# LAND-BASED WIND TURBINES AND FARMS

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## 1.0 SCOPE

This data sheet presents property loss prevention guidelines and recommendations for land-based (onshore) 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 typically part of the wind turbine, farm, or park installation.

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.

Severe hail impacts could cause potentially 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.

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 and other mechanical components. Ice on rotor blades can be hazardous if it dislodges 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. This situation 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 and rotor blades, 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 from wildfire exposure.

E. Earthquake

Seismic shaking has the potential to cause widespread damage to wind farms. Weak foundation-bearing strata 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 result from 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 currently a common hazard for most land-based wind farms; but as wind farms become more prevalent, 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).

H. Lightning

Damage due to lightning strikes is a high-frequency event and a common cause of losses at wind farms. Lightning damage can impact multiple wind turbines and significant parts of the electrical system at a wind farm.

Direct lightning strikes can result in damage to wind turbine blades and the associated Lightning Protection System (LPS) to varying degrees. LPS receptors may sustain damage such as melting, and down conductors can melt or detach from the support structure, affecting the integrity of the LPS. Damage to the blades can also vary, including surface damage (e.g., scorching and surface stripping), tearing or cracking of the blade, a blade tip blowout (especially when drainage holes are clogged), blade section separation and burnout. Catastrophic damage to the turbine can occur depending on the sustained blade damage (e.g., a tower strike potentially resulting in a tower collapse or an ensuing 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, 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 that starts 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, leading to the spread of fire with the potential to involve other wind farm structures and equipment.

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

Fire service response can be limited due to the remote nature of wind farms. Controlling ignition sources and implementing other passive measures to prevent a fire from occurring within the nacelle is critical.

### 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, rotor overspeed can also occur upon the loss of grid power and 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 is a very common problem, including gear/tooth failures, shaft failures, 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 impacts 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.

### 1.1.5 Collision

The combination of wind turbine 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 the 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.

### 1.1.6 Corrosion

Corrosion can cause damage to many components of a wind turbine, including structural, mechanical and electrical components.

### 1.2 Changes

**October 2025.** Interim revision. The following significant changes were made:

A. Clarified modifications to IEC61400-1 for wind design.

B. Clarified human factor planning and response to severe environmental events.

C. Removed recommendations for hail protection.

## 2.0 LOSS PREVENTION RECOMMENDATIONS

### 2.1 Introduction

Figures 2.1-1 and 2.1-2 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.

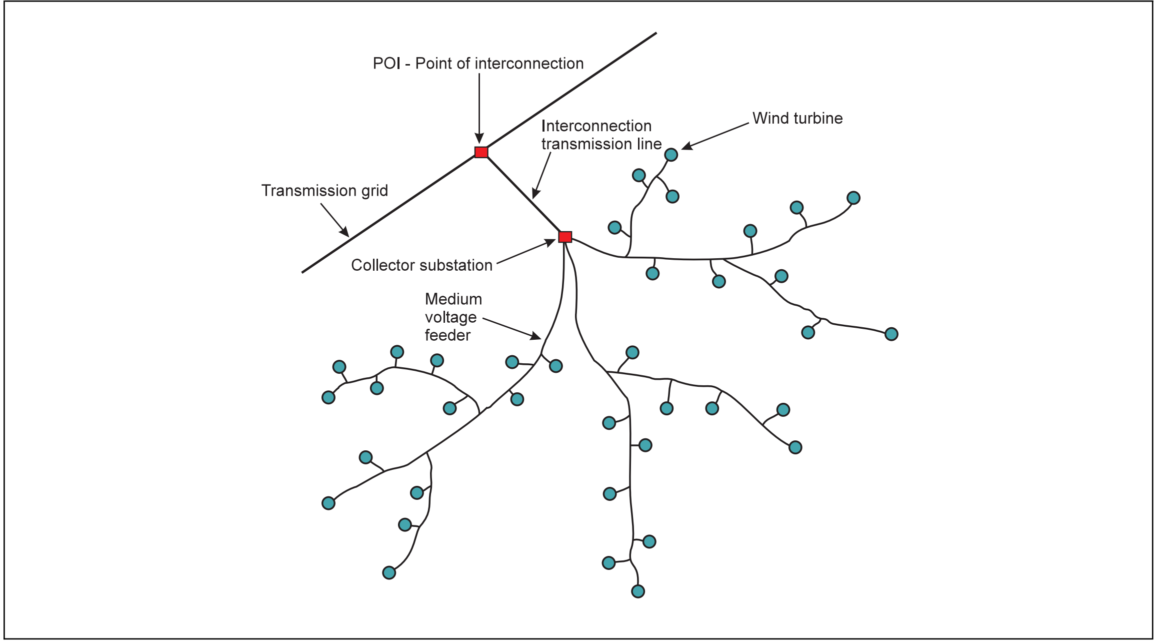



*Fig. 2.1-1. Typical wind farm layout*

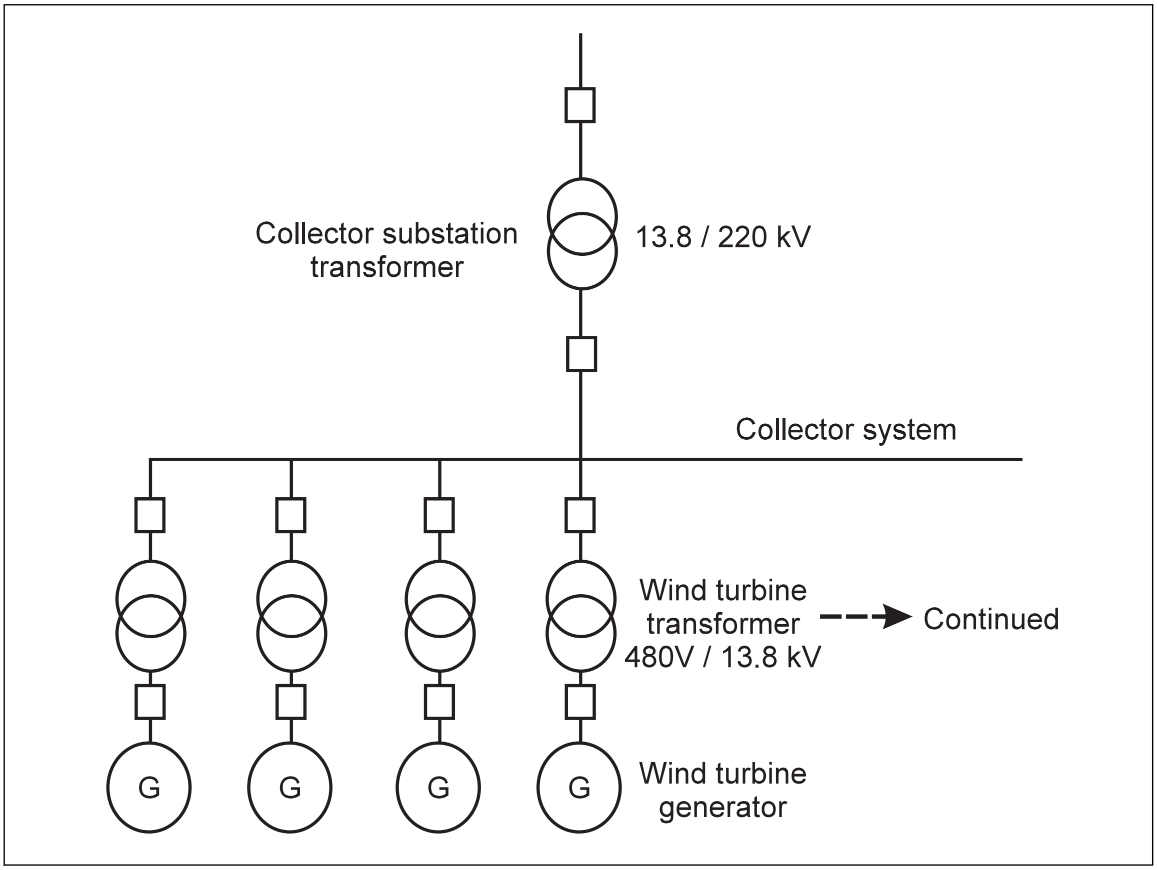



*Fig. 2.1-2. Electrical systems of a typical wind farm (voltages displayed for example only)*

## 2.2 Construction and Location

### 2.2.1 Wind Turbine Design and Classification

Apply design load cases from IEC61400-1 with the modifications recommended in the sections below and in Table 2.2.1.8.

2.2.1.1 Design wind turbines, interior equipment, and exterior components and equipment to withstand the normal temperature and relative humidity for the installation location, and provide a humidity/water mediation/mitigation system. Consult the OEM for special precautions related to extreme environments and material behavior.

See Appendix D for illustrative examples to determine wind turbine classifications.

2.2.1.2 Use the appropriate Wind Turbine Class (Class I, II, III, IV, or S) based on the Reference Wind Speed ($V_{ref}$) at the turbine hub height. Ensure that $V_{ref}$ meets or exceeds the wind speed at the turbine's hub height ($V_{hub}$), where $V_{hub}$ is found using the basic wind speed (V).

See Table 2.2.1.2 for abbreviation definitions and example wind speeds.

*Table 2.2.1.2. Relevant Wind Speeds for Wind Turbines*

| *Symbol* | *Description* | *Definition* | *Typical Values*[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)[2] | Location specific |
| $V_{hub}$ | 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 $V_{hub}$ is based on an extreme wind speed |
| $V_{ref}$ | Reference wind speed | Extreme wind speed at the hub height, typically used to define the standard wind turbine class; $V_{ref}$ must not be less than $V_{hub}$ | Location specific |
| $V_{in}$ | 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 |
| $V_{out}$ | Cut-out wind speed | Maximum wind speed at which the wind turbine operates4 | 5 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 |
| $V_r$ | 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. Speeds are estimates of typical values applicable to common sizes of new commercial wind turbines
Note 2. See Appendix A of this data sheet for descriptions of ground roughness

2.2.1.3 Determine basic 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, refer to a nationally recognized local code or standard or a site-specific wind study to determine the basic wind speed; and use a basic wind speed based on a return period (mean recurrence interval, or MRI) of 50 or 100 years.

