repaired, strengthened, or replaced. For offshore towers, pay particular attention to possible impact damage from service vessels at the waterline.

2.9.4.2.4 Examine corrosion-resistant coatings on the steel tower and connections. Repair any damage or holidays with an appropriate in-kind touch-up coating. For offshore towers, also check that the cathodic protection system is operating properly.

2.9.4.2.5 Perform nondestructive evaluation (NDE) on critical welded and bolted tower connections. Base the frequency of the NDE on standard industry practice and the manufacturer's recommendations.

2.9.4.3 Concrete Towers

2.9.4.3.1 For concrete towers, check for rust staining, cracking, and spalling, particularly at the tower section joints, at any post-tensioned tendon or prestressed strand anchorages, and at any splice sleeves.

2.9.4.4 Foundations and Substructure

2.9.4.4.1 Check for cracking or spalling of the concrete foundation, particularly near the anchor rods or other exposed steel connections.

2.9.4.4.2 Check the condition of the scour protection at offshore wind turbine foundations. This should be carried out in accordance with the manufacturer's or wind farm operations specifications but should be performed at least once every 5 years.

2.9.4.4.3 For grouted connections, which attached the transition piece to the foundation for offshore wind turbines and substation support structures, check the grout seals and the integrity of the grouted connection. Check that the connection has not deteriorated and allowed differential settlement or movement between the transition piece and the foundation structure that could be detrimental to the proper operation and performance of the wind turbine.

2.9.4.4.4 For onshore wind turbines, inspect foundations for damage if flooding occurs or severe stormwater runoff happens within the wind farm boundaries. Verify that water did not wash away the soil or cause any undermining of the tower foundations. See Data Sheet 1-40, *Flood*, for additional details on floods.

2.10 Condition Monitoring

Condition monitoring (CM) is a key component of a condition-based or predictive maintenance program. CM is based on trending critical parameters to identify equipment degradation and to detect/predict incipient failures. If implemented well, a CM system can:

- detect incipient failures early, reducing the risk of catastrophic failures
- evaluate component health conditions to support a condition-based or predictive maintenance system, and
- be used to analyze the root cause of failures.

In a condition monitoring system, various operational parameters are tracked to identify any trends that may indicate deviation in expected operating conditions. These parameters can be categorized as follows:

- non-controllable parameters such as wind speed and temperature
- performance parameters such as power output and rotor speed
- vibration parameters such as tower acceleration, drive train acceleration, and bearing vibration
- temperature parameters such as gearbox temperature, generator temperature, mechanical brake system temperature, oil and bearing temperatures, and electronic power system component temperature.
- electrical parameters such as stator voltage and current, rotor voltage and current (for wound-rotor and doubly fed asynchronous generators converter) input and output voltage, current, and frequency, and yaw and pitch motor current.

When the inputs from these different operating parameters are combined, the ability to isolate the location of problems can be improved.

If condition-based or predictive maintenance strategies are used for a wind turbine, ensure sufficient operating parameters and analytical models are available to perform adequate assessment on the state of the turbine. Areas where condition monitoring has proven to be effective for wind turbines are the rotor blades, structures, and drive train.

For wind turbine components that use condition-based or predictive maintenance strategies, provide condition monitoring systems as described below.

2.10.1 Rotor Blades and Structures

2.10.1.1 Monitor the condition of rotor blades, nacelle, tower, and foundations with vibration sensors, strain gauges or by acoustical monitoring.

2.10.2 Drive Train

Provide the following CM systems for the key components of the drive train.

2.10.2.1 Vibration Monitoring

2.10.2.1.1 Provide vibration monitoring for the following key components of the drive train: the gearbox (if provided), main bearing/shaft, and generator.

2.10.2.2 Oil Supply System Monitoring

2.10.2.2.1 Provide monitoring for bearing temperature, oil pressure, temperature and tank level, oil pump, and oil quality (to detect contamination and degradation).

2.10.2.2.2 Provide monitoring for oil quality (to detect contamination and degradation).

Oil monitoring can be accomplished using online (real-time continuous monitoring) or by offline oil sample analysis. See Data Sheet 13-7, *Gears*, for additional information on oil monitoring systems.

If online oil monitoring is selected, provide particle-counting sensors, which measure total particle counts, including ferrous and nonferrous particles, and oil-condition sensors, which measure changes in oil quality caused by acidic level, water content, etc.

If online instrumentation indicates abnormal conditions, conduct offline oil sample analyses to help identify component failures in progress.

If offline oil sample analysis monitoring is selected, perform offline oil analysis in accordance with the wind turbine manufacturer's recommendation (typically one sample every six months). Manually take an oil sample from the gearbox lubrication system and send the sample to a laboratory for analysis. A typical oil sample analysis includes particle counts, water content, total acid number, viscosity, and particle element identification.

If online oil monitoring is being done, also conduct offline oil sample analysis in addition to the online continuous monitoring. The main purposes of this redundancy are to:

- monitor parameters not covered by online instruments.
- conduct elemental analysis to identify components that are generating excessive wear particles.
- assist root cause analysis for some component failures.

2.10.3 Collector Substation

2.10.3.1 Refer to Data Sheet 5-4, *Transformers*, for recommendations relating to condition monitoring systems for the collector substation transformer.

2.10.3.2 Refer to Data Sheet 5-19, *Switchgear and Circuit Breakers*, for recommendations relating to condition monitoring systems for the switchgear in the collector substation.

2.10.4 Subsea Cable for Offshore Wind Farms

2.10.4.1 Refer to Data Sheet 5-31, *Cables and Bus Bars*, for condition monitoring recommendations.

2.11 Contingency Planning

2.11.1 Equipment Contingency Planning

When a wind turbine equipment breakdown would result in an unplanned outage to site processes and systems considered key to the continuity of operations, develop and maintain a documented, viable wind turbine equipment contingency plan per Data Sheet 9-0, *Asset Integrity*. See Appendix C of that data sheet for guidance on the process of developing and maintaining a viable equipment contingency plan. Also refer to sparing, rental, and redundant equipment mitigation strategy guidance in that data sheet.

In addition, include the following elements in the contingency planning process specific to wind turbine equipment:

A. Availability of viable mechanical and electrical equipment to minimize the downtime associated with a wind turbine equipment failure. This includes the following:

- Set of blades, main shaft with bearing, gearbox (where applicable), generator, converter (where applicable), protection and control equipment, switchgear, cable, and transformer.

B. Rental transformers and/or mobile substations if the collector substation transformer fails.

C. Subsea export cable repair or inter-array cable replacement (where applicable) that includes at the following major elements:

- Appropriate electronic gear to locate the fault quickly. Time domain reflectometry pulses can be used to determine the distance down the cable that the fault occurred. However, this technique, if it is intended to be used, must be thought out ahead of time so the devices that can conduct such a test can be located.
- Subsea export cable with sufficient length for at least one repair operation. When the submarine cable is connected to a land-based cable, land cable with sufficient length for at least one repair operation should be provided.
- Inter-array cable with sufficient length for at least one replacement.
- Accessories such as armor hang-off, submarine repair splices (joints), sea-land power transition joint, and armor anchoring device.
- Contract to have an experienced repair team available, including an experienced jointer, when repair is need.
- Appropriate repair tools, such as cable jointing equipment, de-burial equipment, and burial equipment.

D. Provisions for special equipment:

- Cranes, rigging, and even helicopters to gain access to the nacelle for repairs.
- Contract to have a repair vessel (offshore locations)available when repair is needed. In some cases, the contract might not guarantee the availability of the repair vessel. The equipment contingency plan needs to include alternatives for such a situation.

2.12 Human Factor

2.12.1 Emergency Response and Pre-Incident Planning

Design and institute an emergency response plan in accordance with Data Sheet 10-1, *Pre-Incident and Emergency Response Planning*.

2.12.1.1 Fire

Ensure the emergency response plan addresses potential fire scenarios. Refer to Data Sheet 10-1, and Data Sheet 9-19, *Wildland Fire*, with the fire service.

Due to the remote location of many wind farms, firefighting response may be delayed. Once the fire service has arrived, access to fight a wind turbine fire may be limited. Therefore, pre-incident planning with the fire service is critical.

2.12.1.1.1 Arrange and prepare documented procedures to expedite access and emergency response to situations such as fires throughout the wind farm.

2.12.1.1.2 Prepare schematics to guide responders and indicate the location of access routes throughout the wind farm.

2.12.1.1.3 Train and authorize designated personnel to serve as liaisons with the public fire service.

2.12.1.1.4 Provide the local fire service with sufficient knowledge of fire hazards and response procedures to aid them in conducting firefighting operations. Document this information in the pre-incident plan with the local fire service.

2.12.1.2 Environmental Hazards

2.12.1.2.1 Form an emergency response team (ERT) to perform the work necessary to prepare wind turbines for severe windstorms, extreme low and freezing temperatures, and associated weather conditions, including snow and icing, hailstorms, and other conditions that could adversely affect a wind turbine. Severe weather conditions can cause grid loss; therefore, any safety or protection systems that rely on the power grid and are without independent backup power could be impaired.

2.12.1.2.2 Develop a written ERT procedures manual and keep the manual current with any relevant changes, such as changes to personnel and contact information, equipment, etc. Post copies of the ERT procedures at each wind turbine. Ensure the ERT procedures manual includes the following:

A. Detailed description of the emergency procedures.

B. Crews, vehicles, vessels, routes, and equipment dedicated to specific wind turbines throughout the wind farm.

C. Communications protocol and equipment to allow ground personnel to have real-time contact control/ monitoring personnel.

2.12.1.2.3 Conduct and document periodic training of ERT technicians and other personnel. Include dry runs of the shutdown procedure to determine a realistic estimate of manpower and time requirements. Ensure ERT response times are well within typical windstorm forecasting lead times.

2.13 Repowering

Repowering can involve a full activity, such as dismantling and replacing an earlier project's entire fleet of project infrastructure in the site boundary, or a partial activity, such as replacing only select turbines or components thereof, and associated facilities. Repowering can also involve interconnection infrastructure with the power grid.

2.13.1 Treat repowering projects as new wind turbine(s) and apply all section of this data sheet.

2.14 Alerts

Original equipment manufacturers and alternative service providers issue technical alerts or bulletins when design or operating problems occur that differ from expectations. Implement an alert/bulletin management process to track, prioritize and implement these alerts, as well as evaluate how they may affect the management of change process and regard to procedure, design, drawings, etc.

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Natural Hazards/Foundations/Structural

3.1.1 Wind

3.1.1.1 Wind Speed and Wind Turbine Class

Standard wind turbine classes are based on the 50-year, 10-minute mean, reference wind speeds (V_{ref}) at the hub height for extreme wind model (EWM) design wind load cases.

Basic wind speeds (V) can be based on several time-dependent measurement methods, including 3-second gusts, 10-minute mean, 60-second sustained, mean hourly, or fastest mile. Conversions between the various methods are fairly well established; some can be found in this data sheet.

In many parts of the world, basic wind speeds are based on either 3-second gust or 10-minute mean. Equivalent 3-second gust and 10-minute mean wind speeds are therefore included in the tables associated with wind turbine class.

Since wind turbine class is determined by the wind speed at the height of the wind turbine hub, but basic wind speed is generally taken at 33 ft (10 m) above grade, the effects of wind shear must be accounted for when relating the two wind speeds.

V_{ref} is the wind speed used to determine the standard wind turbine class and is associated with extreme wind speeds when the wind turbine is not operational.

3.1.1.2 Wind Load on Ice-Encrusted Rotor Blades

Ice accretion on rotor blades can cause damage to rotor blades under two basic conditions. When the rotor is not spinning, ice accretion causes increased wind load to be imposed on the blades due to the increase in “effective” projected area (sometime called “sail area”); this increased wind load also acts in combination with the weight of the ice. When the rotor is spinning, ice accretion causes increased loads similar to the case where the rotor is not spinning, but also causes increased dynamic loads to be imposed on the rotor due to the mass of the ice and the imbalanced distribution of the ice mass.

The use of rotor blade coatings intended to shed ice (ice-phobic coatings) may help to reduce the size of the ice buildup or the time the ice is adhered to the rotor blades. Rotor vibration monitoring which is intended to detect rotor out-of-balance conditions, including out-of-balance due to ice accretion on the rotor blades may help to ensure the rotor will not spin with substantial imbalanced ice on the blades.

3.1.1.3 Upwind Versus Downwind Wind Turbines

Most modern horizontal axis wind turbines (HAWT) are “upwind” turbines, meaning the rotor is upwind of the support tower (i.e., the rotor is windward of the tower). Upwind turbines require a motorized or mechanized active yaw mechanism to rotate the nacelle and rotor so the rotor faces into the wind. For upwind turbines, the rotor blades must not come in contact with the support tower under any design wind conditions; this is accomplished by offsetting the rotor from the tower and by designing the rotor blades with adequate stiffness.

Some turbines are designed as “downwind” turbines, meaning the rotor is downwind of the support tower (i.e., the rotor is leeward of the tower). Many downwind turbines can “weathervane”, meaning yaw adjustment is passive and is changed by wind direction, and a motorized yaw mechanism is not required. One of the advantages of downwind turbines is that, compared to upwind turbines, turbine blades can be made more flexible, since wind-induced blade deflection (bending) will be away from the tower. The overriding disadvantage to downwind turbines is that the “wind shadow” or “wind shade” caused by the wind turbulence in the wake of the support tower imposes fluctuations in wind pressure and additional vibration in the rotating turbine blades.

3.1.2 Earthquake

There are generally two methods used to design and analyze wind turbine structures for earthquake forces: the dynamic modal method and the equivalent static force method. Both are acceptable methods when used properly.

3.1.2.1 Response Modification Factor [R]

Wind turbine structures behave similar to inverted pendulum structures, and, therefore, the use of a response modification factor (R) no greater than that intended for inverted pendulum structures is considered appropriate for determining design loads for wind turbine superstructures (e.g., support towers) and foundations.