The wind study should be based on the 50-year or 100-year wind speed mean recurrence interval (MRI), the measured time basis (3-second gust or 10-minute mean), the baseline height (33 ft [10 m] above grade), and the surface roughness. Ensure units of measurement, including time basis and MRI are consistent throughout the entire process of classifying the wind turbine.

2.2.1.4 For land-based wind turbines located on hills, ridges or escarpments, applying additional topographic speed-up factors ($K_{zt}$) 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.

2.2.1.5 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 for extreme wind shear (i.e., wind speed-up factors for extreme wind speeds) as noted in the previous paragraph.

2.2.1.6 For locations where ice accretion (due to atmospheric icing, freezing rain, sea spray, snow or other means) is known to occur, 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. This method assumes that no substantial reductions are made to load factors (partial safety factors) in the appropriate design load cases and combinations.

2.2.1.7 Use Category A turbulence intensity for the normal and extreme turbulence models (NTM and ETM) unless a lesser category is justified. The most commonly used guidelines, including IEC 61400-1 and GL IV-1, identify up to three wind turbulence intensity categories (A, B, and C).

2.2.1.8 Follow the below guidance when using IEC61400-1 design load cases 6.1 and 6.3: Extreme Wind Model (EWM), ultimate strength analysis and use a normal partial safety factor, load factor [$L_w$].

A. Use recommended basic wind speeds (V) as found in Section 2.2.1.3 for cases where the 50-year or reduced 50-year wind speed is needed (design load case 6.1 from IEC 61400-1).

B. Use a partial safety factor (load factor [$L_w$]) of no less than 1.5.

C. Apply a wind load Importance Factor ($I_w$) of 1.15 as a supplemental partial safety factor for loads ($I_w$ x $Y_f$) in the following locations:

1. Shoreline areas as defined Data Sheet 1-28, *Wind Design*, Exposure Category D
2. Tropical cyclone-prone regions as defined in Data Sheet 1-28.
3. Coastal areas as defined by Eurocode EN 1991, *Terrain Category 0*
4. Lakefront areas or areas without obstacles, having negligible vegetation, as defined by Eurocode EN 1991, *Terrain Category I*

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

*Table 2.2.1.8. Summary of Safety Factor Variations between FM and IEC 61400-1*

| *Design Situation* | *Design Load Case* | *Partial Safety Factor ($L_w$)* | | *Wind Load Importance Factor ($I_w$)* | | *Yaw Error* | |
|---|---|---|---|---|---|---|---|
| | | IEC | FM | IEC | FM (Note 1) | IEC | FM |
| Parked (Note 3) | 6.1 | 1.35 (Normal) | 1.5 | 1.0 | 1.15 | - | - |
| | 6.2 | 1.1 (Abnormal) | Same as IEC | 1.0 | 1.15 | - | See Note 2 |
| | 6.3 | 1.35 (Normal) | 1.5 | 1.0 | 1.15 | | Same as IEC |
| Parked (Note 3) with electrical fault | 7.1 | 1.1 (Abnormal) | Same as IEC | 1.0 | 1.15 | | Same as IEC |
| Transport, erection, and repair | 8.2 | 1.1 (Abnormal) | Same as IEC | 1.0 | 1.15 | - | - |

Note 1. $I_w$ of 1.15 applies to locations as noted in Sections 2.2.1.8.c. or 2.2.1.9.b.
Note 2. Refer to Section 2.2.1.9. Yaw error recommendations.
Note 3. “Parked” indicates that the wind turbine rotor is idle or standing still.

2.2.1.9 Use this guidance for the EWM if no independent electrical network power supply exists for the yaw control that meets the below requirements. This guidance is representative of IEC 61400-1, Design Load Cases 6.2, 7.1, and 8. These design load cases use ultimate strength analysis and an abnormal partial safety factor (load factor).

- 12 hours of capacity for tropical cyclone-prone regions
- 6 hours of capacity for all other locations

This analysis is intended to account for situations where the wind turbine loses connection to the electrical power network and/or a fault other than loss of connection to the electrical power network occurs that causes loss of yaw control.

A. Use basic wind speeds (V) as recommended in Section 2.2.1.3.

B. Use an abnormal partial safety factor (load factor [Lw]) of 1.10.

C. Use a wind load Importance Factor (Iw) as recommended in Section 2.2.1.8.c, or Section 2.2.1.8.d.

D. If an independent emergency power supply for yaw control systems with at least 12 hour capacity for land-based wind turbine locations in tropical cyclone-prone regions or six hour capacity for all other land-based wind turbine locations does not exist, 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 assumption will apply to Design Load Case 6.2 from IEC 61400-1.

2.2.1.10 Determine the wind speed at hub height $V_{hub}$ based on turbine height by using Table 2.2.1.10-1 (mph, ft), Table 2.2.1.10-2 (m/s, m) or Equation 1.

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

*Table 2.2.1.10-1. 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 2.2.1.10-2. Wind Speed (m/s) at Hub Heights ($V_{hub}$) for Basic Wind Speeds (V)*

| *Wind Speed (m/s) at Hub Height ($V_{hub}$)* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hub Height (m) | 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.

2.2.1.11 Specify the proper standard wind turbine class using the reference wind speed ($V_{ref}$) found in Table 2.2.1.11.

$V_{ref}$ must be greater than $V_{hub}$ ($V_{ref} > V_{hub}$). $V_{hub}$ and $V_{ref}$ must have the same measured time basis (e.g. 3-second gust or 10-minute mean).

*Table 2.2.1.11. 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 |

Note 1. $V_{ref}$ is the reference wind speed at the hub height and represents the maximum permissible wind speed for the given wind turbine class.

### 2.2.2 Foundations

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

2.2.2.2 Ensure the potential for liquefaction due to seismic ground shaking and/or wind turbine operational vibration is accounted for in the foundation design and included in the geotechnical study.

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

2.2.2.4 Include adequate fatigue resistance in the design in accordance with a reputable standard specific to wind turbines.

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

2.2.2.6 Perform a case-specific study that includes the foundation geometry, topography, geotechnical conditions, and water scouring due to slope or location.

2.2.2.7 Provide adequate scour and erosion protection in the form of armor stone, rip-rap or similar to protect overburden and prevent foundation undermining.

2.2.2.8 Place the bottom of shallow foundation spread footings sufficiently below grade, based on geotechnical report, to protect against frost. Use local building codes for the recommended depth for frost protection if not provided in the geotechnical report.

2.2.2.9 For shallow foundations with tension anchors, 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

2.2.2.10 Provide adequate corrosion protection for rock/soil anchors such as galvanizing, epoxy coating, or encasement in cement grout for steel anchor rods.

2.2.2.11 Account for and include wind turbine vibrations in the geotechnical study if friction pile foundations are to be used.

2.2.2.12 Verify the unbraced length of piles used for design capacity. Account for the impacts of soil liquefaction, saturated soils and buoyancy.

2.2.2.13 Provide adequate measures to protect the concrete foundations from chloride-based degradation and corrosion of embedded steel reinforcing materials.

### 2.2.3 Support Tower

2.2.3.1 Base the thickness of encrusted ice on the nacelle and support tower on the 50-year MRI. Use an ice thickness not less than 0.5 in. for locations where ice accretion is known to occur.

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

2.2.3.3 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).

2.2.3.4 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.

2.2.3.5 Consider the as-built natural frequencies of the tower, including rotor rotational frequencies and blade-passing frequencies, when performing natural frequencies and damping calculations.

2.2.3.6 Include adequate fatigue resistance in the support tower design in accordance with a nationally recognized standard specific to wind turbines, such as IEC 61400-1.

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

2.2.3.8 For tubular steel towers with bolted connections, design bolts to provide adequate resistance to all applicable load conditions, including fatigue resistance. Use pre-tensioned, slip-critical (friction grip) bolted connections; and avoid using simple snug-fit (bearing) bolted connections at tower section flanges.

2.2.3.9 Use similar metals when in contact. Avoid mixing hot-dip galvanized components with mechanical galvanized components in a single fastener assembly.

### 2.2.4 Nacelle

2.2.4.1 Use noncombustible or fire-resistant materials for nacelle construction.

2.2.4.2 Separate the nacelle from the tower with noncombustible construction.

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

### 2.2.5 Rotor Blades

2.2.5.1 Use rotor blades that provide adequate strength, stiffness, fatigue resistance and durability to function properly for intended design and operational conditions.

2.2.5.2 Design blades to withstand the normal temperature and relative humidity for the installation location and provide a humidity/water mediation/mitigation system.

2.2.5.3 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, $V_{hub} = V_{ref}$, 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.

2.2.5.4 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 IEC 61400-23.

2.2.5.5 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.

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

2.2.5.7 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. In the absence of this risk assessment, an estimate of the horizontal blade throw radius is:

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

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

### 2.2.6 Hail

2.2.6.1 Refer to Data Sheet 1-34, *Hail Damage*, and the Nat*Haz* Toolkit and Maps on fm.com for locations in the United States subject to hailstorm and for guidance regarding hailstone size, velocity and impact energy.

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

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

2.2.6.3 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.

### 2.2.7 Flood and Surface Water

2.2.7.1 Locate wind turbines outside known flood zones.

2.2.7.2 Protect the tower foundation, tower, equipment and associated utilities from flood waters. Refer to Data Sheet 1-40, *Flood*, for additional guidance. Of particular importance are the effects of surface water on geotechnical/foundation properties, including but not limited to reduced soil bearing capacity, buoyant effects, foundation undermining and settlement, and loss of credited overburden.

2.2.7.3 Implement a surface water drainage strategy throughout all stages of construction and operation. Ensure water drainage does not negatively impact wind farm construction, access roads, staged materials and any other critical construction areas.

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

### 2.2.8 Ice and Snow

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

2.2.8.2 Install an icing prevention system on the rotor blades such as ice-shedding or ice-phobic blade coatings, electric heating, hot air heating or other method to reduce ice buildup.

2.2.8.3 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), wind direction indicators (vanes) and other sensors for control systems or safety (protection) systems.

2.2.8.4 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. See Equation 3 and Equation 4 to calculate ice shedding radius.

2.2.8.5 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. See Equation 5 to calculate ice throw radius.

2.2.8.6 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).

2.2.8.7 Protect from ice shedding and ice throws using a reinforced roof (concrete) or protection via heavy steel grating or similar for lightweight roof construction (metal roofs, steel deck, wood, etc.).

2.2.8.8 Base the weight and impact velocity of ice projectiles on a site-specific wind turbine risk assessment.

A. Ice Shedding (Rotor Stationary):

Equation 3(mph, ft): Horizontal Ice Shedding Radius (ft) = $(V_{hub}) \times (D/2 + H)/130$
Equation 4 (m/s, m): Horizontal Ice Shedding Radius (m) = $(V_{hub}) \times (D/2 + H)/58$

B. Equation 5: Ice Throws (Rotor Spinning):

Horizontal Ice Throw Radius = $1.5 \times (D + H)$

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.

### 2.2.9 Earthquake

2.2.9.1 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).

2.2.9.2 For locations outside the United States, 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.

2.2.9.3 For 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 (SDS or SD1) for the appropriate FM earthquake zone as the basis for determining earthquake loads. Refer to Data Sheet 1-2, *Earthquakes*, for more information.

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

A. Local geotechnical conditions such as soils, groundwater, liquefaction, etc.

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 based on a rational analysis by the structural engineer of record. 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 criteria applies 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 based on a rational analysis by the structural engineer of record.

2.2.9.5 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 structural members and components) and an abnormal partial safety factor (load factor) not less than 1.1.

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

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

### 2.2.10 Wildland Fire

2.2.10.1 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 2.2.10.1. Horizontal clearances are based on the distance from the wind turbine tower to the vegetation.

*Table 2.2.10.1. 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*[Note 1] |
|---|---|
| ≥ 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. Linear interpolation is acceptable.

2.2.10.2 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 5b for recommendations regarding vegetated clearance zones.

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.

Horizontal clearances assume 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.

2.2.10.2 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 2.2.10.2 for recommendations regarding vegetated clearance zones.

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.

Horizontal clearances assume 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.

Horizontal clearances are based on the distance from the wind turbine tower to the vegetation.

*Table 2.2.10.2. Vegetation Clearance Zones for Protection of Wind Turbines from Crop Field Fires*

| *Hub Height – Rotor Radius* | *Horizontal Clearance to Crop Vegetation*[Note 1] |
|---|---|
| ≥ 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. Linear interpolation is acceptable.

### 2.2.11 Control and Lubrication Oil Systems

2.2.11.1 Where FM Approved industrial fluids are not provided in accordance with Section 2.3.1.1, provide containment features in accordance with Data Sheet 7-83, *Drainage and Containment Systems for Ignitable Liquids*, to achieve the following:

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.

2.2.11.2 Provide sufficient capacity to handle the safe containment of all the ignitable liquids and, if applicable, the total fire protection system discharge quantity.

2.2.11.3 Design and maintain rigid piping to account for potential vibration and deflection in the nacelle.

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

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

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

2.2.11.7 Follow the below recommendations if flexible hose connectors are required to prevent excess stresses due to vibration, settling or thermal change.

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 plain 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.

### 2.2.12 Electrical, Transformers, and Cables

2.2.12.1 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.

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

2.2.12.3 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*.

2.2.12.4 Provide arc-resistive switchgear within the nacelle.

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

2.2.12.6 Route cables to minimize exposures from oil piping as much as practical. Where separation is not possible, locate cables above adjacent oil piping so cables do not provide channels to spread oil.

2.2.12.7 Locate cables away from rotating or vibrating equipment.

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

2.2.12.9 Seal penetrations through which cables pass from one area to the other with an FM Approved firestop.

## 2.3 Occupancy

### 2.3.1 Lubrication and Control Oil Systems

2.3.1.1 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.

2.3.1.2 Refer to Data Sheet 7-98, *Hydraulic Fluids*, for additional information regarding the conversion of equipment from a mineral oil-based hydraulic fluid to FM Approved fluids.

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

### 2.3.2 Housekeeping

2.3.2.1 Maintain high standards of housekeeping in all areas.

2.3.2.2 Keep all areas free of combustibles, including oil or grease spills.

2.3.2.3 Provide a reporting channel for prompt correction of housekeeping deficiencies.

## 2.4 Protection

### 2.4.1 Lightning Protection

2.4.1.1 Install a lightning detection system that can send notifications to operators when a turbine is struck by lightning. The minimum reported parameters for lightning detection should include peak current, charge transfer and specific energy.

2.4.1.2 Provide a lightning protection system for wind turbines that has been designed, certified and tested to Lightning Protection Level LPL 1, capable of protecting against a peak current of at least 200kA 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. 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 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.

2.4.1.3 Provide surge arrestors for the generator and transformer.

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

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

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

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

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

### 2.4.2 Electrical Protection

2.4.2.1 Provide equipment and electrical protection systems to maintain the wind turbine in a safe condition during 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. Safeguard the internal settings of the protection system to prevent unauthorized interference.

2.4.2.2 Arrange the protection to activate upon a control-function failure or when an internal/external failure or dangerous event occurs.

2.4.2.3 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.

2.4.2.4 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.

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

2.4.2.6 Provide a single FM Approved Dissolved Gas Analysis Monitoring System for oil-filled wind turbine transformers.

2.4.2.8 Provide electrical protection for the wind turbine generator to meet the intent as shown in Figure 2.4.2.8. See Table 2.4.2.8-1 for a description of the protective device. Provide additional protection for synchronous generators per Table 2.4.2.8-2.

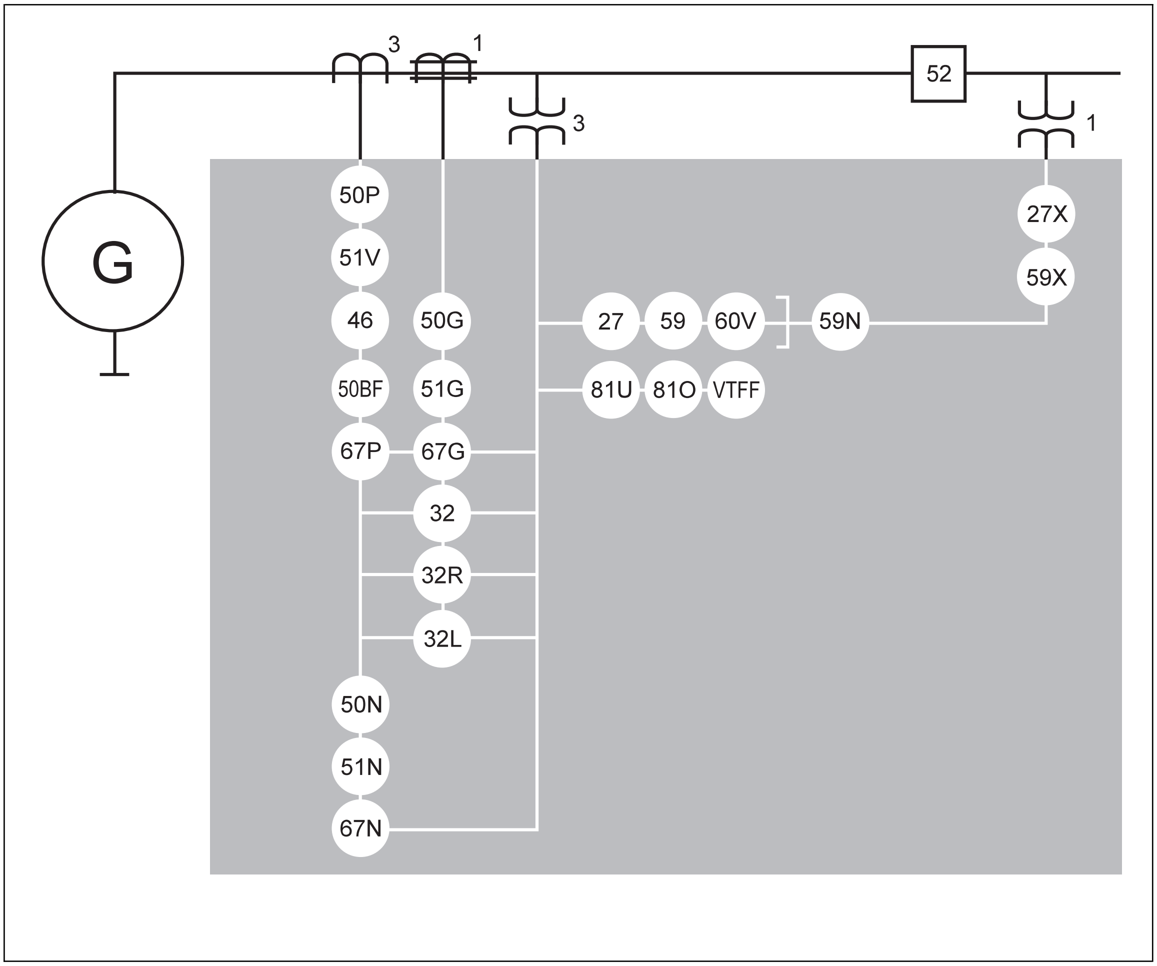



*Fig. 2.4.2.8. Recommended protection scheme for wind turbine generators*

*Table 2.4.2.8-1. The Protective Devices in Figure 2.4.2.8 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 2.4.2.8-2. 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 |

### 2.4.3 Mechanical Protection

2.4.3.1 Provide Protective Devices in Accordance with Table 2.4.3.1.

*Table 2.4.3.1. 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 2.4.1) | 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.

2.4.3.2 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 2.4.4.5 for trips associated with fire detection.

### 2.4.4 Fire

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

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.

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).

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 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 of fixed-temperature and rate-of-rise heat detectors.

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

2.4.4.3 Provide detection and protection for collector substations in accordance with Data Sheet 5-4, *Transformers*, Data Sheet 5-19, *Switchgear and Circuit Breakers*, Data Sheet 5-32, *Data Centers and Related Facilities*, and other FM Property Loss Prevention Data Sheets as applicable.

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

2.4.4.5 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.