3.1.2.2 Structural Damping

The design spectral response acceleration values derived from many model building codes and standards are based on the assumption that the structure will develop at least 5% of critical damping during seismic shaking. For many building structures 5% of critical damping is an appropriate assumption; however, non-building structures, including support towers for wind turbines, often will have critical damping values substantially less than 5%, which will result in greater design spectral response accelerations and therefore greater effective seismic design loads.

3.1.3 Foundations

3.1.3.1 Land-Based Foundations

3.1.3.1.1 Shallow Foundations

The most common tower foundations are reinforced concrete spread footings, which are usually placed below grade and have some depth of soil covering them. Often the design engineer will include the beneficial effects of the weight of the soil over the footing (the overburden) in the resistance to uplift and overturning. Crediting the overburden is generally acceptable provided the overburden is well protected and will remain in place over the long term.

In addition to providing adequate strength, stability, and fatigue resistance, foundations supporting wind turbines must also provide lateral and rotational stiffness to meet the requirements of the turbine manufacturer.

3.1.3.1.2 Frost Protection and Differential Settlement

Wind turbines are sensitive to disturbance of the axial orientation of the support tower (i.e., the tower becoming out of plumb); therefore, the differential movement associated with frost heaving acting on the tower foundation, and resulting disturbance to the orientation of the support tower, can disrupt proper wind turbine operation.

Similarly, differential settlement of the soils supporting shallow foundations can have adverse effects on wind turbine operations. Proper geotechnical investigation and engineering, and construction-phase site work such as soil preparation and compaction, de-watering, and frost protection will help to ensure adequate resistance to differential settlement and frost heaving.

3.1.3.2 Offshore Substructure

The substructure includes the transition piece and foundation.

There are several different types of foundation systems used for offshore wind turbines. These include steel monopile, steel tripod, concrete gravity base, and suction caisson (or suction bucket).

Important factors to consider for ensuring the long-term adequacy of the foundation include proper scour protection and corrosion protection.

Scour protection will often consist of layers of rock, or sometimes a concrete slab apron. Potential scour damage will depend on the type of foundation. For a monopile foundation, scour of the seabed will increase the effective length of the monopile (essentially cantilever from the seabed), thereby exposing more of the monopile to hydrodynamic loads while also deceasing the embedment depth of the monopile. For gravity base foundations, scour can undermine the foundation and cause it to settle unevenly, thereby causing the tower to go out of plumb.

Corrosion is an important issue with offshore wind turbine foundations. Marine exposure can cause steel reinforcing and exposed steel connections in concrete components to corrode, which can be detrimental to the structural capacity of the foundation. For steel foundations, corrosion can decrease the section thickness of the steel shell and other steel components, causing a reduction in structural integrity. Corrosion can be particularly aggressive in the splash zone.

Marine growth can cause an increase in hydrodynamic loads by effectively increasing the width and roughness of the foundation elements. In addition to affecting hydrodynamic loads, marine growth can damage corrosion-resistant coatings and make periodic visual inspections more difficult.

The transition piece is the part of the support structure that connects to both the support tower and the foundation. Many foundations, including steel monopile foundations, which are the most commonly used foundation for offshore wind turbines, use a grouted connection to attach the transition piece to the monopile. This grouted connection is generally made by pumping high compressive strength cement grout into the annular space between the steel shell of the transition section and the monopile (the grout slurry being held in place with grout seals). In recent years, the structural integrity of this type of grouted connection has sometimes been found to degrade, which over time has allowed the transition piece to move or settle in relation to the monopile foundation, and therefore prompted the need for repair.

A portion of the transition piece is generally located within the splash zone and therefore can be exposed to a severely corrosive environment. Proper protection systems and inspections are therefore needed to ensure adequate long-term performance and limit the deleterious effects of corrosion.

3.1.4 Support Towers

3.1.4.1 Steel Towers

Most support towers are made of a steel tubular shell (i.e., conical or tapered tubular steel monopole towers). The size of the steel shell and thickness of the steel shell plate varies depending on the size of the wind turbine and the structural design loads.

Steel monopole towers have cross-sections that are either round or many-sided polygons (e.g., 32- to 48-sided), and are generally the most common type of tower used for commercial wind turbines. In addition to the tapering of tubular towers, the wall thickness of tubular sections often decreases with the height of the tower to ensure an efficient use of material.

The structural capacity of the tower can be compromised by local damage or deformation to the steel shell (for example, impact damage from a failed rotor blade or maintenance equipment).

Self-supporting latticed steel (truss-type) towers are sometimes used for land-based wind turbines. Latticed towers may pose a greater potential problem associated with rotor blade strike for upwind HAWT due to the width (footprint) of the tower. Latticed towers with guy wires are generally avoided since these wires could interfere with and damage turbine rotor blades.

Compared to steel latticed towers, steel monopole tower structures are generally less difficult to maintain, provide better protection from weather (for electrical and other equipment and components), provide safer climbing access for service technicians, and, for locations where icing is known to occur, pose less concern regarding ice accretion and the resulting structural loads due to wind acting on ice-encrusted members.

Typically, the support tower is too large to fabricate and transport in one piece for land-based wind turbines; therefore, the tower is usually fabricated and transported in several sections, generally in 60 ft (18 m) to 100 ft (30 m) lengths that are erected by crane and welded or bolted together at the site. Individual tower sections often are fabricated with internal flanges that are bolted together at the site with pre-tensioned bolts to form slip-critical connections. Slip-critical connections are generally preferred over bear-type connections mainly for their superior resistance to fatigue loads.

The support towers for offshore wind turbines are often larger than for land-based locations. However, because the tower is often fabricated at a portside facility and transported by barge to the offshore wind farm site, the transportation-related size restrictions that apply to land-based towers will often not apply to offshore towers.

The support tower must have adequate strength and stiffness to support all design load cases and combinations in particular, stiffness requirements imposed by the wind turbine manufacturer. The tapered shape of the tower, and use of thicker shell walls at the bottom of the tower, allows the tower to support the gravity loads (e.g., the weight of the nacelle and rotor), torsional loads, and lateral loads, which are greatest at the base of the tower.

3.1.4.2 Concrete Towers

Concrete towers are less commonly used than steel monopole towers for land-based wind turbines, but are sometimes used for offshore wind turbines.

Due to the size of the towers, concrete towers are generally precast on-site in modular sections and post-tensioned with steel tendon once the sections are erected.

The greater mass of concrete towers, as compared to steel towers, will impose greater seismic loads on the tower and tower foundation. Special care must be taken to ensure seismic loads are adequately resisted and sufficient detailing is provided to ensure adequate ductile seismic performance.

A recent development is the use of “hybrid” towers that use both steel and concrete sections for a single tower, with the steel sections at the top.

3.1.4.3 Tower Corrosion

Corrosion is an important issue with offshore wind turbine towers for both concrete and steel towers.

For concrete towers, marine exposure can cause steel reinforcing and exposed steel connections to corrode, which can be detrimental to the structural capacity of the tower, and also cause concrete to crack and spall, thereby making the structure even more vulnerable to corrosion.

For steel towers, corrosion can decrease the section thickness of the steel shell and other steel members, causing a reduction in structural integrity. Corrosion can be particularly aggressive in areas of stress concentration, which often includes welded and bolted connection assemblies. The portions of the tower and tower appurtenances that may be within the splash zone will be exposed to a severely corrosive environment. Therefore, a properly designed and maintained protection system is needed to ensure adequate long-term protection against corrosion.

3.1.5 Rotor Blade Throws

The results of the available rotor blade throw studies vary considerably. The complexities of wind drag, blade launch angle and launch velocity make generalized predictions difficult.

The number of blade throws is relatively small compared to the number of ice throws from blades. One blade failure per year for every 100 wind turbines is often cited in the industry as a reasonable approximation, and of those blade failures, some will involve a thrown blade and some will not. Installing protection from thrown rotor blades is not likely to be feasible given that the rotor blades, or large fragments of rotor blades, are quite massive and could involve very large impact energy. For example, a typical 125 ft (38 m) rotor blade might weigh roughly 14,500 lbs (6,500 kg), although the portion thrown will represent not more than roughly 15% to 30% of the total blade weight.

3.1.6 Siting, Spacing, and Setbacks

Wind turbines in a wind farm are typically spaced based on the rotor diameter. Adequate spacing is needed to ensure the wind wake from one turbine, which causes wind turbulence and reduced wind speed in its wake, will not negatively affect the performance of the downwind turbine. Turbine spacing is generally 5 to 10 times the rotor diameter in the direction parallel to the prevailing wind, and 2 to 5 times the rotor diameter in the direction perpendicular (cross wind) to the prevailing wind.

Setbacks from adjacent structures and roads are based on the possible physical hazards that wind turbines can pose, including ice throws from blades, blade throws, and turbine collapse. Additionally, other factors can affect setbacks; for instance, proximity to airports or helipads (where wind turbine height restrictions and lighting requirements may apply), and proximity to residential areas based on nuisance issues (e.g., aesthetics or noise).

Siting is based on the wind efficiency (for power generation) of the area, which can include ideal wind operational speeds and topography, as well as connectivity to the electrical power grid.

Tower-to-Tower Impact from Collapse

Based on the ratio of rotor diameter (D) to hub height (H) of typically 0.7 to 1.1, and the maximum collapse radius of a wind turbine (H + D/2), and using the low range of typical cross-wind turbine spacing (2 x D), the maximum possible collapse radius is likely to be less than the typical turbine spacing and therefore the risk of damage to one tower due to the toppling of another is low.

3.2 Fire Protection

3.2.1 FM Approved Industrial Fluids

Hydraulic control systems for wind turbines operate at very high pressures (thousands of psi; hundreds of bar), and therefore present potential severe spray fire hazards when the control system is pressurized by mineral oil or other hydrocarbon-based fluid. While the pressures in lubrication oil systems are significantly lower, these systems also use hydrocarbon-based fluids.

Mineral oil and other hydrocarbon-based lubricating and hydraulic fluids have relatively high flash points, but can be readily ignited by strong ignition sources. Once released and ignited, these fluids will burn with a very high heat release rate that is typical of all hydrocarbons, regardless of flash point.

Some so-called “fire-resistant fluids” will burn very intensely when released and ignited as a spray or aerosol. FM Approved industrial fluids, which are listed in the *Approval Guide*, are tested to demonstrate a limited heat release rate, and therefore do not in and of themselves require fire protection measures.

3.2.2 Containment

The key objectives of spill containment are to limit an oil pool size within the nacelle, and prevent the spread of oil into the wind turbine tower. Properly engineered containment systems will limit the extent of damage that could result from oil fires within the nacelle, and prevent potential damage to the tower.

3.3 Mechanical

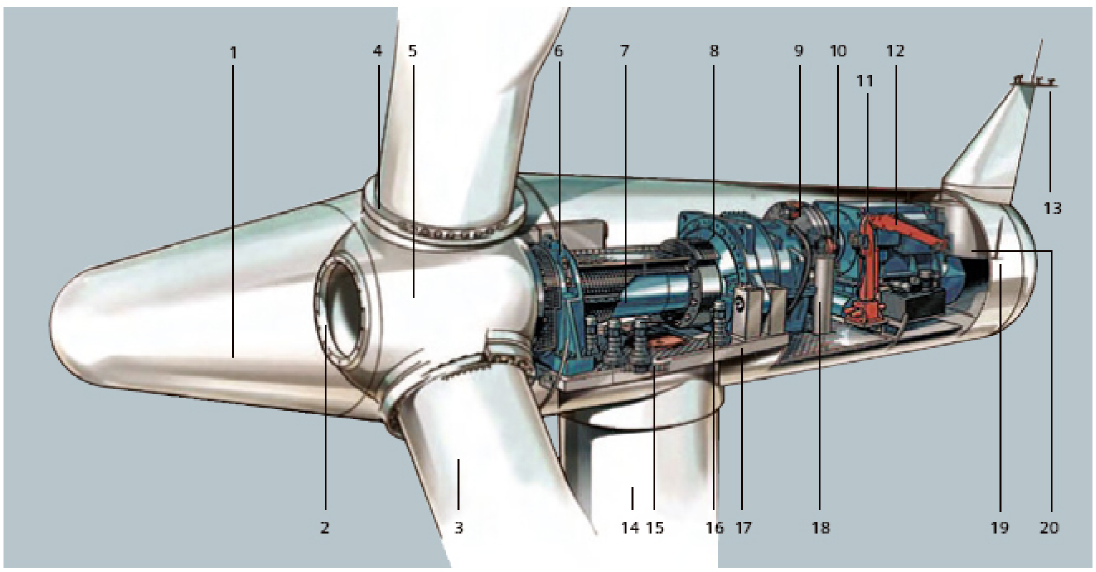
Wind turbine technology is evolving rapidly as manufacturers continue to enhance their designs to increase capacity. As a result of this rapid evolution, there are technology development risks associated with wind turbines.

Wind turbine components are designed for a 20- to 30-year life span. This is a relatively young industry, with many of the components being exposed to extreme cyclic loads, and some of the heavily stressed components, such as the gearboxes, have fallen short of their design life goal. To minimize the risk of failures, regular inspections and maintenance should be performed.

The main groups of mechanical components in a wind turbine are:

A. The rotor
B. The yaw system
C. The drive train
D. The nacelle

Most of the components in these groups are shown in Figure 3.3. It may be useful to refer to this figure while reading the various component discussions that follow.



Legend:

1. Spinner
2. Spinner bracket
3. Blade
4. Pitch bearing
5. Rotor hub
6. Main bearing
7. Main shaft
8. Gearbox
9. Brake disc
10. Coupling
11. Generator
12. Service crane
13. Meteorological sensors
14. Tower
15. Yaw ring
16. Yaw gear
17. Nacelle bedplate
18. Oil filter
19. Canopy
20. Generator fan

Fig. 3.3. Nacelle arrangement for a Siemens SWT-2.3-93 wind turbine (Courtesy of Siemens, all rights reserved. Used with permission.)