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

2.4.4.7 Provide detection in other areas of the wind turbine if combustible loading exists. Combustible loading may include, but is not limited to the presence of grouped cable that is not arranged as recommended in this standard, the use of oil-filled non-Approved transformers, and electrical cabinets.

2.4.4.8 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 information is included in the organization's documented maintenance program. Refer to Data Sheet 4-5, *Portable Extinguishers*, for additional guidance.

### 2.4.5 Corrosion-Related Protection

2.4.5.1 Provide corrosion protection for all rotor and nacelle 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 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.

2.4.5.2 For steel support structures, determine the appropriate atmospheric-corrosivity category using ISO 12944-2, and provide an appropriate corrosion protection system.

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.

2.4.5.3 For concrete support structures, provide a corrosion protection system based on a site-specific study of the corrosive climate and appropriate for the construction materials.

### 2.4.6 Collision Protection

2.4.6.1 Provide wind turbines and any related significant wind farm structures with proper collision avoidance warning systems in accordance with local aviation authorities. These systems typically involve visual warnings (such as signage and lighting).

## 2.5 Equipment and Processes

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

## 2.6 Operation and Maintenance

### 2.6.1 Wind Turbine and Farm

2.6.1.1 Implement a periodic inspection, testing, maintenance and outage program based on the wind turbine manufacturer's documentation and recommendations. Table 2.6.1.1 contains general inspection practices to supplement OEM documentation and the specific recommendations in the Operation and Maintenance section.

2.6.1.2 Establish and implement a wind turbine quality program. See Data Sheet 9-0, *Asset Integrity*, for guidance on developing this program.

2.6.1.3 All inspection, testing, and maintenance activities should be conducted by qualified personnel.

2.6.1.4 Perform inspections in a manner that allows for documentation and tracking of findings over time. Inspection methods could include, but are not limited to telephoto lenses, high-definition cameras, drones, tower climbs, ultrasonic or blade crawlers.

2.6.1.5 Establish and implement a deficiency management process as part of the inspection program to ensure all identified equipment condition deficiencies are evaluated and tracked to closure.

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

2.6.1.7 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.

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

2.6.1.9 For gearbox reliability, establish an effective inspection and lube-oil monitoring program in accordance with the OEM's guidelines.

*Table 2.6.1.1. Wind Turbine Assemblies Requiring Periodic Inspection*

| *Assembly* | *Inspect for/Possible Defects*[Note 1] | *Inspection Frequency*[Note 2] | |
|---|---|---|---|
| | | 6 Months | Annual |
| Rotor blades, hub and pitch system | Surface damage, cracks, and structural discontinuities | | X |
| | Weep/drain holes are clear | | X |
| | Damage to lightning protection system[Note 3] | | X |
| | Proper tensioning of bolts, every 10th bolt or as specified by the OEM<br>*Inspect after 6-month break-in period | | X |
| Drive train | Lubrication | | X |
| | Condition of gearing (lube oil laboratory testing, if applicable) | X[4] | |
| | Leakage | X | |
| | Unusual noises | X | X |
| | Corrosion protection system | | X |
| | Proper tensioning of bolts, every 3rd bolt or as specified by the OEM<br>*Inspect after 6-month break-in period | | X |
| Hydraulic and/or pneumatic systems | Damage | | X |
| | Leakage | X | |
| | Corrosion | | X |
| Safety devices, sensors and braking systems | Function | | X |
| | Compliance with design limits | | X |
| | Damage | | X |
| | Wear | | X |
| Lightning Protection System[3] | Grounding and bonding | | X |
| | Damage to blades, nacelle and towers | | X |
| | Visual wear to lightning attachments points - i.e., air terminations, diverter strips, or coatings | | X |
| | Visual wear or damage to LPS components - i.e., sliding contacts, spark gaps, surge protection devices, measurement devices, etc. | | X |
| | Connections and mechanical supports for down-conductors and blade securement | | X |
| | Water and moisture infiltration | | X |
| | Blade drains and air heating | | X |
| | Resistance testing of entire LPS | | 2 years |
| Nacelle | Leakage | | X |
| | Housekeeping | | X |
| Electrical | Major components (transformers, breakers, relays, etc.) | | X |
| | Bolted connections | | X |
| | Power electronics | | X |
| | Cables | | X |
| Towers and foundations | Cracking, spalling, corrosion | | X |
| | Soil scouring and undermining | | X |
| | Structural damage | | X |
| | Damage to protective coatings | | X |

Note 1. All inspections are performed by qualified personnel. Results are properly and thoroughly documented with reports and photos where applicable.
Note 2. The frequency of inspections and maintenance is normally defined within the OEM's maintenance manuals. If OEM manuals are not available, follow this guidance.
Note 3. Inspect LPS after lightning strikes, regardless of time since last inspection.
Note 4. Annual is acceptable if continuous online monitoring is used.

### 2.6.2 Lightning Protection and Grounding Systems

2.6.2.1 Inspect and test the grounding and bonding for the Lightning Protection System (LPS) in accordance with Data Sheet 5-20, *Electrical Testing* and after severe lightning impacts as indicated by lightning detection and monitoring solutions.

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

2.6.2.3 Inspect the blade and hub LPS yearly and after lightning strikes.

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

2.6.2.5 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.

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

2.6.2.7 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.

2.6.2.8 If visual damage to the lightning protection system is identified, document damage and repair or replace damaged components; and conduct testing as identified in Section 2.6.2.11.

2.6.2.9 Inspect for water and moisture infiltration in the blade.

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

2.6.2.11 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.

### 2.6.3 Blades

2.6.3.1 Annually inspect blades for surface damage, cracks, structural discontinuities, and for weep/drain hole blockage.

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

2.6.3.3 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.

2.6.3.4 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*.

### 2.6.4 Electrical

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

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

2.6.4.3 For medium-voltage switchgear, circuit breakers and protection relays, refer to Data Sheet 5-19, *Switchgear and Circuit Breakers*, for operation, maintenance and testing recommendations.

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

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

2.6.4.6 Verify all power electronics' cooling systems are performing as intended.

2.6.4.7 Verify the power electronics' high-temperature protection/monitoring system is performing as intended.

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

2.6.4.9 Inspect, test and maintain cables in accordance with Data Sheet 5-31, *Cables and Bus Bars*.

### 2.6.5 Wind Turbines Generators

2.6.5.1 Refer to Data Sheet 5-12, *Electric AC Generators* for operation, maintenance and testing recommendations of synchronous round rotor, doubly fed asynchronous generators, wound rotor and salient pole generators.

2.6.5.2 Refer to Data Sheet 5-17, *Motors and Adjustable Speed Drives* for operation, maintenance and testing recommendations of squirrel cage induction generators.

2.6.5.3 Perform additional testing of squirrel cage induction and wound rotor generators as recommended in Table 2.6.5.3.

*Table 2.6.5.3. Additional Generator Testing*

| *Squirrel Cage Generators* | *Wound Rotor Induction Generators* |
|---|---|
| Insulation resistance between shunt capacity terminals and case | Resistance of the variable rotor resistor |
| Capacitance of switched capacitor bank (all terminals) | |
| Resistance of internal discharge resistor for each capacitor | |
| Functional test of capacitor bank switches | Functional test of induction generator soft starter |
| Functional test of induction generator soft starter | |

2.6.5.4 Follow OEM guidance regarding magnet securement and fastening for synchronous generators that are provided with permanent magnets instead of rotor windings or slip rings.

### 2.6.6 Tower and Foundation

2.6.6.1 For concrete towers check, track and correct as needed any 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.

2.6.6.2 Conduct periodic inspections of the structural support systems in accordance with the manufacturer’s recommendations.

2.6.6.3 Check for corrosion or other damage to steel components, particularly the anchor bolts, the base of the tower shell, exposed tower section flange bolts and any welded tower connections.

2.6.6.4 Check for deformed flanges, flange gaps, and loose bolts. If interior access to flanges is unavailable, check for tower flange gaps from exterior grade level using binoculars or other means. Repair or strengthen any deformation or gaps at the flanges.

2.6.6.5 Check for physical damage to the steel tower shell or steel lattice members. Repair, strengthen or replace members with visible damage.

2.6.6.6 Inspect corrosion-resistant coatings on the tower and connections. Repair any damage or holidays (spots where the coating has fallen off) with an appropriate in-kind coating.

2.6.6.7 Perform nondestructive evaluation (NDE) on critical welded and bolted tower connections. Base the frequency of the NDE on manufacturer’s recommendations and industry best practices.

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

2.6.6.9 Visually verify soil has not been washed away or undermined from the tower foundations after flooding or severe storm water runoff occurs.

### 2.6.7. Fire Protection and Detection

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

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

### 2.6.8. Pre-Warranty End Inspections

2.6.8.1. Conduct pre-warranty expiration inspections and testing on all control and safety systems to ensure operability. Complete these inspections sufficiently in advance of the warranty expiration date to allow for any necessary corrective actions under the OEM warranty.

## 2.7 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.

### 2.7.1 Rotor Blades and Structures

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

### 2.7.2 Drive Train

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

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

2.7.2.3 Provide monitoring for gearbox 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 performed, offline oil sample analysis should also be conducted. The main reasons for this redundancy are to:

- Monitor parameters not covered by online instruments.
- Conduct elemental analysis to identify components that are generating excessive wear particles.
- Assist with root cause analysis for some component failures.

#### 2.7.3 Collector Substation

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

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

### 2.8 Contingency Planning

#### 2.8.1 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 specific to wind turbine equipment in the contingency planning process:

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. Provisions for special equipment:

- Cranes, rigging and even helicopters may be needed to gain access to the nacelle for repairs.

### 2.9 Human Factor

#### 2.9.1 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*.

#### 2.9.2 Fire

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.

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

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

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

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

2.9.2.4 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 for the local fire service.

### 2.9.3 Environmental Hazards

2.9.3.1 Form an emergency response team (ERT) to prepare wind turbines for severe environmental events and other conditions that could adversely affect a wind turbine. Severe environmental events may include (based on geographic location) but are not limited to: windstorms, extreme high and low temperatures, freeze, drought, wildfires, flood, soil saturation, tropical storms, tornados and lightning.

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.

2.9.2.2 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 for each peril (i.e., severe wind, extreme low and freezing temperature, etc.)

B. A source of reputable weather forecasting and tracking information to be used as the site's authoritative source(s)[1] for weather information

C. Documented procedures specifying the required actions and associated timelines for implementing severe weather response measures, which may include parking and securing wind turbines. Parking and securing procedures should be developed using OEM's recommendations for critical items (as installed), cut-out speed, blade feathering, yaw position, parking brakes, etc.

D. Verification that units have been stowed correctly per written procedures

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

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

Note 1: For wind farms spanning extensive geographic areas, utilizing multiple weather data sources to ensure accurate and comprehensive weather monitoring may be necessary.

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

### 2.9.4 Ignition Source Control

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

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

2.9.3.2 Avoid hot work in the nacelle whenever possible.

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

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

### 2.10 Repowering

Repowering can involve a full activity, such as dismantling and replacing an 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.

2.10.1 Treat repowering projects as new wind turbine(s), and apply all sections of this data sheet.

### 2.11 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. The process should also evaluate how the alerts may affect the management of change process with 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, and some can be found in this data sheet.

In many parts of the world, basic wind speeds references 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 when the rotor is not spinning, but it also causes increased dynamic loads on the rotor due to the mass of the ice and its imbalanced distribution.

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 amount of time the ice remains on the rotor blades. Rotor vibration monitoring is intended to detect rotor out-of-balance conditions, including out-of-balance due to ice accretion on the rotor blades. Monitoring may help 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 contact the support tower under any design wind conditions. This requirement is addressed 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. Thus, 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 primary disadvantage to downwind turbines is that the “wind shadow” or “wind shade” caused by wind turbulence in the wake of the support tower causes fluctuations in wind pressure and additional vibration in the rotating turbine blades.

### 3.1.2 Earthquake

Two methods are generally 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. 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 have critical damping values substantially less than 5%, resulting 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 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 ensure adequate resistance to differential settlement and frost heaving.

### 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 challenge 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) and provide safer climbing access for service technicians. For locations where icing is known to occur, they 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 tower must have adequate strength and stiffness to support all design load cases and combinations—in particular, the 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.

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 larger 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

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. It can also cause concrete to crack and spall, 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. 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. Of those blade failures, some will involve a thrown blade; and some will not. Installing protection from thrown rotor blades is not typically 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 be no 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 turbulence and reduced wind speed from one turbine’s wake will not negatively affect the performance of the downwind turbine. Turbine spacing is generally five to 10 times the rotor diameter in the direction parallel to the prevailing wind, and two to five 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) (typically 0.7 to 1.1), the maximum collapse radius of a wind turbine (H + D/2) and the low range of typical crosswind turbine spacing (2 x D), the maximum possible collapse radius is likely less than the typical turbine spacing. 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 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. Therefore, they 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. This rapid evolution creates technology development risks.

Wind turbine components are designed for a 20- to 30-year life span. This industry is relatively young, with many of the components being exposed to extreme cyclic loads. 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:

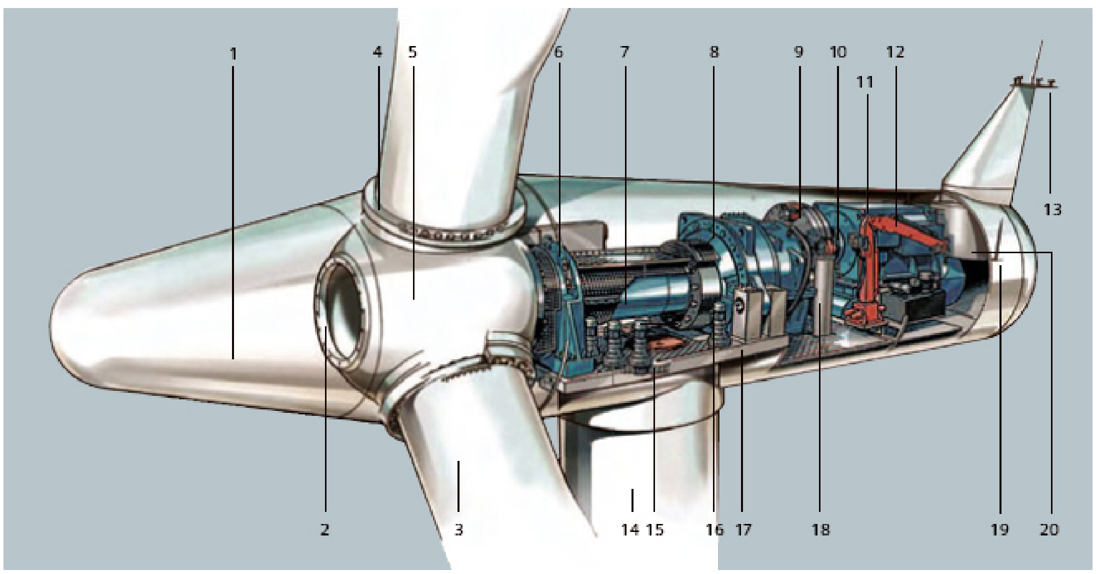
A. The rotor

B. The yaw system

C. The drive train

D. The nacelle

Most of the components in these groups are shown in Figure 3.3. 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 commonly used in the wind turbine industry. This review will introduce relevant nomenclature, as well as the function of some 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 operates 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.

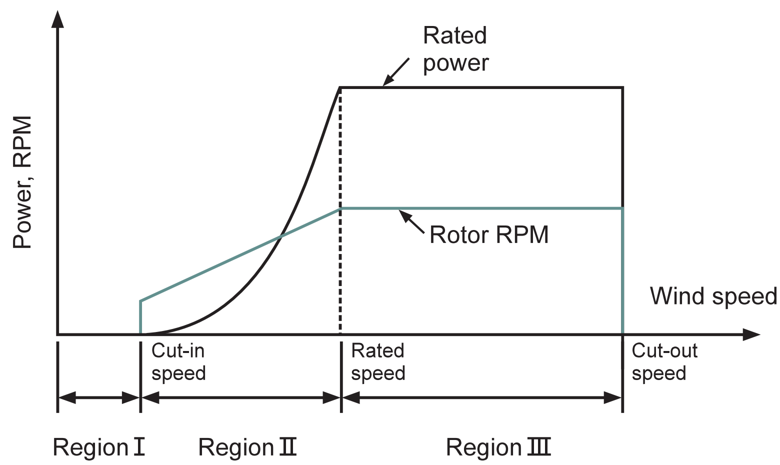



*Fig. 3.3.1. Typical power curve*

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 system 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 in order 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, the turbine is typically aligned 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 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 under periodically, rapidly changing 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), the structural design challenges increase.

Since the 1970s, most blades for horizontal axis wind turbines have been made from composites. Composites have become the preferred blade material, because they have high strength-to weight ratios, high stiffness-to-weight ratios, are corrosion resistant, are electrical insulators and they 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 a debonding between the matrix and the fibers occurs. Debonding and delamination (separation) over a wider area may follow. Eventually, individual fibers break and then completely fracture.

Blade damage during transportation is also a major concern. Upon receiving the blades at the site, a qualified inspector should examine them 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 are usually made of either welded or cast steel. They must be strong enough to withstand and transmit all the static and aerodynamic loads on the blades, including dynamically induced loads such as those due to rotation and yawing.

#### 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.

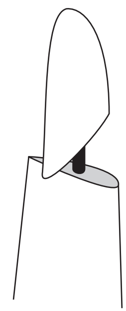


*Fig. 3.3.2.3. Tip brake*

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 is normally 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 it has experienced high failure rates in this application. Early gearbox designs were hampered by fundamental 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 61400-4:2024, *Wind Turbines Part 4: Design requirements for wind turbine gearboxes*

B. ANSI/AGMA/AWEA 6006-B20, *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, providing filtration and active cooling of the oil may be necessary. To maintain high reliability, periodic oil samples must be taken and tested to assess the condition of the oil and to check for signs of internal wear. Commonly encountered issues are additive depletion, dissolved moisture and particulate contamination. Significant benefit would be gained by using an online condition-monitoring system for this application.

#### 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, such as 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. If the gearbox experiences an internal failure, the brake 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 for this type of brake 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, the turbine is typically aligned with the wind to achieve optimum performance. If the yaw system is being used to regulate power, the rotor may be turned away from the wind to reduce power.

The yaw system components used depend the type of yaw system (free or active). 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 may also 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 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 bearing 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 to supply adequate power using 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 movement 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 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 supported by the tower. A small number of nacelles include noncombustible construction such as steel. On larger wind turbines, the nacelle is large enough for personnel to enter and inspect/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, the wind turbine must be safely shut down. This shutdown can be accomplished by using either a failsafe mechanical braking system or aerodynamic braking system. As the size of wind turbines has increased, aerodynamic braking systems have become the preferred approach because of the high rotational 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, failsafe systems to shut down the turbine must be provided 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, housed 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, housed in the nacelle, provide backup operational capability of the braking system in the event of hydraulic power unit failure.