Before discussing the components of a wind turbine in detail, the following section will review the different control strategies that are commonly utilized in the wind turbine industry. This controls discussion will introduce relevant nomenclature as well as introduce the function of some of the mechanical components of a wind turbine.

3.3.1 Controls

The power output of a wind turbine varies with wind speed. Figure 3.3.1 shows a hypothetical power output curve along with the corresponding rotor speed (rpm). The power curve shows the power output as a function of the hub height wind speed. The turbine shown is controlled to operate at a constant rotor speed once it has reached rated speed. Alternatively, the wind turbine can be designed to operate at variable speeds.

The following four key points are labeled on the figure below:

A. Cut-in speed: the minimum wind speed where the wind turbine can produce useful power.
B. Rated speed: the wind speed at which the rated power can be produced.
C. Cutout speed: the maximum wind speed at which the turbine can operate safely.
D. Rated power: the maximum power that the generator can produce.

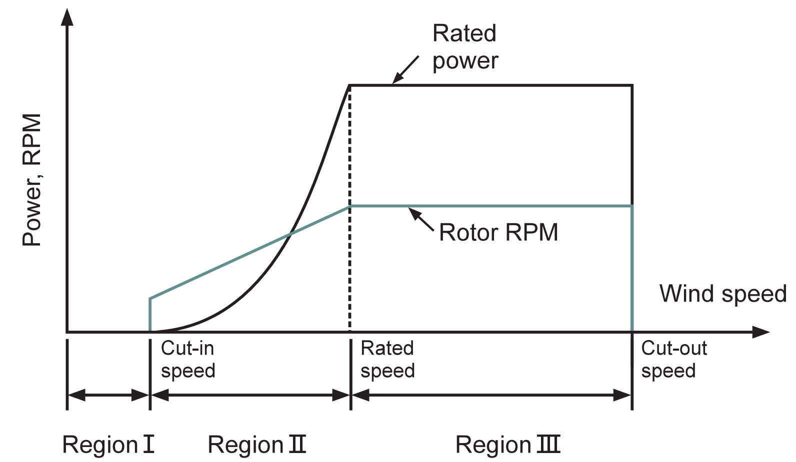


Fig. 3.3.1. Typical power curve

The key functions of the wind turbine control system include the following:

A. Maintain the rotational speed within a certain range.
B. Maintain the power output within a certain range.
C. Start and stop the turbine.
D. Yaw the turbine.

To control the wind turbine power and to limit the power at high winds the following control strategies are used:

- Stall regulation
- Pitch regulation
- Yaw regulation.

Each of these strategies is discussed below. Ideally, the control system should ensure a smooth power output and also optimize the power output at lower wind speeds.

A stall regulation system utilizes the aerodynamic characteristics of the rotor to control the power output. The fixed-pitch blades are designed to operate near the optimal tip speed ratio at lower wind speeds and, as the wind speed increases, the blade enters the stall region. This reduces the rotor efficiency and limits power output.

A pitch regulation system varies the rotor blade angle (along the long axis) in response to the available wind speed to optimize the aerodynamic flow conditions. To limit the power output, the pitch regulating system will pitch the blades to reduce the rotor efficiency. At and above the rated wind speed, the power output is limited to rated power. At high wind speeds, the pitch system functions as an aerodynamic brake and is an integral part of the wind turbine protection system.

A yaw regulation system orients the wind turbine relative to the direction of the wind to control the power output. In normal operation it is typical to align the turbine with the wind to achieve optimum performance. To limit the power output, the yaw control system will turn the rotor away from the wind. Yaw regulation systems have been used mainly on small wind turbines and are not common for larger wind turbines.

3.3.2 Rotor

The rotor of a wind turbine is designed to extract power from the wind and to convert it to rotary motion. The rotor includes the blades and hub, and may include aerodynamic control surfaces. Wind turbine rotors must operate under conditions that include steady state as well as periodically and rapidly varying loads. Since load variations occur over a large number of cycles, fatigue is a major design consideration.

3.3.2.1 Blades

Wind turbine blades are long, slender structures used to convert the force of the wind into the torque needed to generate useful power. The basic shape and dimensions of the blades are determined primarily by the overall layout of the turbine and aerodynamic considerations. This data sheet addresses horizontal axis wind turbines (HAWTs). A three-blade configuration is the most common for HAWT turbines. Details of the shape, particularly near the root, which is a high stress area, are also influenced by structural considerations. As wind turbines continue to grow in size (see Appendix C) this increases the structural design challenges.

Since the 1970s, most blades for horizontal axis wind turbines have been made from composites. Composites have become the preferred blade materials because they have high strength-to weight ratios, high stiffness-to-weight ratios, are corrosion resistant, are electrical insulators, and lend themselves to a variety of fabrication methods. The typical composites used are based on fiberglass, carbon fiber, or wood. Typical binders (matrix) include epoxy, polyester, and vinyl esters.

Fatigue damage to composite materials, a major consideration for wind turbine blades, occurs by a different mechanism than it does with many other materials. Typically, the matrix cracks, then cracks begin to combine and there is a debonding between the matrix and the fibers. This may be followed by debonding and delamination (separation) over a wider area. Eventually, this is followed by the breaking of individual fibers and finally by complete fracture.

Blade damage during transportation is also a major concern. Upon receiving the blades at the site, they should be examined by a qualified inspector to identify any transportation damage that may have occurred. If such damage is found, the blade should either be repaired using an OEM-approved procedure or, if the damage is severe enough, replaced.

Performing routine inspections and correctly diagnosing problems early will limit the extent of the damage and the repairs required. It will also allow any required repairs to be properly scheduled to minimize the impact on turbine availability. Routine blade inspections are an integral component of an effective loss prevention program.

3.3.2.2 Hub

The rotor hub of a wind turbine is the component that connects the blades to the drive train. Hubs usually are made of either welded or cast steel, and must be strong enough to withstand and transmit all of the loads that can arise from the static and aerodynamic loads on the blades, including dynamically induced loads, such as those due to rotation and yawing.

The most common type of hub is a rigid hub, which is designed to maintain all of the major rotor parts in a fixed position relative to the main shaft

The hub of a pitch-controlled turbine includes bearings at the blade roots, pitching mechanisms and a means of securing the blades against all motion except pitching.

3.3.2.3 Aerodynamic Control Surfaces

Aerodynamic control surfaces are devices that can be moved to change the rotor's aerodynamic characteristics. There are many control surfaces that can be used, and the selection of a particular type of aerodynamic control surface is dependent on the turbine's overall control strategy (see Section 3.3.1). Two of the more common designs are discussed below.

Stall-regulated wind turbines may use an aerodynamic control surface to supplement the passive stall control. Typically, these can be tip brakes, flaps, or spoilers. An example of a tip break is shown in Figure 3.3.2.3. The tip brake is activated by increasing centrifugal force and acts as an aerodynamic brake.

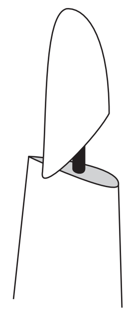


Fig. 3.3.2.3. Tip brake

In a conventional pitch-controlled wind turbine, the entire blade rotates about its long axis to form a control surface. One approach is to use a pitching mechanism that pitches all of the blades simultaneously, using a pitch rod that passes through the main shaft, together with a linkage in the hub. The pitch rod is driven by a motor or hydraulic cylinder mounted in the nacelle, and the linkages are connected to the roots of the blades. Alternatively, individual pitch drivers (electric motors or hydraulic cylinders) are mounted in the hub to pitch each blade separately.

Regardless of the design approach used, the pitching mechanisms are a major part of the wind turbine protection system and should be designed to be failsafe. The use of pitching systems as an aerodynamic brake and the failsafe design of the system are discussed further in Section 3.3.5.

3.3.3 Drive Train

The drive train includes the main shaft (including the main bearing), the gearbox (if used), the mechanical break, couplings, and the generator.

3.3.3.1 Main Shaft

The main (low-speed) shaft supports the weight of the rotor and transfers torque from the rotor to the rest of the drive train. The main shaft is supported by bearings that transfer the reaction loads to the main frame of the turbine. The main shaft normally is made of steel.

3.3.3.2 Coupling

Couplings are used to connect shafts, with the primary function being to transfer torque between the two shafts. Additionally, a coupling may be used to dampen torque fluctuations and to allow for some slight shaft misalignment. In a wind turbine, couplings are typically used between the main shaft and the gear box, and between the gearbox output shaft and the generator.

3.3.3.3 Gearbox

Most wind turbine drive trains include a gearbox to increase the speed from the main shaft to the generator. An increase in speed is necessary because wind turbine rotors turn at a much lower speed than that required by most electrical generators. Small wind turbine rotors turn at a speed on the order of several hundred rpm. Larger wind turbines operate more in the range of 10 to 30 rpm. Most conventional generators turn at 1800 rpm (60 hertz) or 1500 rpm (50 hertz). Some gearboxes also perform the secondary function of supporting the main shaft.

The two types of gearboxes most commonly used in wind turbine applications are parallel shaft gearboxes and planetary gearboxes. See Data Sheet 13-7, *Gears*, for a discussion of gearboxes and the general hazards associated with them.

The gearbox is one of the heaviest and most expensive components in a wind turbine, but has experienced high rates of failure in this application. Early gearbox designs were hampered by fundamental gearbox design errors and consistent underestimation of the operating loads. The operating conditions and loads experienced by a wind turbine gearbox are significantly different from most applications because of the dynamic loads. The industry has attempted to address these problems by developing the following standards:

A. ISO/IEC 81400-4:2005, *Wind Turbines Part 4: Standard for Design and Specification of Gearboxes*
B. ANSI/AGMA/AWEA 6006-A03, *Standard for Design and Specification of Gearboxes for Wind Turbines*

Despite reasonable adherence to these accepted design standards, wind turbine gearboxes still have not achieved their design life goal of 20 years. Most systems require significant repair or overhaul well before the intended design life is reached.

Lubrication is a significant consideration in gearbox operation. Lubricants must be selected to minimize wear on the teeth and bearings and to function properly under the environmental conditions in which the turbine will operate. In the case of larger turbines, it may be necessary to provide filtration and active cooling of the oil. To maintain high reliability, it is essential that periodic oil samples be taken and tested to assess the condition of the oil and to check for signs of internal wear. Common issues encountered are additive depletion, dissolved moisture, and particulate contamination. This is an application where a significant benefit would be gained by using an online condition-monitoring system.

3.3.3.4 Mechanical Brake

Most wind turbines use a mechanical break somewhere along the drive train. This type of brake is normally included, in addition to any aerodynamic brake. The mechanical brake can be used (a) as a backup system for the aerodynamic braking system, in which case it must be capable of stopping the rotor from full load, or (b) as a parking brake, once the turbine has idled, as is the case for a pitch-controlled turbine. Pitch-controlled turbines rarely need to activate the mechanical brake (except for maintenance work), since the rotor idles once the rotor blades are pitched to feather or stall.

The brake may be located either on the high-speed shaft or the low-speed shaft. If it is located on the low-speed side of the gearbox, it would require a much higher torque than if located on the high-speed side, resulting in a much larger brake. However, if the brake is located on the high-speed side it will act through the gearbox and, if the gearbox experiences an internal failure, it may not be able to slow down the rotor.

The two types of brakes commonly used on wind turbines are disk brakes and clutch brakes. Another less-common type of brake is a dynamic brake. The basic principle is (after disconnecting the wind turbine's generator from the electrical grid) to feed power to a resistor bank and put a load on the generator. This load puts a torque on the generator and decelerates it.

3.3.3.5 Generator

The generator is the final component of the drive train. This electrical component is addressed in Section 3.4.

3.3.4 Yaw System

The function of the yaw system is to orient the wind turbine relative to the direction of the wind. In normal operation, it is typical to align the turbine with the wind to achieve optimum performance. If the yaw system is being used to regulate power, it may involve turning the rotor away from the wind to reduce power.

The yaw system components used depends on whether the turbine uses free yaw or active yaw. The type of yaw system is usually determined by the orientation of the rotor (upwind or downwind of the tower). Most downwind turbines operate with free yaw. Upwind turbines use an active yaw system. Yaw systems include at least a yaw bearing and also may include a yaw drive (gear motor and bull gear) and a yaw break.

Regardless of the type of yaw system, all HAWTs require some type of yaw bearing. The yaw bearing must carry the weight of the main part of the turbine as well as transmit the thrust loads to the tower. Typically, a slewing ring bearing is used for this application. For free yaw turbines, this may be the only component required.

For an active yaw system, the yaw drive normally consists of an electric motor, speed reduction gears, and a pinion gear. Gyroscopic loads need to be considered in the design of a yaw drive system. The yaw drive speed needs to be reduced so that the yaw rate is slow enough that adequate power can be supplied by small motors.

One problem encountered with active yaw systems has been rapid wear of the yaw drive due to continuous small yaw movements of the turbine. This occurs because of backlash (see Data Sheet 13-7, *Gears*) between the yaw drive pinion and the bull gear. This frequent motion results in many shock load cycles between the gears. A yaw brake is normally used to mitigate this wear issue.

3.3.5 Nacelle

The nacelle includes a main frame (bedplate) that provides support for mounting the components and a means of protecting them from the elements (the nacelle cover). It houses the principal components of the wind turbine, except for the rotor.

3.3.5.1 Main Frame (Bedplate)

The main frame (bedplate) is the structural component that supports the rotor support bearings, gearbox, generator, and mechanical brake. It provides a rigid structure to maintain the proper alignment of these components. It also provides a point of attachment for the yaw bearing, which is bolted to the top of the tower.