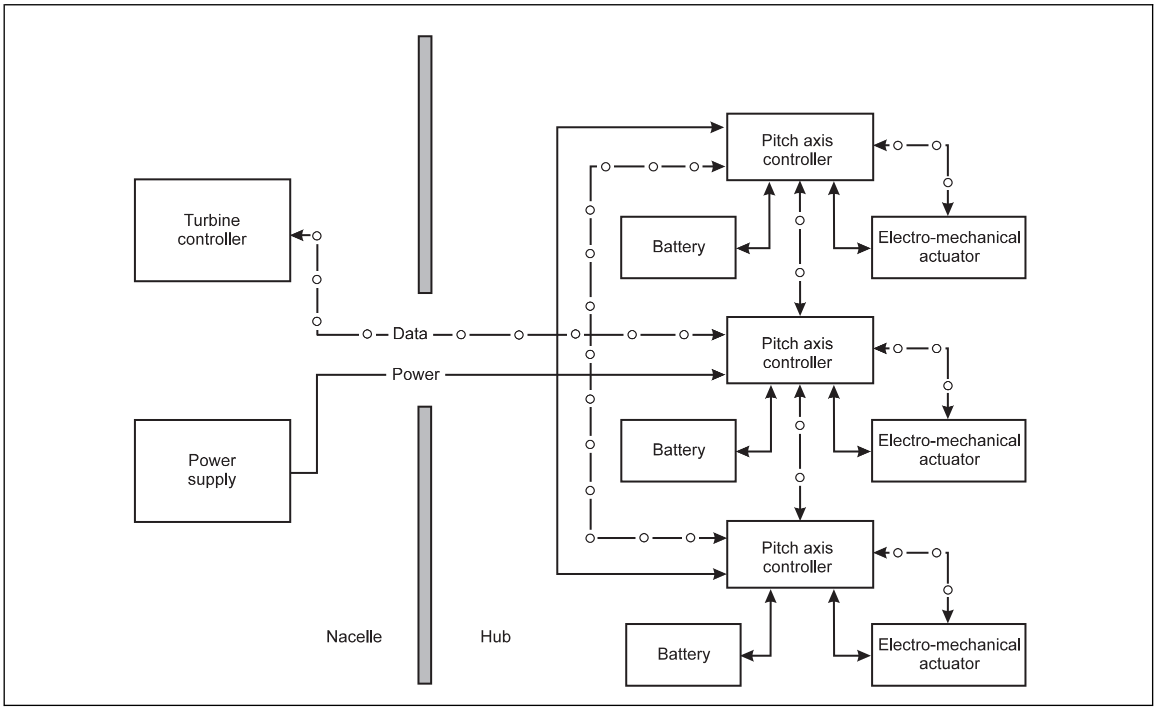



*Fig. 3.3.6-1 Electric blade pitch control system schematic*

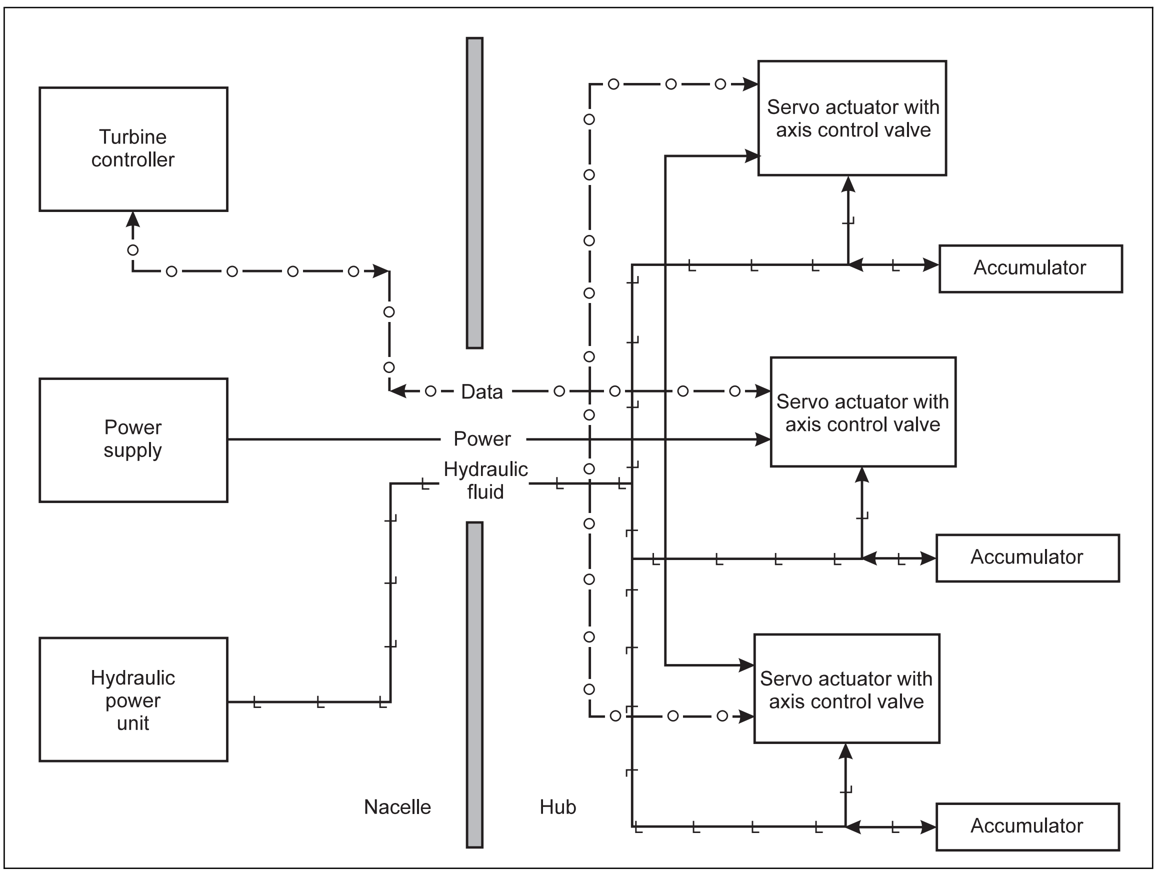



*Fig. 3.3.6-2. Hydraulic blade pitch control system schematic*

## 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.

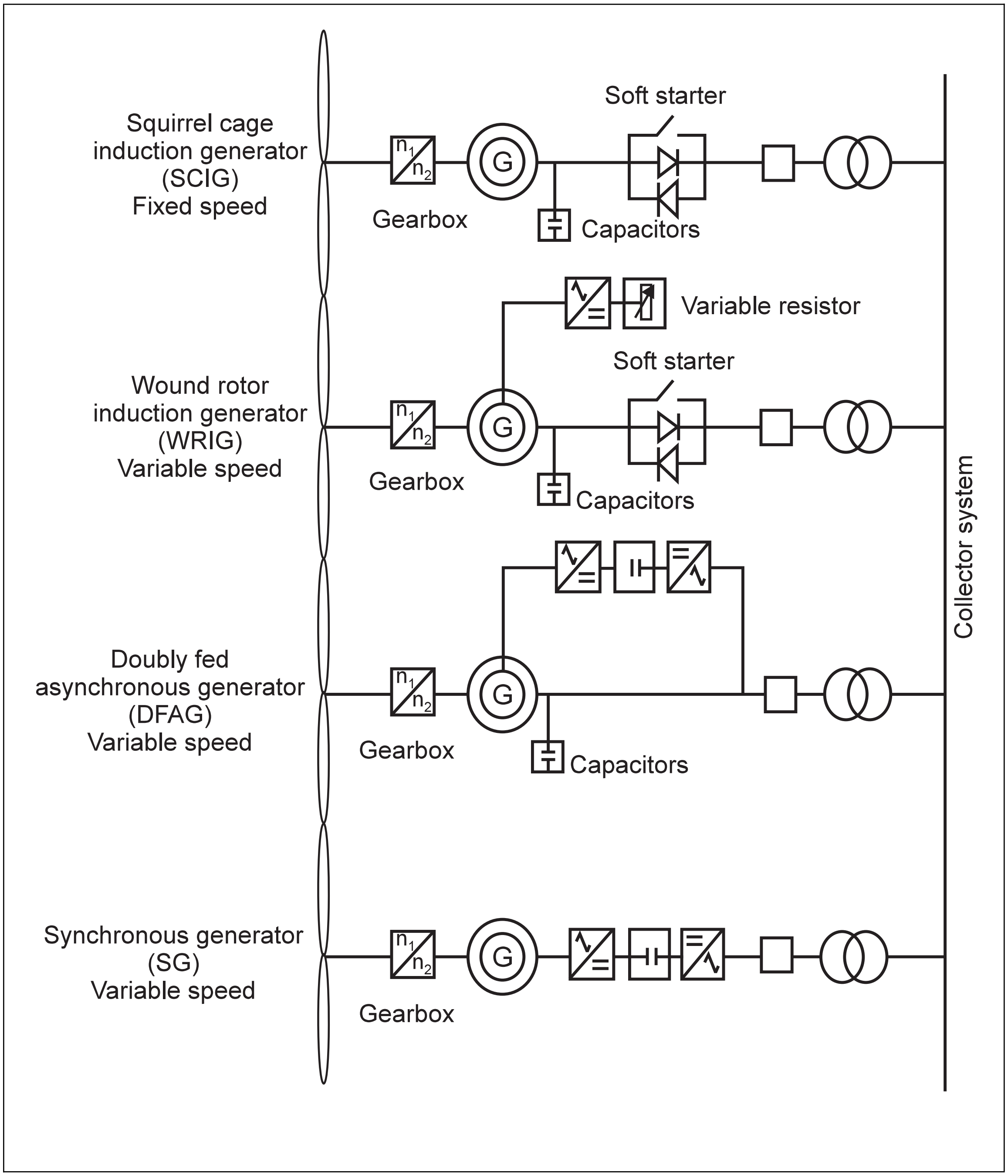



*Fig. 3.4.1. Wind turbine generator topologies*

### 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 needs to be about one third of the rated power of the generator).

Today, doubly-fed, asynchronous generators are estimated to 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.

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

Because induction generators create significant 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).