The main frame must be capable of transmitting all of the loads from the rotor, and the reaction loads from the generator and mechanical brake, to the tower structure. It also must be rigid enough to limit the relative movement between the rotor support bearings, gearbox, generator, and mechanical brake.

3.3.5.2 Nacelle Cover

The nacelle cover provides weather protection for the components located in the nacelle. These include mechanical and electrical components that would be affected by sunlight, rain, ice, or snow.

Nacelle covers are normally made from fiberglass or other lightweight material to minimize the weight to be supported by the tower. A small number of nacelles include noncombustible construction such as steel. On larger wind turbines, the nacelle is large enough to allow personnel to enter to inspect and maintain the internal equipment. The equipment in the nacelle is cooled by either natural or forced ventilation.

3.3 6 Protection Systems

When an event such as wind speed in excess of cut-off speed, loss of grid connection, generator overload or fault, or excessive vibration occurs, it is necessary to safely shut down the wind turbine. This can be done by using either a failsafe mechanical braking systems or aerodynamic braking systems. As the size of wind turbines has increased, aerodynamic braking systems have become the preferred approach because of the high rotating inertia of the rotor.

Aerodynamic braking systems use the types of control systems discussed in Sections 3.3.1 and 3.3.2.3 to safely shut down the turbine. To utilize these systems for this purpose, it is necessary to provide failsafe systems to shut down the turbine, even if the control system fails. The following examples will describe two failsafe pitch control systems commonly used to safely shut down the turbine.

The first system, shown in Figure 3.3.6-1, uses an electrical blade pitch control system. In this system, two independent electrical systems control the adjustment of the individual blades. The first system is for normal pitch control. It consists of three sets of motor/gear drives arranged in the hub that move the rotor blades together via gear mechanisms. Individual batteries, accommodated in the nacelle, provide backup operational capability for the braking system in the event of loss of electrical power.

The second system, shown in Figure 3.3.6-2, uses a hydraulic blade pitch control system. In this system, two independent hydraulic systems control the adjustment of the individual blades. The first system is for normal pitch control and consists of three hydraulic cylinders arranged in the hub that move the rotor blades together via separate linking mechanisms. Hydraulic accumulators accommodated in the nacelle provide backup operational capability of the braking system in the event of failure of the hydraulic power unit.

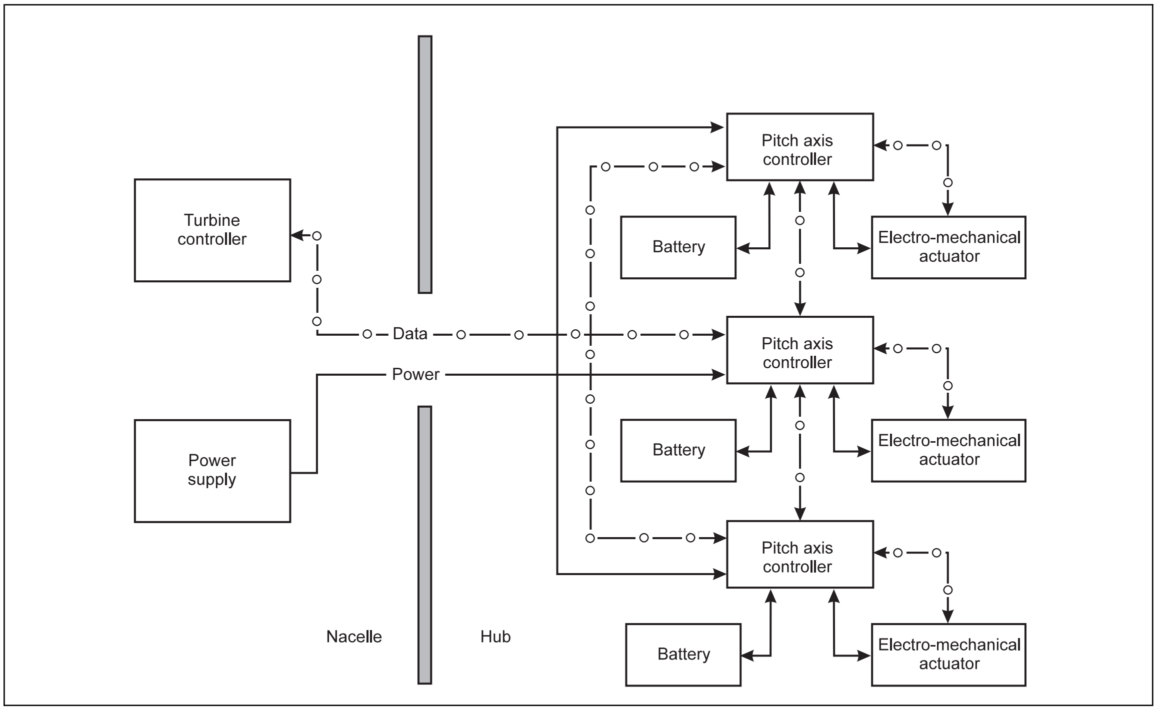


Fig. 3.3.6-1 Electric blade pitch control system schematic

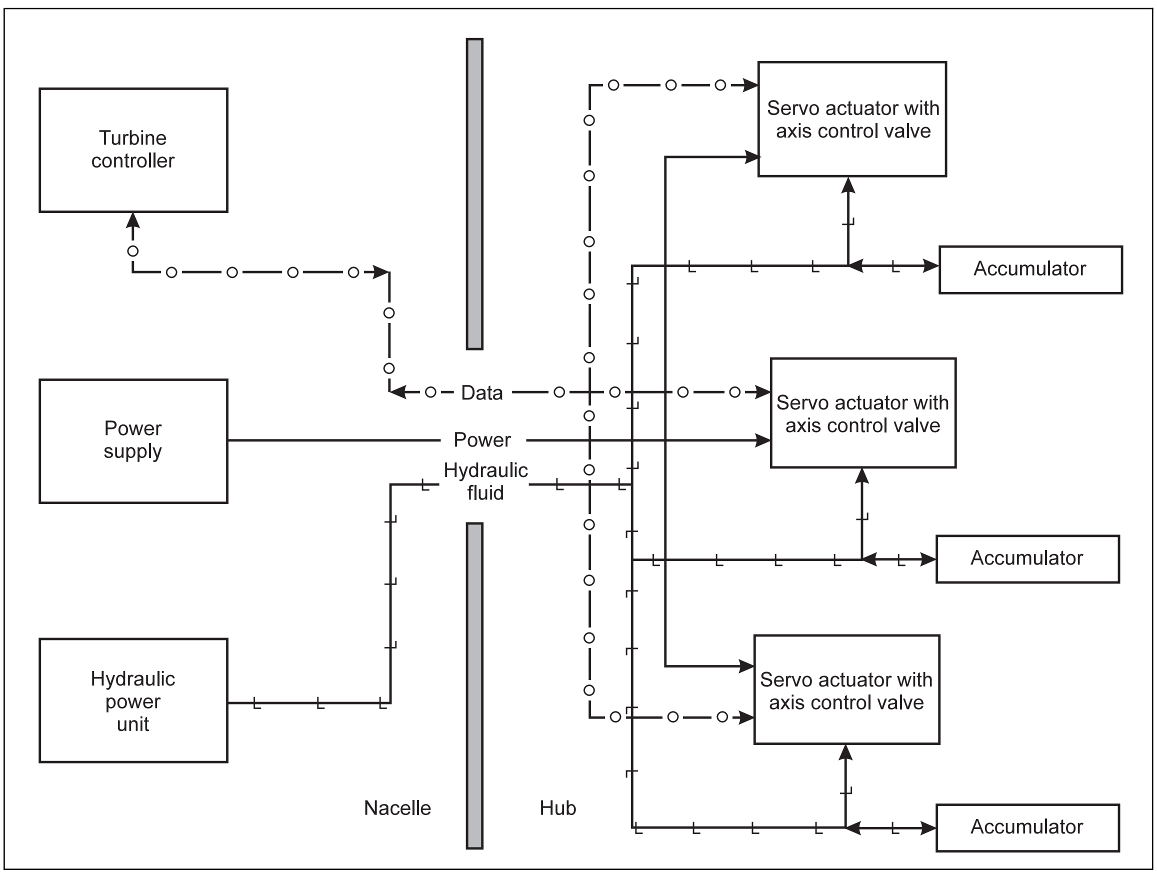


Fig. 3.3.6-2. Hydraulic blade pitch control system schematic

3.4 Electrical

3.4.1 Generator Topology

There are four major wind turbine generator topologies. These topologies are described in Figure 3.4.1.

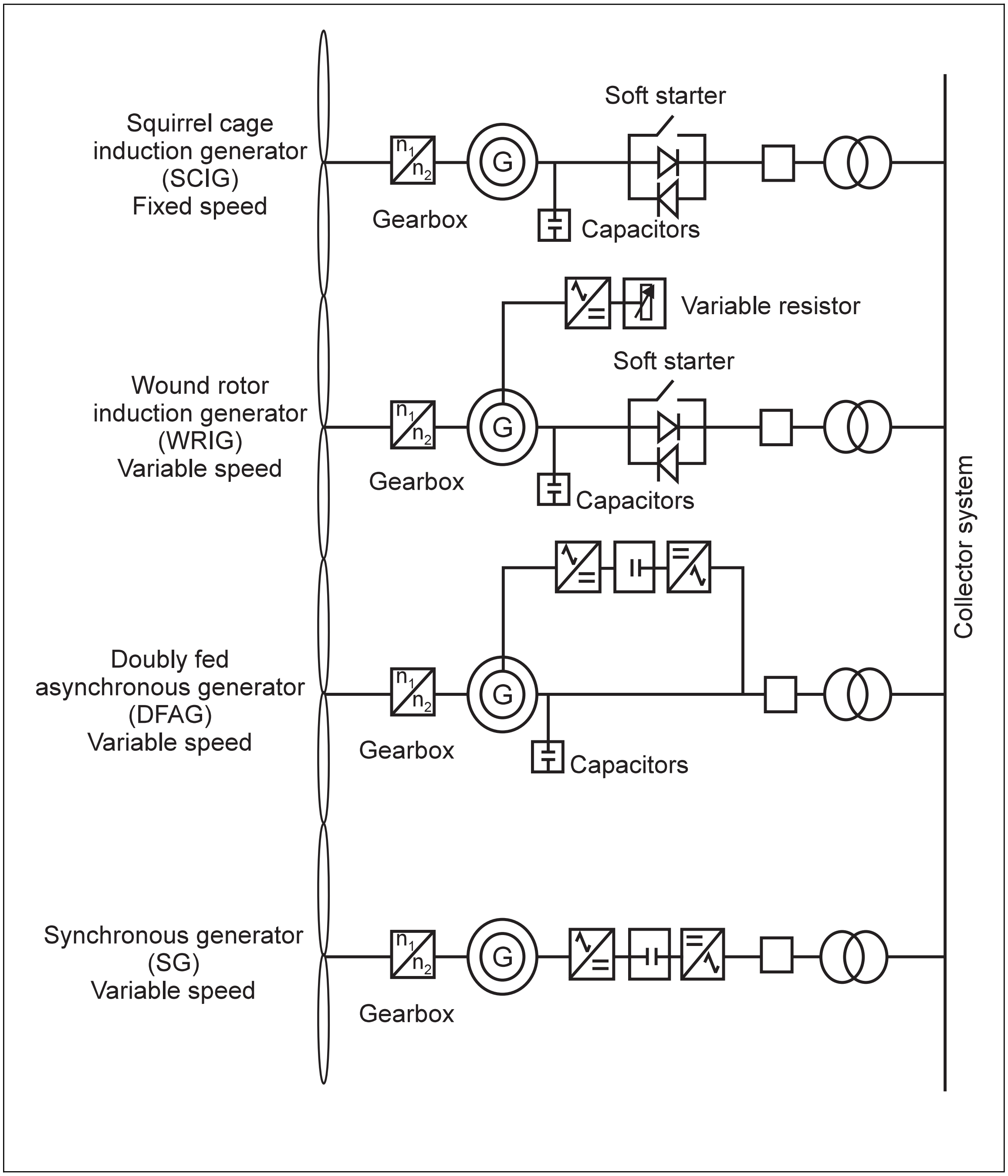


Fig. 3.4.1. Wind turbine generator topologies

3.4.2 Generator Types

Any type of ac or dc generator can be coupled to a wind turbine. Prior to 1995, the two most commonly used generator types were the ac synchronous generator and the ac induction generator. Induction generators used in fixed-speed wind turbines were ordinary squirrel cage machines. Induction generators used in limited variable-speed wind turbines had wound rotors with an adjustable rotor resistance.

After 1995, ac doubly fed asynchronous generators began to dominate the market due to the cost advantages in the sizing of the variable speed converter used to connect this type of generator to the grid. (The rated power of the converter for a doubly fed asynchronous generator only has to be about one third of the rated power of the generator).

Today, it is estimated that doubly fed asynchronous generators account for over 70% of all wind turbine generators. Synchronous generators make up the majority of the rest of wind turbine generators, with squirrel cage induction generators representing a very small portion of wind turbine generators.

Generator voltages are typically less than 1000 V with 440 V, 480 V and 690 V being common generator voltages.

Because induction generators create a lot of heat due to electrical slip, the generators need to be well cooled. Air-to-air heat exchangers are commonly used, where cool air from the outside is blown through a heat exchanger mounted on the generator frame (see Figure 3.4.2).

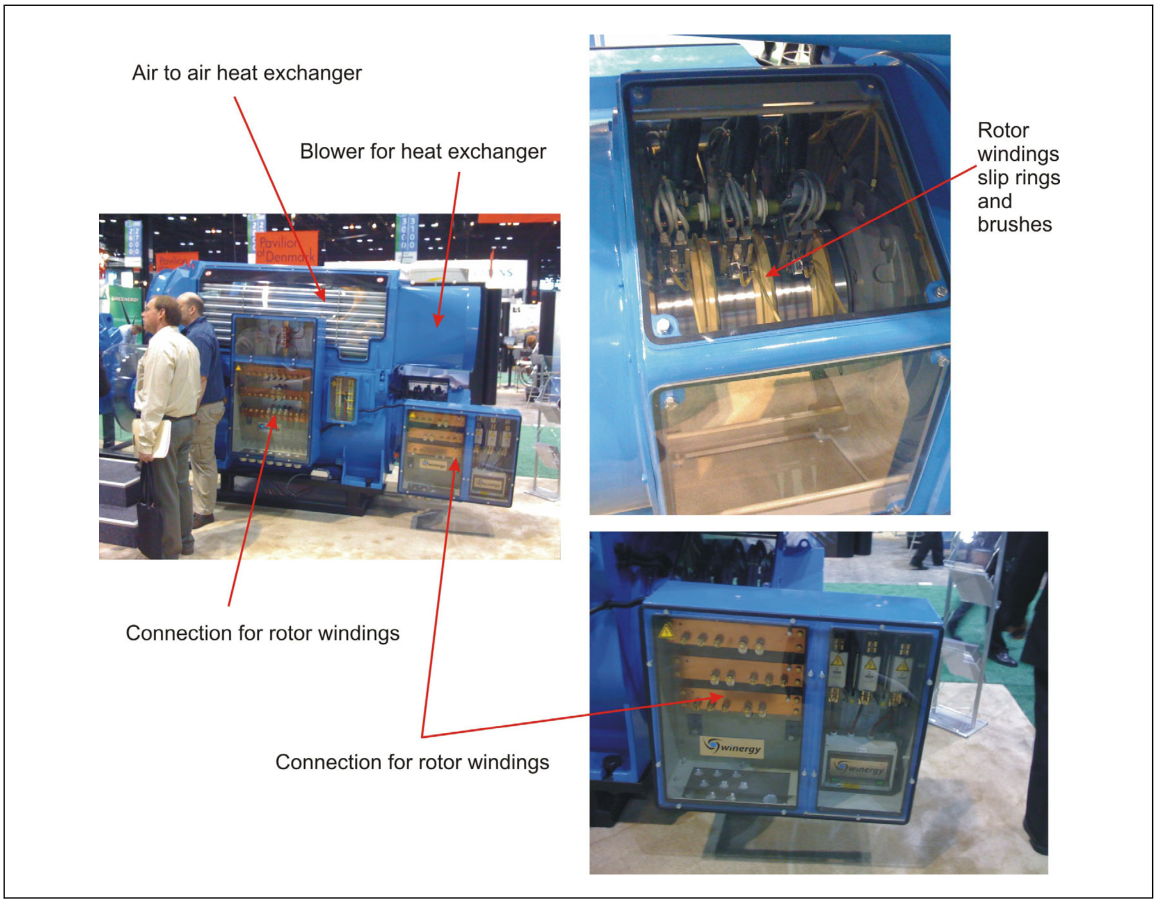


Fig. 3.4.2. A 4-pole, 1800 rpm, 2.0 MW doubly fed asynchronous generator with an air-to-air heat exchanger

3.4.3 Power Electronics

Synchronous generators will have a full, back-to-back, ac to ac converter that connects the generator to the grid. The two converters in this back-to-back arrangement are commonly called “machine-side” and “line-side” converters. The machine-side converter rectifies the variable frequency and variable magnitude ac power from the generator stator into dc power. This dc power is then inverted by the line-side converter to a fixed frequency, fixed magnitude ac power for transmission to the grid. The machine-side converter also supplies DC excitation power for the rotor windings. The synchronous generator's reactive power is controlled by varying the excitation power.

Doubly fed asynchronous generators also have a back-to-back, ac to dc converter. However, this converter only handles the power from the rotor for transmission to the grid. The power from the stator is directly connected to the grid. Therefore, the converters for doubly fed asynchronous generators only need to be sized for about one-third of the generator power. The machine-side converter for the doubly fed synchronous generator also supplies magnetization current for the stator core and controls the reactive power from the generator. These two requirements mean the diode or thyristor rectifiers cannot be used on the machine-side converter; instead GTO and IGBT rectifiers have to be used.

Figure 3.4.3-1 shows examples of the power electronics for the synchronous generator and the doubly fed asynchronous generator.

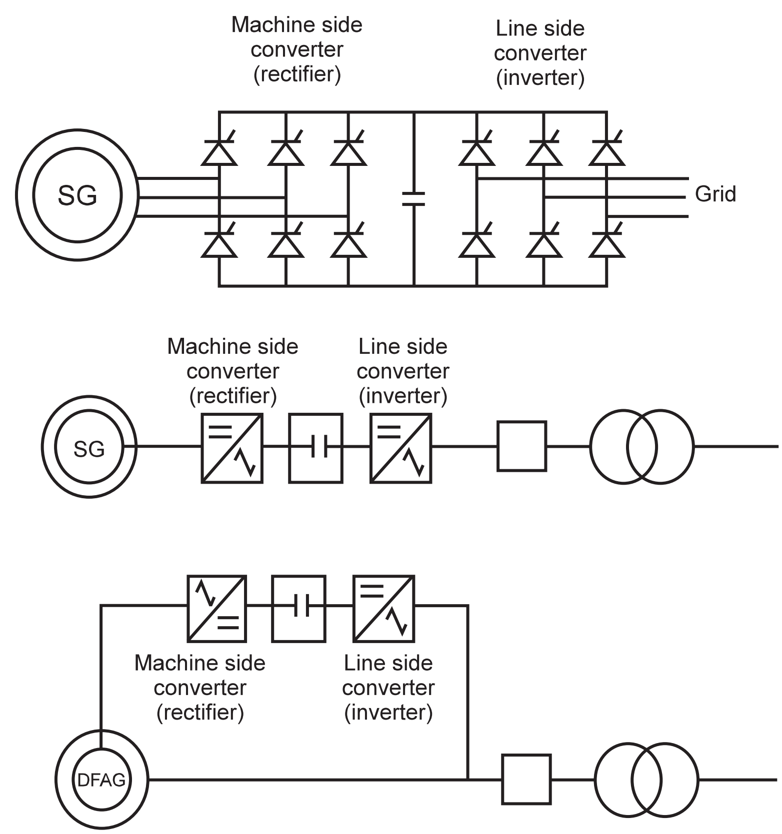


Fig. 3.4.3-1. Power electronics for synchronous and doubly fed asynchronous generators

Induction generators and wound rotor induction generators are supplied with a soft starter to allow the generator to be smoothly connected to the grid (by reducing the generator in-rush current). The soft starter consists of two SCR's connected anti-parallel, in each phase. By controlling the firing angle for the SCR's the in-rush current can be controlled. The soft starter is bypassed after the in-rush period is over to reduce losses.

The power electronics for a wind turbine are controlled by PLC's or microprocessor based controllers. These PLC's and controllers are either standalone or interconnected as part of a DCS or SCADA system for the wind farm.

Fig. 3.4.3-2. A 1.5MW doubly fed asynchronous generator connected to an air cooled, IGBT with PWM power converter

3.4.4 Transformer Types

Wind turbine transformers are typically off-the-shelf distribution pad-mount transformers. They are used to step up the wind turbine generator's low voltage to a medium voltage for distribution to the collector substation. These off-the-shelf, distribution pad-mount transformers are easily replaced.

These transformers are usually located at ground level. In North America, they are located on a pad a short distance from the base of the tower. Outside North America, they may be located inside the base of the tower.

Some wind turbines may use dry-type transformers or Nomex insulated, silicone-filled transformers if fire or environmental risk due to transformer fires is a concern. These transformers are not usually off-the-shelf equipment and may be harder to replace. These transformers may also be located in the nacelle and could require special equipment and rigging to replace.

The collector substation transformers are usually fluid filled power transformers sized for the wind farm load, with the right voltage ratio to connect the wind farm to the transmission grid.

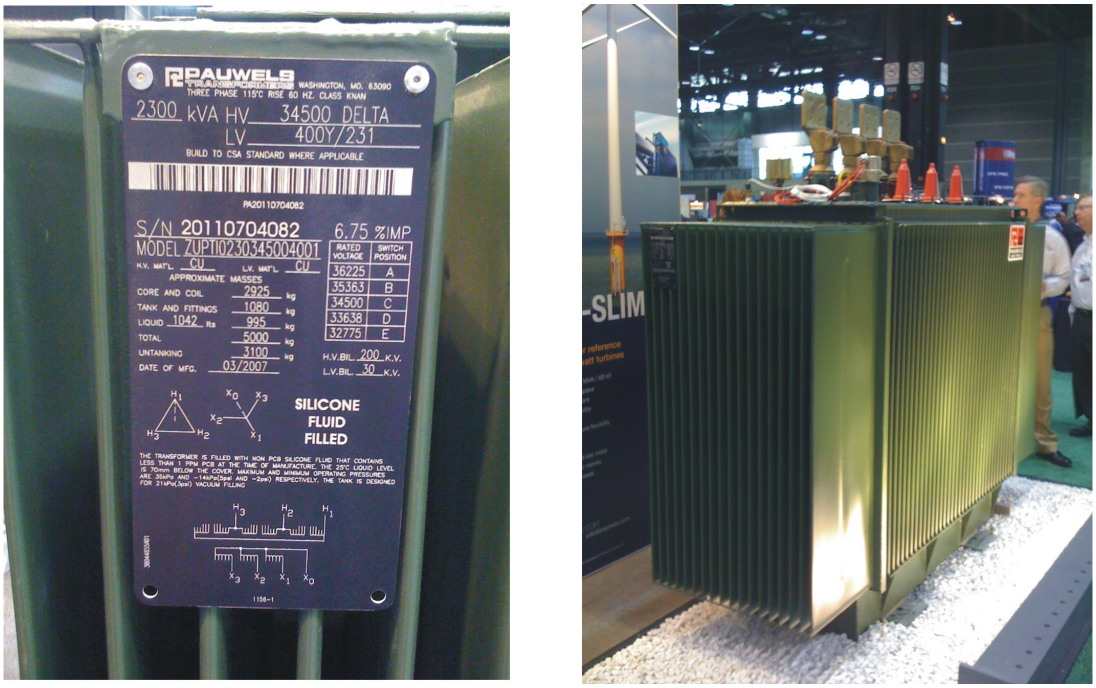


Fig. 3.4.4. A 2,300 kVA, 34.5kV/400V, Nomex insulated, silicon filled wind turbine generator transformer.

3.4.5 Grid Interconnection Requirements – Impact on Risk

As wind farms become larger in size, they can have a significant impact on the operation of the power grid and can affect power system stability, security and reliability. To manage this, regulators impose grid interconnection requirements that govern how wind farms interact with the power grid during system disturbances. These requirements may have an adverse impact on wind turbines and should be carefully investigated.

3.4.6 Auxiliary Power

Auxiliary power is required in the nacelle to operate the following systems:

A. Yaw control systems and drives
B. Pitch control systems and drives
C. Ventilation and cooling systems (e.g., cooling fans and pumps for the slip ring enclosure, generator heat exchanger, transformer, converter, nacelle, lubrication oil)
D. Heater systems (e.g., slip ring enclosure, generator enclosure, lubrication oil, nacelle heating)
E. Lubrication oil pumps
F. Hydraulic oil pumps
G. Communications, protection, and control systems
H. Instrumentation and sensors (e.g., voltage, current, wind speed, wind direction)
I. Battery chargers for uninterruptible power sources
J. General purpose and navigation lights

For low-voltage wind turbine generators, auxiliary power is typically provided directly from the generator terminal connections. Small transformers may also be provided to obtain special control voltages to operate the various systems in the nacelle. When the generator is not in service, the wind turbine generator transformer can back-feed auxiliary power to the wind turbine from the grid (see Figure 3.4.6-1).

For medium-voltage generators, a separate source of low-voltage power, a dedicated auxiliary transformer supplied from the generator, or a three-winding wind turbine transformer may be provided (see Figure 3.4.6-2).

Loss of grid power can result in loss of auxiliary power. Some manufacturers provide battery backup for critical systems, such as pitch control, as well as protection and control systems. The duration of this battery backup is decided between the manufacturer and the wind farm owner. Longer durations of backup power will require more batteries, and it may not be practical or cost-effective to provide a large number of batteries. Supplemental backup power in the form of diesel emergency generators supplying the entire wind farm may be provided.

The auxiliary power load demand for a typical 1.8 MW doubly fed asynchronous wind turbine generator with hydraulic pitch control and electric yaw motors is about 50 kW. The main loads are the hydraulic motor (20 kW), yaw motors (10 kW), heating systems (12 kW), lubrication oil pumps (3 kW), and transformer no load loss (4 kW). This is the load needed for an operating wind turbine. The load needed to keep an idle wind turbine in a safe condition will be much less.