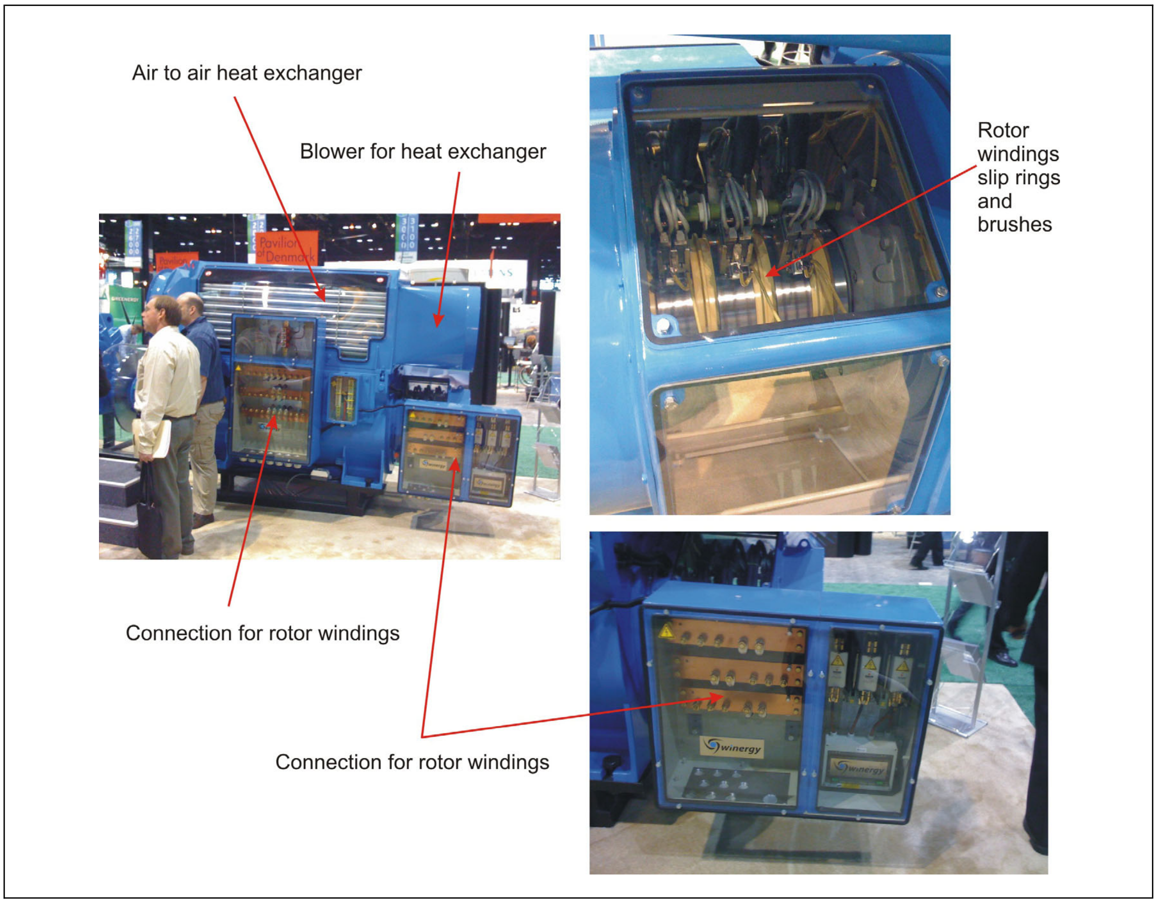



*Fig. 3.4.2. A 4-pole, 1800 rpm, 2.0 MW doubly fed asynchronous generator with an air-to-air heat exchanger*

### 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 must be used.

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

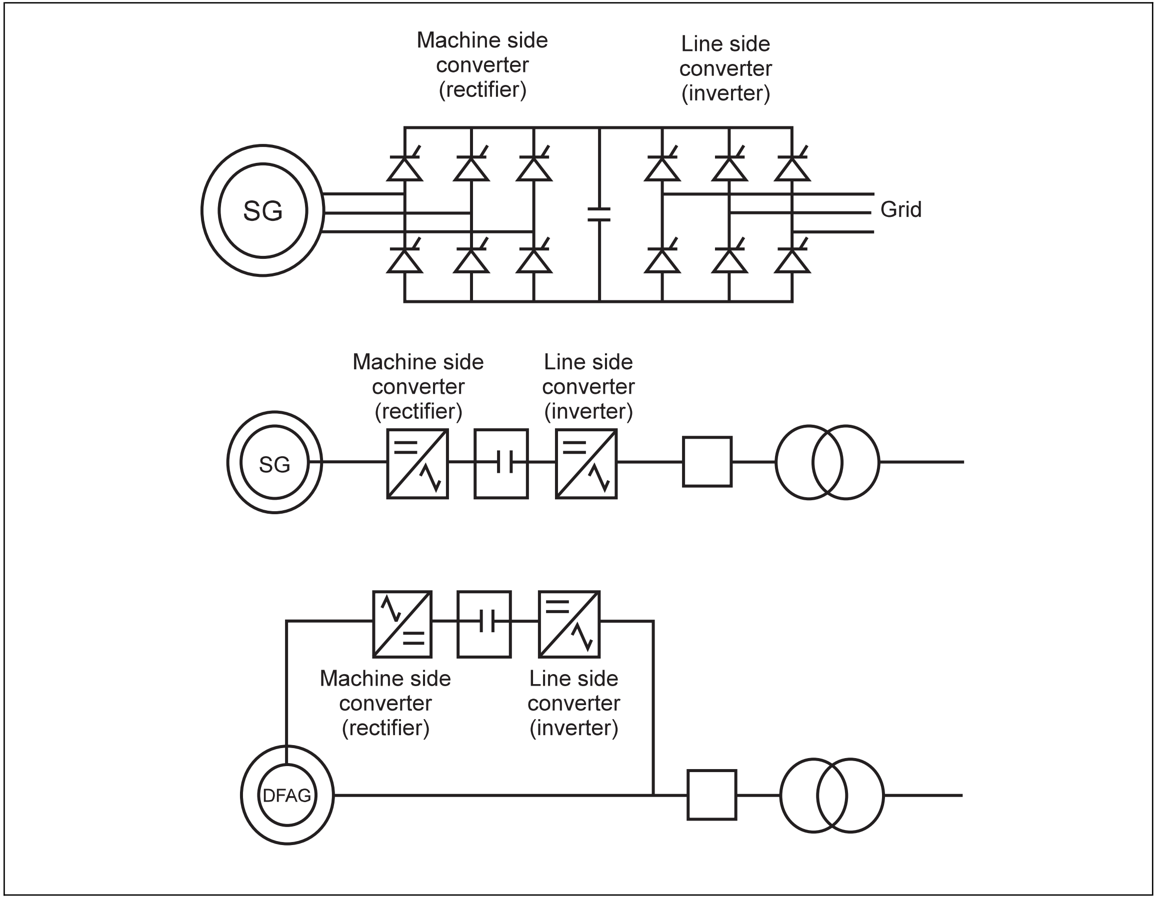



*Fig. 3.4.3-1. Power electronics for synchronous and doubly fed asynchronous generators*

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 SCRs, the in-rush current can be controlled. The soft starter is bypassed after the in-rush period to reduce losses.

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


*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 appropriate voltage ratio to connect the wind farm to the transmission grid.

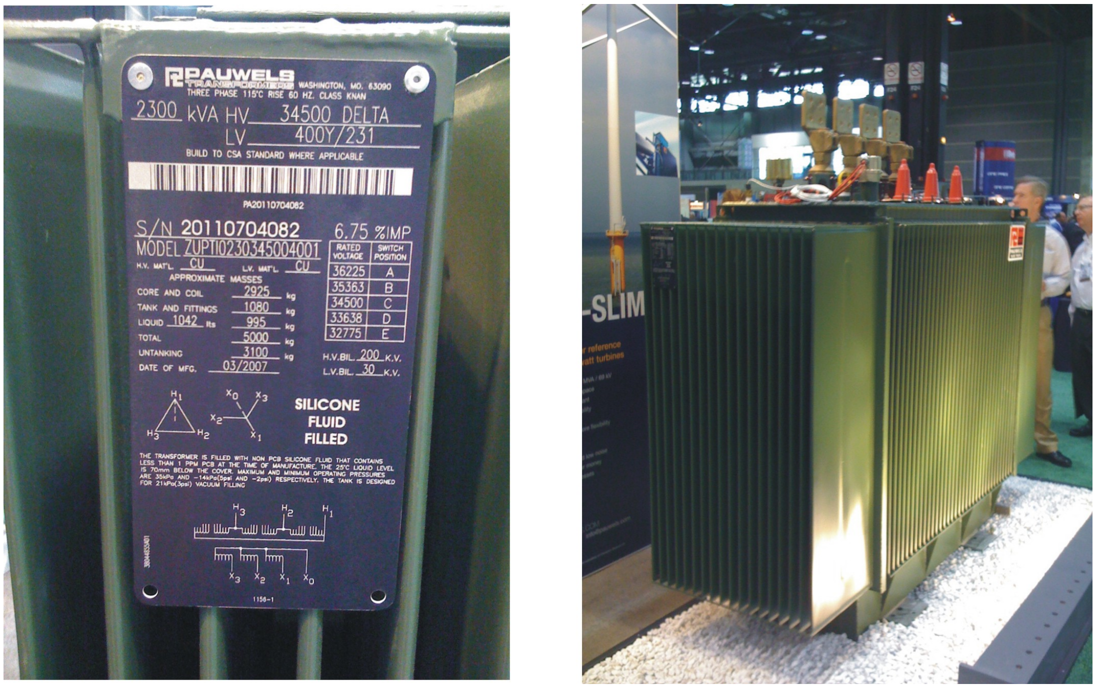



*Fig. 3.4.4. A 2,300 kVA, 34.5kV/400V, Nomex insulated, silicon filled wind turbine generator transformer*

### 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 risk, 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 for 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 for 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 providing a large number of batteries may not be practical or cost-effective. 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 load is needed for an operating wind turbine. The load needed to keep an idle wind turbine in a safe condition will be much less.