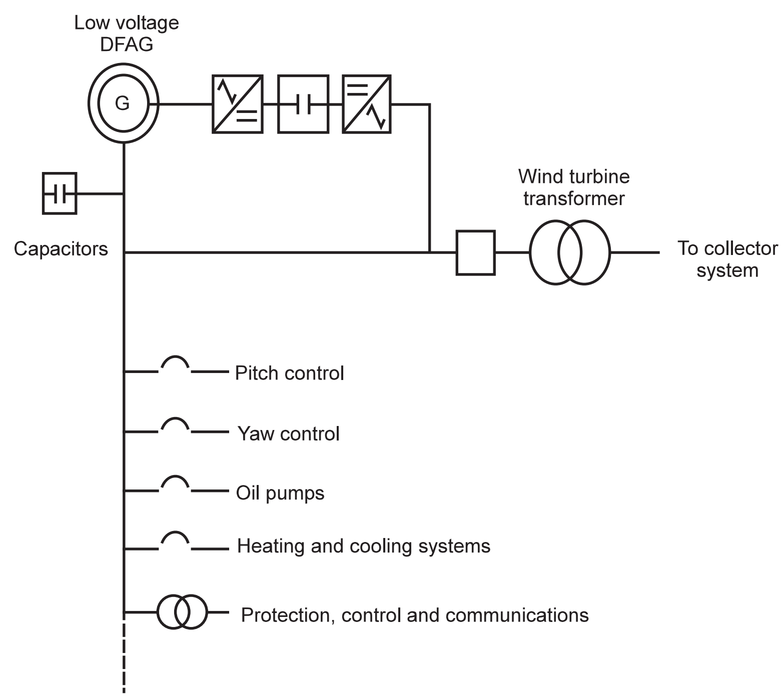


Fig. 3.4.6-1. Auxiliary power supply for low-voltage generator

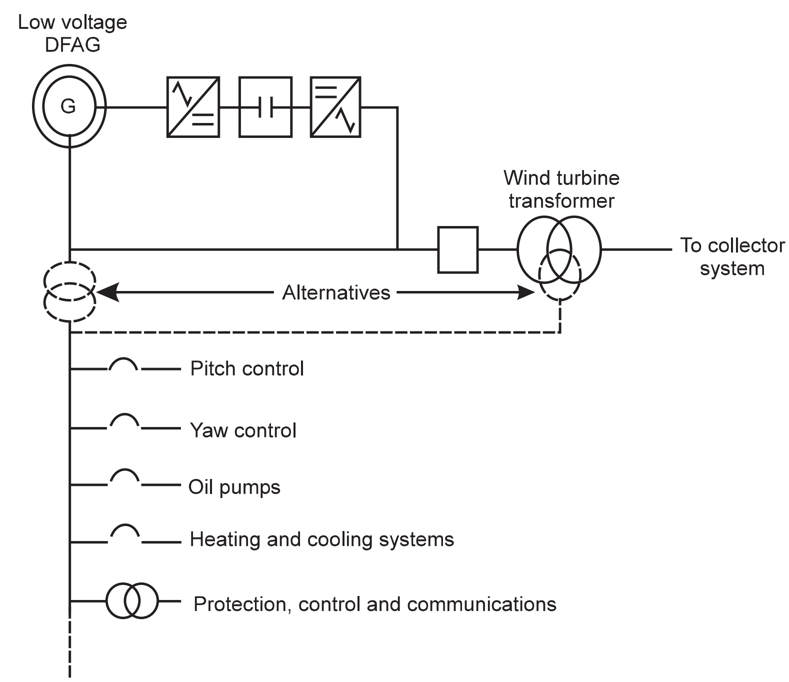


Fig. 3.4.6-2. Auxiliary power supply for medium-voltage generator

3.4.7 Lightning Protection

Lightning protection is usually provided based on an assessment of the isokeraunic level as well as the criticality of the equipment and systems be protected. However, this approach may not be applicable to wind farms because the wind turbines themselves may alter the propensity of lightning strikes. Therefore, FM Global recommends lightning protection be provided for all wind turbine blades, nacelles, gearboxes, bearings, towers, electrical equipment, and systems regardless of the isokeraunic level.

Common industry practice is for OEMs to provide wind turbines with an integrated lightning protection system from the blade tip right through to the foundation. Lightning strikes are thus normally discharged without causing damage to the rotor blade or other turbine components. The rotor blade is provided with conductive lightning receptors at the tip and along the side of the blade that are connected to the lightning protection ring (discharge ring) at the blade root. The lightning strike is normally discharged primarily via the lightning protection ring and rod or rolling cylinder. The lightning current is then conducted via coper cables (down conductors) into the ground surrounding the foundation. Normally, lightning strikes up to 200,000 A can be absorbed by these systems.

Lightning damage to the gearbox and bearings occurs when lightning current flows through the bearings or gears to ground. This can generate arcing and heating damage to the bearing and gear surfaces. Protection against this damage can be achieved by providing an alternative path for lightning current to flow that does not include bearing and gear surfaces. One possible solution is to insulate all bearing pedestals, provide an insulating coupling between the drive shaft and the generator shaft, and use a grounding brush to conduct lightning current from the hub to down conductorco

Lightning strikes can cause incremental damage to blade lightning attachment points, and this damage is considered a major contributor to LPS underperformance.

Lightning protection for electrical equipment and systems is achieved through the use of standard overvoltage protection practices such as proper grounding and bonding, shielding of cables and equipment, surge arrestors, and transient voltage surge suppressors.

3.4.8 Failure Modes (Electrical)

Many of the failure modes for induction generators and synchronous generators used in wind power applications are common to motors and generators used in industrial and utility applications. These failure modes are discussed in Data Sheet 5-17, *AC Motors and Drives*, as well as in Data Sheet 5-12, *Electric AC Generators*.

There are, however, some failure modes that are unique to double fed asynchronous generators used in wind turbine applications. These failure modes are:

- Failure of rotor end winding banding, rotor coil lead connections due to mechanical stresses arising from the following factors:
- A harsh operating environment with extreme temperature fluctuations, foreign and corrosive contaminants, as well as periods of high humidity
- Frequent load fluctuations due to the variability of wind;
- The same stresses also contribute to premature failure of the stator and rotor winding insulation as well as other components of the generator including the power converter
- Premature failure of the rotor winding insulation due to voltage spikes generated by pulse width modulated power converter supplying the rotor current
- Premature failure of the slip ring insulation due to the same voltage spikes generated by the power converter leading to slip ring flashovers and arcing
- Premature wear of carbon brushes due to the high harmonic content of the rotor current
- Slip ring flashovers due to high levels of carbon dust generated by the fast-wearing brushes
- Harmonic current-induced failures of the non-driven end bearing due to the converters used to supply rotor current
- Bearing and insulation failures due to the additional mechanical stress imposed by the 3 to 5 degree tilt of the generator foundation

Wind farm owners found that early off-the-shelf DFAGs used in wind power applications needed to be rewound after about 3 to 5 years due to these premature failures.

Generator manufacturers have learned from these early failures and made the following improvements to their product.

- New slip ring brush material with improved resistance to harmonics
- Improved bearing and slip ring insulation
- Improved materials for stator and rotor winding insulation systems
- New certification processes and qualification testing of generators to prove their performance in harsh wind power applications, including fatigue vibration stress generated by wind turbulence

Some additional technologies are:

- Permanent magnet generators
- Multiple generators driven by a single planetary gearbox (e.g., Clipper design shown in Figure 3.4.8)
- Directly connected salient pole, synchronous generators
- Directly connected synchronous generators driven by a Voight coupling
- Medium-voltage generators
- Large (5 MW and 10 MW class), medium-voltage generators utilizing high-temperature superconducting material for the stator and rotor windings
- New reactive and active power control systems to allow the wind farm to behave more like a conventional fossil fuel fired generating station
- Energy storage systems to allow more efficient dispatch of wind energy

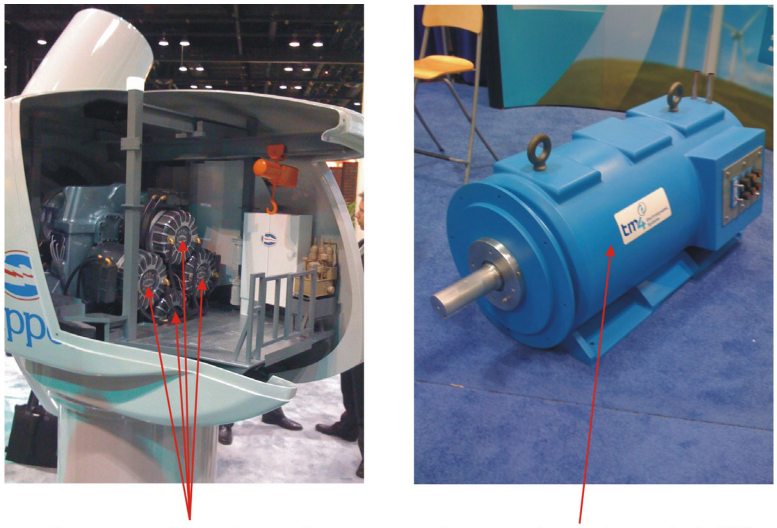


Fig. 3.4.8. A 660 kW Megaflux permanent magnet generator, and four of these generators used in the Clipper 2.5 MW Liberty wind turbine

3.4.9 Submarine Cable and Offshore HVAC Substations in Offshore Wind Farms

In general, there are three options to be used for connecting an offshore wind farm to the main electrical grid on shore, partly depending on the number and size of the wind turbines:

- Medium voltage alternating current up to about 36 kV
- High voltage alternating current (HVAC), generally from 100 kV to 200 kV
- High voltage direct current (HVDC) up to about 500 kV past 500 kV the connectors may not yet be developed of sufficient reliability.

The voltage output from an individual wind turbine is usually stepped up by an internal transformer to medium voltage level such as 36 kV to reduce transmission losses. In general, for wind farms less than 100 MW and less than about 15 km to shore it directly uses multiple medium voltage AC cables connected to wind turbine transformers to a shore substation. No offshore substation is needed. For higher output or greater distances, it usually connects the individual turbines with in-field cables to an offshore transformer substation to step up the voltage to a higher voltage first. Then the electricity is connected to shore through HVAC export cables. As the distance increases, such as more than 35 km for AC transmission, a significant amount of reactive power will use up much of the capacity in the cables such that an HVDC offshore substation becomes more economical to use. The electricity is transmitted to shore through HVDC export cable. However, the application of offshore HVDC substations is not as common as offshore HVAC substations.

3.4.9.1 Subsea Cable

There are two types of subsea cables in off-shore wind farms: (1) the cables installed between individual wind turbines and the substation (in-field cable), and (2) the subsea cable connecting the offshore substation and the onshore substation (export cable). The cable between offshore wind turbines in-field is typically around 36 kV AC, and the export cable is typically 132-245 kV for the transmission of the power from the offshore substation to the onshore grid. Export cables for wind farms are usually very much longer and larger in dimensions than in-field cables between wind turbines and consequently require different installation and protection considerations. Depending on the power and need for redundancy, the export cable may be selected as either single or multiple cable separated by a distance.

3.4.9.2 Offshore HVAC Substations

Offshore HVAC substations are generally used for large wind farms with capacity bigger than 100 MW and distance to shore greater than 33,000 ft (10 km). Their function is to step up the MV voltage of the inter-array network to a higher voltage, such as 138 kV. Then the electricity is connected to shore through HVAC export cables.

The basic electrical design of offshore HVAC substations is close to land-based substations. However, they face the challenge of corrosive working environment due to moisture and salt. Figure 3.4.9.2 shows several examples of installed offshore substation.

Nysted, Denmark
165 MW
750 tonnes
Tide range less than 3.3 ft (1 m)
Low wave height
Gravity foundation
No helicopter deck

Horns Rev, Denmark
160 MW
Tide range: 16 ft (5 m)
Medium wave height
Multi-pile foundation
Helicopter deck

Holland
120MW
650 tonnes
Tide range: 20 ft (6 m)
High waves
Monopile foundation
No helicopter deck

Fig. 3.4.9.2. Examples of installed offshore substations (Courtesy of Siemens Energy)

The major components in offshore substations are listed below:

- Step-up main transformers (a typical offshore substation houses two main power transformers sharing the load)
- Auxiliary transformers
- HV switchgears
- MV switchgears
- Cables/busbars (all busbars are usually housed in grounded metal enclosures sealed and filled with sulfur hexafluoride gas [SF6])
- Emergency power generators
- Control and protection devices
- Power-factor correction system (in some cases, this system is located in an on-shore substation connected to the off-shore substation)

The transformer platform itself is of high value to the electricity generating capability since many or all of the turbines will feed electricity through it. Failure of the transformers is the major risk for the platform.

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Data Sheet 1-28, *Wind Design*
Data Sheet 1-34, *Hail Damage*
Data Sheet 1-40, *Flood*
Data Sheet 1-54, *Roof Loads for Drainage*
Data Sheet 2-81, *Fire Protection System Inspection, Testing and Maintenance*
Data Sheet 4-1N, *Fixed Water Spray Systems for Fire Protection*
Data Sheet 4-5, *Portable Extinguishers*

Data Sheet 5-4, *Transformers*
Data Sheet 5-11, *Lightning and Surge Protection for Electrical Systems*
Data Sheet 5-17, *Motors and Adjustable Speed Drives*
Data Sheet 5-19, *Switchgear and Circuit Breakers*
Data Sheet 5-20, *Electrical Testing*
Data Sheet 5-31, *Cables and Bus Bars*
Data Sheet 5-32, *Data Centers and Related Facilities*
Data Sheet 5-48, *Automatic Fire Detection*
Data Sheet 7-83, *Drainage Systems for Ignitable Liquids*
Data Sheet 9-0, *Asset Integrity*
Data Sheet 9-19, *Wildland Fire*
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APPENDIX A GLOSSARY OF TERMS

Allowable Stress Design (ASD): A structural design method where design loads are the same as the characteristic loads that is, no load factors are used. The resultant safety factors are dependent on reductions made to material yield, tensile, rupture, or fracture stresses in order to obtain allowable design stresses.

Anemometer: A device used to determine the speed of the wind.

Atmospheric Icing: Ice from freezing rain, snow, in-cloud icing, or icing from sea spray, that can accumulate (accrete) on wind turbine blades or other components.

Basic Wind Speed: The wind speed at 33 ft (10 m) above grade in open terrain or Exposure Category C. Refer to Data Sheet 1-28, *Wind Design*, for additional information. The basic wind speed is a specific type of extreme wind speed used for wind turbine design.

Blade Pitch: The rotation of the rotor blade along its longitudinal axis. Variation in blade pitch is used to regulate rotor speed for optimal power production and is also used for aerodynamic braking of the rotor by adjusting the blade pitch to either the stalled or feathered blade positions.

Capacity Factor: The percentage of actual power generation compared to the theoretical maximum power generation based on rated capacity. For example, if a 3.0 MW rated turbine produced 18 MWh per day on average, the capacity factor (CF) would be 25% (3 MW x 24 hours x 0.25 = 18 MWh).

Cathodic Protection: The protective system used by which the protected material is made a cathode by using either sacrificial anodes or impressed current systems; this includes impressed current systems and sacrificial anode systems.

Design Load Case(s): The design load cases prescribe load conditions, type of analysis, and partial safety factors (load factors) used for the required design situations and load combinations, and are intended to ensure adequate structural and mechanical performance. The design situations include power production; startup; shutdown; parked or idle rotor; and transport, assembly, maintenance, and repair. Some design situations also require consideration of a fault occurrence, such as an electrical fault or loss of yaw control. The wind turbine design must meet or exceed all design load cases, and different design load cases can govern the design of the various wind turbine components. Design load cases are usually provided in industry standards or local codes, with IEC 61400-1 (land-based wind turbines) and IEC 61400-3 (offshore wind turbines) being two of the most widely used. IEC 61400-1 includes 22 design load cases categorized into eight design situations, while IEC 61400-3 includes 34 design load cases categorized into eight design situations. Some design load cases from the applicable industry standards are modified in this data sheet to provide the recommended level of performance.

Extreme Wind Speed: The wind speed based on the 50-year mean recurrence interval (MRI) and used for many extreme wind model (EWM) load cases. The reference wind speed (V_{ref}), on which the wind turbine class is based, is an extreme wind speed. Basic wind speed (V) is an extreme wind speed. Extreme wind speed can also be known as survival wind speed.

Extreme Wind Speed Model (EWM): The design model that uses extreme or survival wind conditions, which are based on the Basic Wind Speed (V). The design loads associated with the EWM apply to design situations where the wind turbine is either parked (rotor standing still or idle), being assembled, or under repair or maintenance. EWM does not apply to design situations associated with power production, startup, or shut down modes.

Hub Height: The height of the rotor hub above grade (above ground) for land-based wind turbines, or above mean sea level for offshore wind turbines.

Ignitable Liquid: Any liquid or liquid mixture that will burn. A liquid will burn if it has a measurable fire point. Ignitable liquids include flammable liquids, combustible liquids, inflammable liquids, or any other term for a liquid that will burn.

Jacket, or Jacket Substructure: A heavy-duty trussed substructure, often used to support large offshore substations and sometimes large offshore wind turbines. Typically consisting of four support legs with trussed cross members and supported on four seabed piles.

J-tube: A tube used in offshore installations to enable submarine cable to be installed by pulling it up from the seabed to the wind turbine support structure or platform.

Lightning Protection Systems (LPS): A combination of air terminations (e.g., lightning receptors or lighting attachment points), insulation, shielding, conductors, connectors, wire mesh, slip rings, spark-gaps and surge protection devices. LPS are comprised of multiple smaller systems, blades, hubs, nacelle, tower and tower bases all arranged to safely conduct lightning currents to the grounding system.

Load Case: See Design Load Case

Load Factor: See Partial Safety Factor

Load and Resistance Factor Design (LRFD): Also known as Strength Design, or ULS design. A structural design method where design loads are obtained by applying a load factor (partial safety factor) to the characteristic loads; also, a resistance factor is applied to the material strength. The load factors are based on a probabilistic approach. A simplified approach is to compare structural demand (load) versus structural capacity (resistance): Factored Load Effects less than or equal to Factored Resistance.

Mean Sea Level (also Mean Water Level): The mean still water level between the highest and lowest astronomical tides.

Mean Recurrence Interval (MRI): The return period, in years, associated with an annual probability of exceedence. For example, for wind speed with an annual probability of exceedance of 2%, the MRI is approximately 50 years, and the event would be commonly labelled the “50-year wind speed.”

Nacelle: The enclosure that houses the rotor shaft and bearings, gearbox, generator, hydraulic systems, braking systems, pitch and yaw mechanisms, and sometimes the transformer. The nacelle typically has an FRP or composite plastic enclosure.

Partial Safety Factor: The factor applied to the characteristic (unfactored) load to determine the design (factored) load. The partial safety factor makes up a substantial portion of the overall safety factor.

Pitch: The position or movement of the wind turbine blade about its longitudinal axis.

Overburden: The soil located over, and within the projected vertical footprint of, the foundation footing that is used to provide some resistance to uplift and overturning of the footing.

Reduced Wind Speed Model (RWM): Similar to the EWM but with reduced wind speeds used concurrently with extreme wave height loads (applicable to offshore wind turbines only).

Rotor: Includes the rotor blades and rotor hub assembly.

Sand Wave: Movement of seabed sediments due to wave action and/or water currents.

Scour: Removal or movement of seabed or lakebed soils by currents or waves caused by structural or other elements interrupting the natural flow regimen above the sea/lake floor.

Shallow Water Wind Farm: A wind farm where the water depth (from sea floor to mean sea level) does not exceed approximately 100 ft (30 m).

Splash Zone: Region of the support structure or equipment that is intermittently wetted by tidal and/or wave action and therefore exposed to a severely corrosive environment. The splash zone upper bound is defined as the 1-year MRI significant wave height added to the highest 1-year MRI still water level, and the lower bound is defined as the 1-year MRI significant wave height subtracted from the lowest 1-year MRI still water level.

Still Water Level: Water level that includes tidal and storm surge effects but excludes variations due to wave action.

Subsea Cables:

(1) Inter-array cable, also called in-field cable: the cable installed between individual wind turbines and the substation. The inter-array cable is typically around 36 kV AC.

(2) Export cable: the submarine cable connecting the offshore substation and the onshore substation. The export cable is typically 132-245 kV.

Substructure: Portions of the offshore wind turbine support structure below the tower and above the seabed; typically includes the transition piece (transition section) and foundation.

Surface Roughness: Refer to FM Global Data Sheet 1-28.

Swept Area: The area of the circle circumscribed by the tips of the rotor blades.

Topside: Refers to the portion of the offshore wind turbine above the substructure.

Transition Piece (Transition Structure): Portion of the offshore wind turbine support structure that connects the tower to the foundation.

Transitional Water Depth Wind Farms: Offshore wind farm locations where the water depth is deeper than for a shallow water wind farm but less than 150 ft (46 m).

Tropical Cyclone-Prone Regions: Refer to Data Sheet 1-28.

Ultimate Limit States Design (ULS): Similar to LRFD, but generally pertains to structural design methods used outside the United States; for example, in Canada, the UK, and Europe.

Vane: A device used to determine the direction and/or change in direction of the wind.

Wave Height: The vertical distance from the highest point (wave crest) to the lowest point (wave trough) of a wave.

Wind Shade (wind shadow): The downwind zone where increased turbulence and other effects are caused by wind flow over an obstruction. For a downwind HAWT, the rotor blades can be affected by the wind shade caused by the support tower.

Wind Shear: The phenomenon where wind speed increases at greater heights above the ground or water.

Yaw: The rotation of the nacelle and rotor about the vertical axis of the support tower for HAWT. Yaw rotation allows the nacelle and rotor to adjust for changing wind directions. Active yaw systems require power to adjust yaw direction of the nacelle and rotor. For passive yaw systems, the nacelle and rotor are free to adjust (without power) to the prevailing wind direction similar to the passive yaw tracking of a wind vane.

Abbreviations and Acronyms

CF: Capacity Factor.

CM: Condition monitoring

D: Diameter of the rotor.

DLC: Design load case

FRP (fiber-reinforced plastic): the material often used for the construction of wind turbine blades and nacelle enclosures.

GL (Germanischer Lloyd): An organization based in Germany that develops guidelines associated with wind turbine design and certification.

IEC (International Electro-Technical Commission): An organization based in Switzerland that develops many of the standards and guidelines associated with wind turbines.

I_w: Wind load importance factor.

H: Height of the wind turbine hub above grade (for land-based) or above mean sea level (for offshore).

L_w: Partial safety factor (load factor) for wind load.

MSL: Mean sea level.

MW: Megawatt.

MWh: Megawatt-hour.

NDE: Nondestructive evaluation.

NREL (National Renewable Energy Laboratory): The US Department of Energy laboratory that conducts much of the research in the United States related to renewable energy, including wind turbines.

OEM: Original equipment manufacturer.

SCADA: Supervisor control and data acquisition.

T: Fundamental natural period (seconds) of a structure or structural member.

WSD: Working stress design: similar to ASD, but generally pertains to structural concrete (see ASD).

APPENDIX B DOCUMENT REVISION HISTORY

The purpose of this appendix is to capture the changes that were made to this document each time it was published. Please note that section numbers refer specifically to those in the version published on the date shown (i.e., the section numbers are not always the same from version to version).

July 2023. Interim revision. The following significant changes were made:

A. Updated recommendations for lightning protection and lightning detection systems.

B. Added recommendations for a blade damage tracking and rating system based on EPRI publicly available guide.

C. Updated recommendations for mechanical and electrical inspection, testing and maintenance frequencies.

July 2022. Interim revision. Minor editorial changes were made.

July 2021. Interim revision. The following significant changes were made:

A. Changed the title of the data sheet from “*Wind Turbines*” to “*Wind Turbines and Farms*.”

B. Updated recommendations to reflect current industry practice.

C. Added tower and blade inspection recommendations.

July 2020. Interim revision. Updated contingency planning and sparing guidance.

January 2013. Added guidance and recommendations for offshore wind turbines.

April 2012. Terminology related to ignitable liquids has been revised to provide increased clarity and consistency with regard to FM Global’s loss prevention recommendations for ignitable liquid hazards.

January 2012. This is the first publication of this document.

APPENDIX C SUPPLEMENTARY INFORMATION

C.1 Size and Power of Typical Wind Turbines

The physical sizes of wind turbine towers and rotor blades, and the available power capacity of the turbines themselves, have increased over the years. See Tables C.1-1 and C.1-2 for an approximate summary of the maximum commercially-available sizes and rated power of land-based and offshore wind turbines.

Table C.1-1. Available Power and Size of Land-Based Wind Turbines

	Year						
	1981	1985	1990	1995	2000	2005	2012
Rotor Diameter, ft (m)	33-50 (10-15)	55-65 (17-20)	80-115 (24-35)	130-165 (40-50)	165-200 (50-60)	245-260 (75-80)	295-330 (90-100)
Hub Height, ft (m)	65 (20)	100 (30)	115-130 (35-40)	165 (50)	200 (60)	260 (80)	280-330 (85-100)
Rated Power (kW)	25-50	75-100	225-300	500-600	750-850	1500-2200	2500-3000

Table C.1-2. Available Power and Size of Offshore Wind Turbines

	Year			
	1990-1995	2000	2005	2012
Rotor Diameter, ft (m)	130-165 (40-50)	165-230 (50-70)	245-280 (75-85)	295-410 (90-125)
Hub Height, ft (m)	200 (60)	245 (75)	280 (85)	280-330 (85-100)
Rated Power (kW)	500-1500	1000-2000	3000-2000	3500-5000

Refer to Figures C.1-1 and C.1-2 for typical land-based and offshore HAWT components and schematics.

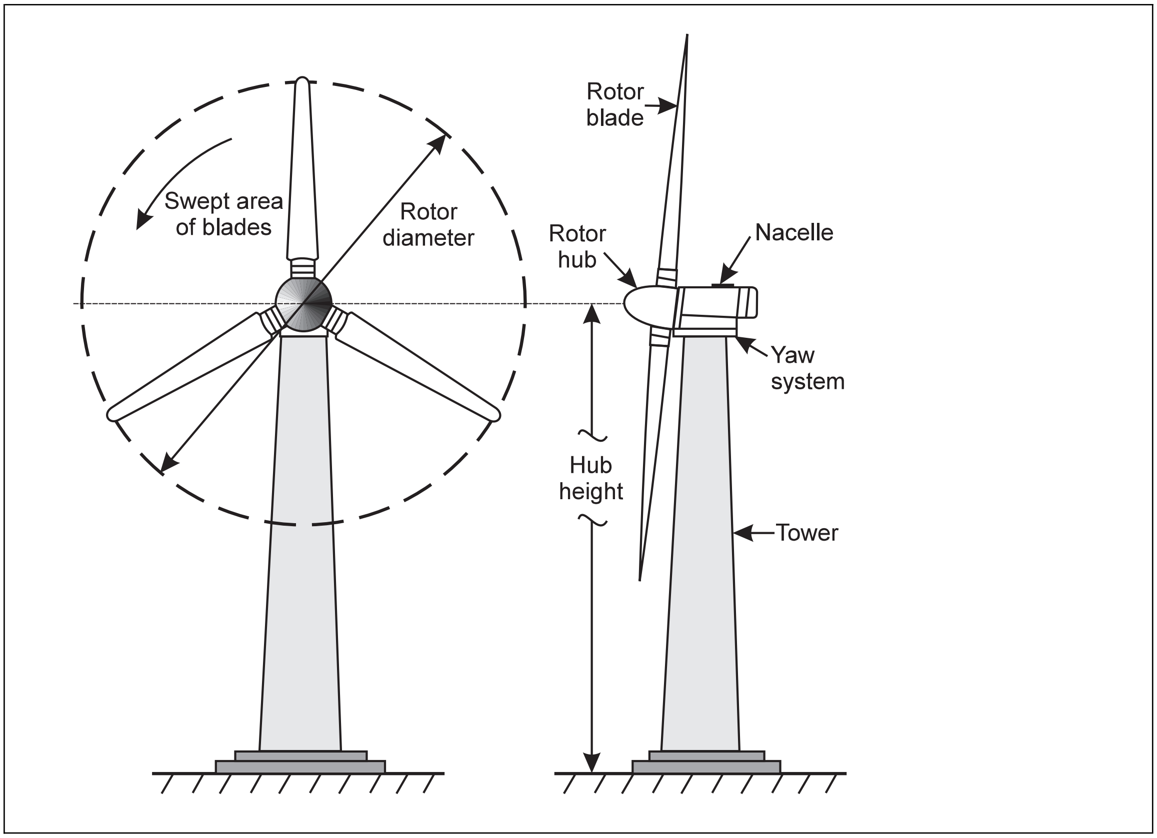

Fig. C.1-1. Typical land-based horizontal axis wind turbine (HAWT) with a conical steel (steel monopole) support tower (foundation, instrumentation [e.g., anemometer] and lighting not shown)