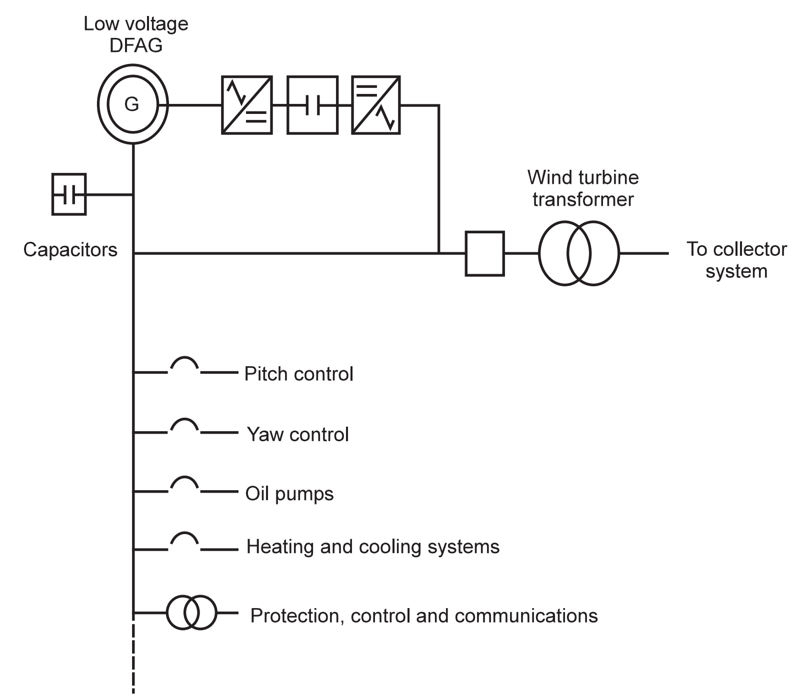



*Fig. 3.4.6-1. Auxiliary power supply for low-voltage generator*

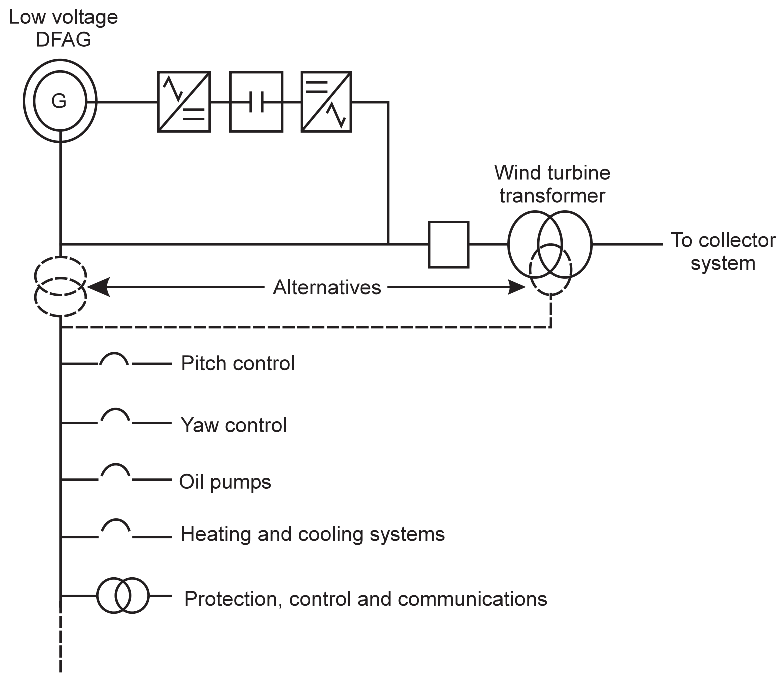



*Fig. 3.4.6-2. Auxiliary power supply for medium-voltage generator*

### 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 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. Conductive lightning receptors at the tip and along the side of the rotor blade 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 copper 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 current 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 the down conductor.

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*.

Some failure modes, however, are unique to double fed asynchronous generators used in wind turbine applications, including:

- 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, and periods of high humidity

  - Frequent load fluctuations due to the variability of wind

These same stresses also contribute to premature failure of the stator and rotor winding insulation and other components of the generator, including the power converter.

- Premature failure of the rotor winding insulation due to voltage spikes generated by the 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 from 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 supplying the 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 three to five years due to these premature failures.

Generator manufacturers have learned from these early failures and made the following improvements to their products:

- 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 active and reactive power control systems that 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

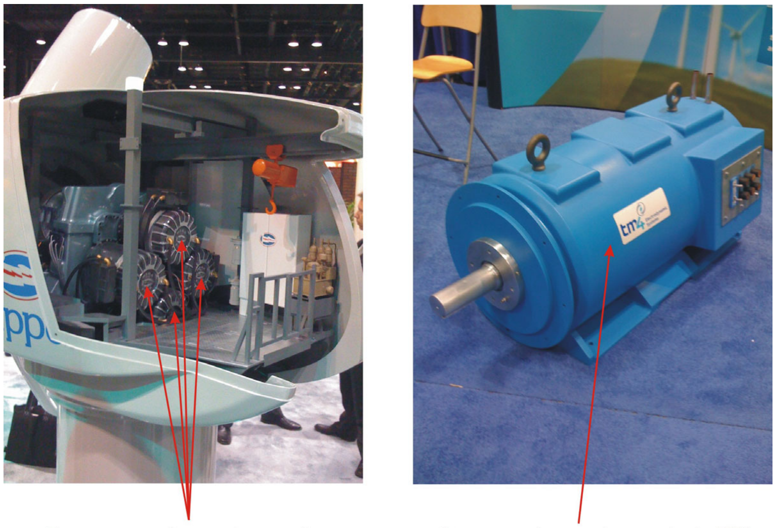



*Fig. 3.4.8. A 660 kW Megaflux permanent magnet generator, and four of these generators used in the Clipper 2.5 MW Liberty wind turbine*

## 4.0 REFERENCES

### 4.1 FM


Data Sheet 1-2, *Earthquakes*
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 and Containment Systems for Ignitable Liquids*
Data Sheet 9-0, *Asset Integrity*
Data Sheet 9-19, *Wildland Fire*
Data Sheet 10-1, *Pre-Incident and Emergency Response Planning*
Data Sheet 10-3, *Hot Work Management*
Data Sheet 13-7, *Gears*


### 4.2 Others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AS/NZS 1170.2:2011 Australian/New Zealand Standard, *Structural Design Actions Part 2: Wind Actions*

## 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. It 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:** A protective system that prevents corrosion by making the protected material a cathode, using either sacrificial anodes or impressed current 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. They 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) 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.

**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.

**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 and a resistance factor 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 should be less than or equal to Factored Resistance.

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

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

**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.

**Parked:** The turbine rotor is intentionally stopped and held stationary, typically with the blades feathered or pitched to minimize aerodynamic loads. In the parked state, the turbine’s control systems remain active to monitor conditions and ensure safe reactivation when appropriate.

**Repetitive Defects:** Three or more defects/failures of the same component model, with consistent failure modes, occurring at the same farm within a 12-month period.

**Rotor:** Includes the rotor blades and rotor hub assembly.

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

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

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

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

**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, such as in Canada, the UK and Europe.

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

**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.

**Yaw Error:** Describes a condition when the turbine is not correctly aligned with the wind direction. This can reduce efficiency and increase mechanical stress on the turbine components.

**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 land-based).

$L_w$: 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).

**October 2025.** Interim revision. The following significant changes were made:

A. Clarified modifications to IEC61400-1 for wind design.

B. Clarified human factor planning and response to severe environmental events.

C. Removed recommendations for hail protection.

**April 2025.** Full revision. The following significant changes were made:

A. Changed title to *Land-Based Wind Turbines and Farms*.

B. Removed all offshore windfarm guidance and references.

C. Completely restructured Section 2.

D. Clarified recommendations for lightning protection and lightning detection systems.

E. Clarified recommendations for wind turbine inspections, techniques, frequency and documentation.

F. Updated recommendations for Emergency Response Team procedures.

**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 and C.2 for an approximate summary of the maximum commercially-available sizes and rated power of land-based and offshore wind turbines.

*Table C.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 |

Refer to Figure C.1 for typical land-based HAWT components and schematics.

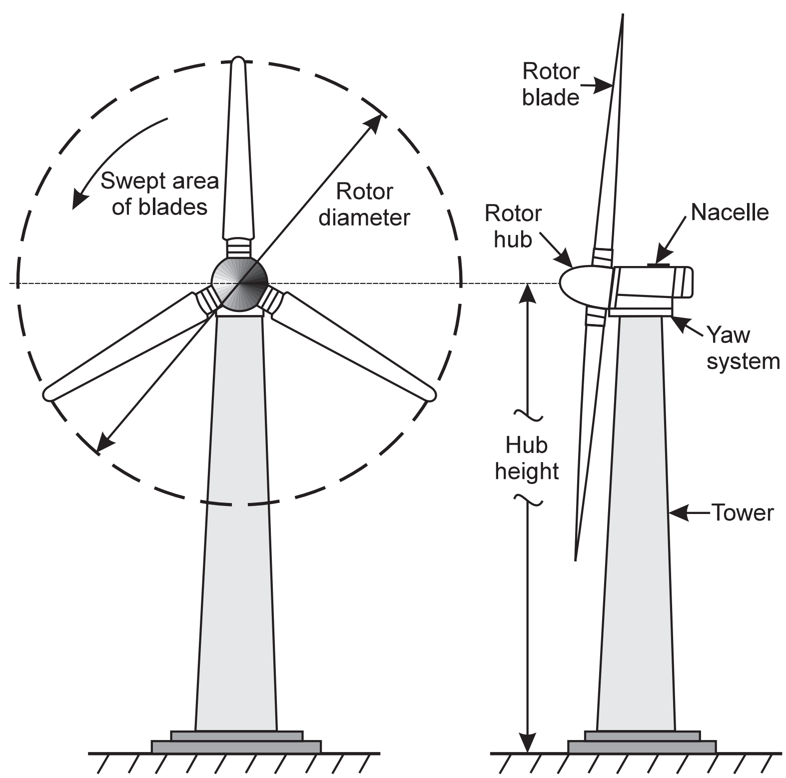


*Fig. C.1. Typical land-based horizontal axis wind turbine (HAWT) with a conical steel (steel monopole) support tower (foundation, instrumentation [e.g., anemometer] and lighting not shown)*

## C.2 Installed Wind Generating Capacity

Table C.2 shows the total cumulative installed commercial wind turbine capacity

*Table C.2. Total Cumulative Installed Commercial Wind Turbine Capacity at 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.

### 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

Danmarks Tekniske Universitet (DTU) Wind and Energy Systems
https://wind.dtu.dk/

WindEurope
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:

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 Lw = 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 $(\text{Hub Height}/33\text{ ft [10 m]})^{0.11}$ = (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 $(\text{Hub Height}/33\text{ ft [10 m]})^{0.11}$ = (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 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

$V_{hub}$ = $(V_A)$ x $(\text{Hub Height}/33\text{ ft [10 m]})^{0.11}$ = (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 $(\text{Hub Height}/33\text{ ft [10 m]})^{0.11}$ = (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.