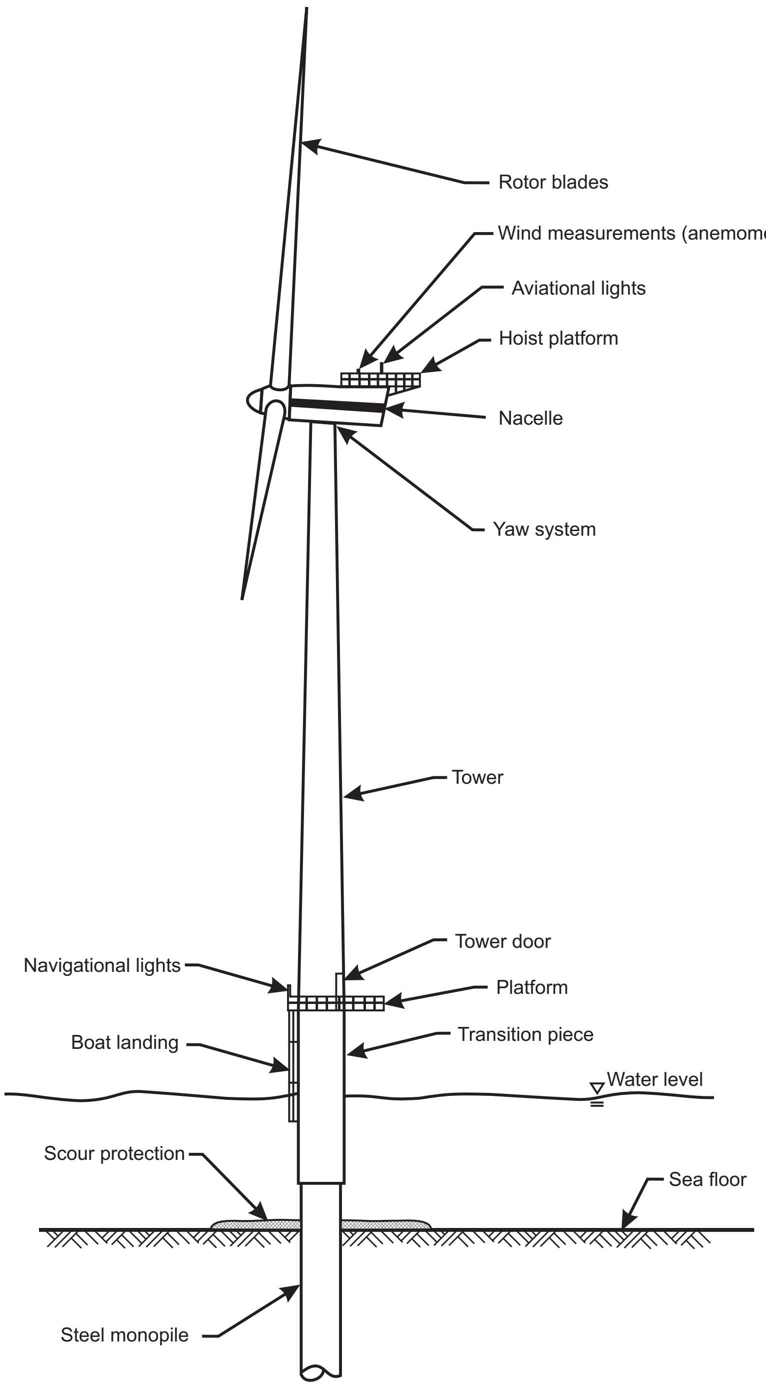

Fig. C.1-2. Typical offshore horizontal axis wind turbine (HAWT) with a conical steel support tower and steel monopile foundation

Refer to Figure C.1-3 for some typical offshore wind turbine substructure and foundation schematics. Note that this figure is not intended to be a complete representation of all available types of substructure construction, but only some of the most commonly used.

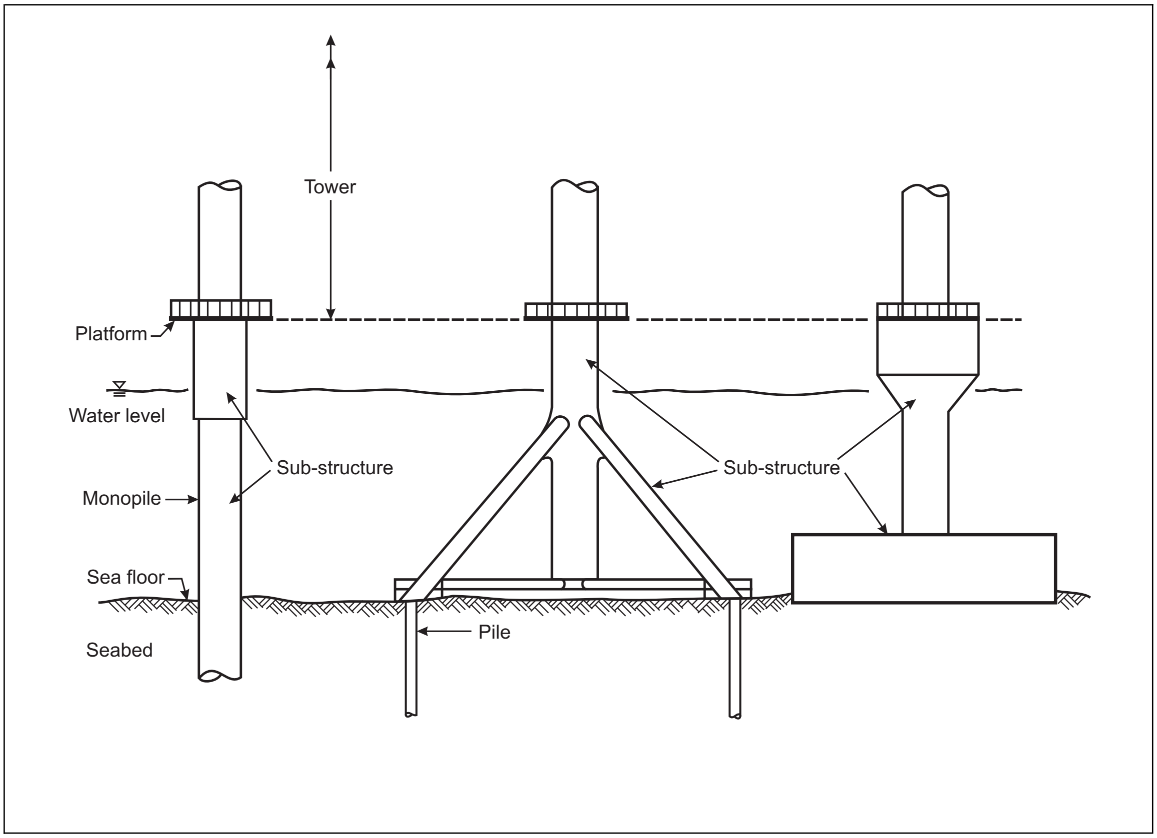

Fig. C.1-3. Some commonly used offshore wind turbine substructures and foundations (from left to right: monopile foundation; tripod foundation with multiple piles; gravity base). Note that scour protection is not shown.

C.2 Installed Wind Generating Capacity

Tables C.2-1 and C.2-2 show the total cumulative installed commercial wind turbine capacity and totall cumulative offshore commercial wind turbine market share by end of 2011.

*Table C.2-1 . Total Cumulative Installed Commercial Wind Turbine Capacity by end of 2011 (by Country)**

Rank	*Country*	*Rated Power (MW)*	*% of Worldwide Total*
1	China	62,364	26
2	United States	46,919	20
3	Germany	29,060	14
4	Spain	21,674	9
5	India	16,084	7
6	France	6,800	3
7	Italy	6,737	3
8	United Kingdom	6,540	3
9	Canada	5,265	2
10	Portugal	4,083	2
	Rest of the world	28,520	12
	Total, top ten	205,526	88
	Total for world	234,046	100

*Note: These values represent both land-based and off-shore wind turbines. Off-shore wind represents approximately 2% of the total cumulative worldwide wind turbine capacity.

Table C.2-2. Total Cumulative Offshore Commercial Wind Turbine Market Share by end of 2011 (% of MW Capacity by Country)

Rank	*Country*	*% of Worldwide Total*
1	United Kingdom	45
2	Denmark	28
3	Netherlands	10
4	Sweden	7
5	China	4
6	Germany	3
7	Belgium	1
8	Finland	1
9	Ireland	1
	Rest of the world	0
	Total for world	100

C.3 Other Wind Turbine Resources

American Wind Energy Association (AWEA)
https://cleanpower.org/

British Wind Energy Association (BWEA)
https://www.thenbs.com/PublicationIndex/documents?Pub=BWEA

Danish Wind Industry Association
http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/index.htm/

European Wind Energy Association (EWEA)
http://www.windeurope.org

Global Wind Energy Council (GWEC)
http://www.gwec.net

U.S. Department of Energy, National Renewable Energy Laboratory (NREL)
http://www.nrel.gov

Windstats Newsletter, Tustin, California.

Wind Power Monthly

Wind Energy Weekly

APPENDIX D ILLUSTRATIVE EXAMPLES AND JOB AIDS

Example 1. Find the Required Standard Wind Turbine Class

Given:

Basic wind speed: V = 90 mph (40 m/s), 3-sec gust, 33 ft (10 m) above grade

Hub height = 300 ft (91 m)

Land-based location, but not located on complex terrain (not on a hill, escarpment, etc.)

Not located in a tropical cyclone-prone regions (as defined in Data Sheet 1-28, *Wind Design*); nor in a shoreline area (as defined by ASCE 7 Exposure D or Data Sheet 1-28, *Terrain Roughness D*); nor in a coastal area (as defined by Eurocode EN 1991 Terrain Category 0); nor in a lakefront area or area without obstacles and with negligible vegetation (as defined by Eurocode EN 1991 Terrain Category I); therefore, recommended I_w = 1.0.

A. Recommended normal L_w = 1.5 and I_w = 1.0, but design wind load cases are based on typical IEC 61400-1 values L_w = 1.35 and I_w = 1.0.

Adjust the basic wind speed to account for L_w and I_w.

Wind Speed Adjustment Factor = $[(1.0)\ (1.5/1.35)]^{0.5}$ = 1.05

V_A (3-sec gust) = 1.05 x 90 mph = 95 mph (42.2 m/s) at 33 ft (10 m) above grade

V_{hub} = (V_A) x (Hub Height/33 ft \[10])$^{0.11}$ = (95 mph) x $(300/33)^{0.11}$ = 121 mph (54 m/s)

Therefore, use Class II wind turbine (V_{ref} = 136 mph [61]), with V_{ref} in 3-second gust.

B. Recommended normal L_w = 1.5, and design wind load cases confirmed to be based on L_w = 1.5 and I_w = 1.0

V_{hub} = (V) x (Hub Height/33 ft [10 m)$^{0.11}$ = (90 mph) x $(300/33)^{0.11}$ = 115 mph (51 m/s)

Therefore, use Class III wind turbine (V_{ref} = 120 mph [54 m/s]), with V_{ref} in 3-second gust.

Example 2: Find the Required Wind Turbine Class

Given:

Basic wind speed: V = 110 mph (49 m/s), 3-sec gust, 33 ft [10 m] above grade

Hub height = 300 ft (91 m)

Land-based location, but not located on complex terrain (not on a hill, escarpment, etc.)

Located in a hurricane-prone region, or typhoon-prone and tropical cyclone-prone region (as defined in FM Global Data Sheet 1-28, *Wind Design*); or in a shoreline areas (as defined by ASCE 7 Exposure D or Data Sheet 1-28 *Terrain Roughness D*); or in a coastal areas (as defined by Eurocode EN 1991 Terrain Category 0); or in a lakefront area or area without obstacles and with negligible vegetation (as defined by Eurocode EN 1991 Terrain Category I); therefore, recommended I_w = 1.15.

A. Recommended normal L_w = 1.5 and I_w = 1.15, but design wind load cases are based on typical IEC 61400-1 values L_w = 1.35 and I_w = 1.0

Adjust the basic wind speed to account for L_w and I_w

Wind Speed Adjustment Factor = $[(1.15)\ (1.5/1.35)]^{0.5}$ = 1.13

V_A (3-sec gust) = 1.13 x 110 mph = 124 mph (55.6 m/s) at 33 ft (10 m) above grade

V_{hub} = (VA) x (Hub Height/33 ft [10 m])$^{0.11}$ = (124 mph) x $(300/33)^{0.11}$ = 158 mph (71 m/s)

Therefore, use Class I wind turbine (V_{ref} = 161 mph [72 m/s]), with V_{ref} in 3-second gust.

B. Recommended normal L_w = 1.5 and I_w = 1.15, and design wind load cases confirmed to be based on L_w = 1.5 and I_w = 1.15

V_{hub} = (V) x (Hub Height/33 ft [10 m])$^{0.11}$ = (110 mph)x$(300/33)^{0.11}$ = 140 mph (63 m/s)

Therefore, use Class I wind turbine (V_{ref} = 161 mph [72 m/s]), with V_{ref} in 3-second gust.