Wind Energy Ireland Guide to Wind Turbine Lifetime Extension

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Contents

Introduction

This document is a high-level guide to the subject area of lifetime extension (LTE) of wind turbines. It should be noted that this guide is not a recommended or best practice guide and the intention of this document is not to replace or replicate actual life extension standards such as IEC 61400-28 or DNV GL-ST-0262 but to act as a companion document which aims to providing useful insights based on the experience of wind industry participants.

Acknowledgment: Wind Energy Ireland would like to thank all those who contributed to the preparation of this document for their time, specialist expertise and knowledge.

Abbreviations

Abbreviation	Meaning
ACFM	Alternating Current Field Measurement
ALARP	As Low as Reasonably Practicable
CMS	Condition Monitoring System
DEL	Damage Equivalent Load
DPI	Dye Penetrant Inspection
ECI	Eddy current inspection
EN	European Standards
IEC	International Electrotechnical Commission
ISO	International Organisation for Standardisation
LTE	Lifetime Extension
LVDT	Linear Variable Displacement Transducers
MPI	Magnetic Particle Inspection
MEC	Maximum Export Capacity
NDT	Non-Destructive Testing
O&M	Operations and maintenance
OEM	Original Equipment Manufacturer
PF	Probability of failure
RCAs	Root Cause Analyses
ToFD	Time of Flight Diffraction
UT	Ultrasonic Testing
WTG	Wind Turbine Generator

1 Overview

1.1 What do we mean by Lifetime Extension?

Wind turbines have typically been designed for a 20-year life based on a set of design (International Electrotechnical Commission (IEC)) conditions. When assessing if a wind turbine is suitable to be installed at a site the site conditions (wind speed, turbulence, inflow angle and wind shear) are compared to the design conditions of the chosen turbine model. If the loading experienced by the wind turbine due to the site conditions is less than the loading under the design conditions to which the turbine was designed, then the turbine is typically suitable for the site.

When examining the possibility of extending the working life of a wind turbine/farm this comparison between the loading due to the site and the design conditions is once again evaluated however at this stage the aim is to evaluate how much longer it could be possible to operate a wind turbine subject to the site conditions at the wind farm until the reliability level (i.e. probability that a major structural component will fail) is equivalent to that expected when designing the wind turbine, i.e. year 20.

Section 2 goes into further detail on design standards and certification of wind turbines, reliability definitions, structural design life and how a structural life assessment is carried out.

In addition to the calculation of the potential extended life of the structural components, there is a requirement for inspections of the wind turbine structural components and safety systems to verify the condition of the components and validate the assumptions in the numerical assessment. In combination with the inspection of the structural components, the major non-structural components including the gearbox, generator, bearings etc would typically be inspected to feed into any economic assessment of the working life. The results of the inspections then feed back into the estimation of the wind turbine structural life and economic life.

Section 3 gives further information on key considerations during LTE inspections as well as the planning and execution of a LTE inspection campaign to inform the overall assessment of the expected end of working life.

As well as considering the structural life of the wind turbine, the wind turbine foundation also needs to be considered. If the actual loading experienced over the life to date of the foundation is less than originally designed for, then there is also a possibility of extending the working life of the foundation. Using the original design documentation and load information a calculation can be made to estimate the potential extended working life. Inspections would also be needed to confirm the condition of the foundations. If due to a lack of data, it is not possible to calculate the foundation life or due to the presence of construction issues / defects then a condition-based life assessment approach may be needed to extend the working life.

Section 4 gives more background information on foundation design and key considerations for extended life as well as describing the analytical life assessment of foundations and the condition-based life assessment approach.

Section 5 provides guidance on important or useful information to save to support future life extension assessments and **Section 6** provides a list of life extension standards and useful reference documents.

Please note that the purpose of this document is to introduce the key concepts regarding extending the life of the main structural components i.e. wind turbine tower, blades, foundations etc. Other elements not discussed here such as control and SCADA systems, electrical cables, transformers etc. will require consideration as part of any LTE project.

2 Lifetime Extension Structural Analysis

2.1 Design standards and certification overview

Onshore wind turbines are most commonly designed according to the IEC standard 61400-1, “Wind Turbines – Part 1: Design requirements[1] or the DNV GL [2] and GL [3] standards. The stated purpose of the IEC design standard is “to provide an appropriate level of protection against damage from all hazards during the planned lifetime.” The IEC and other design standards are intended to be used in conjunction with numerous other IEC and International Organisation for Standardisation (ISO) standards, as well as ISO 2394, [4] and local building codes.

Wind turbines, type certified according to a certification scheme, are deemed to be mostly free from design defects and major engineering oversights; however, type certification does not provide a guarantee of structural integrity because:

i) actual wind conditions and operations experienced by the machine are widely variable; and

ii) manufacturing defects occasionally cause structural problems, and achieved strength is a function of both material properties and the quality achieved within the manufacturing process.

This is particularly the case with blades which are geometrically and materially complex structures.

Project certification or site-specific design assessment is the process by which the project loads are verified to comply with the design conditions of a specific standard given the certified turbine model selected. As part of the project certification process manufacturing, transportation, installation, and commissioning are also surveyed or witnessed to some degree.

Wind turbines certified to a design standard are expected to be capable of withstanding extreme and fatigue loads that would be generated by the wind conditions prescribed for the wind turbine class. The IEC type class specifications according to the 4th edition are provided in **Table 2.1** below.

Table 2.1 IEC Wind turbine type class specifications

Wind turbine class		I	II	III
V_{ave}	m/s	10	8.5	7.5
V_{ref}	m/s	50	42.5	37.5
A+	I_{ref}	18%		
A	I_{ref}	16%		
B	I_{ref}	14%		
C	I_{ref}	12%		

Where the parameter values apply at hub height and

- V_{ave} is the annual average wind speed;
- V_{ref} is the reference wind speed average over 10 minutes;
- A+ designates the category for very high turbulence characteristics;
- A designates the category for higher turbulence characteristics;
- B designates the category for medium turbulence characteristics;
- C designates the category for lower turbulence characteristics; and
- I_{ref} is a reference value of the turbulence intensity

Because of the complexities of commercial and technical design trade-offs, e.g., "platform" product development, many components are designed to withstand higher loads than those generated by the wind turbine class wind conditions, which implies an additional design margin above that achieved by application of the required safety factors for a given component.

Both fatigue and extreme strength must be considered in designing for this specified life. The fatigue limit state is considered to be the primary limitation governing extended wind turbine lifetime.

Note: The foundation wind loading documents are based on a return period of 1 in 50 years, i.e. a turbine designed according to the wind turbine class with a reference wind speed V_{ref} is designed such that it can withstand the environmental conditions in which the 10-min mean of the extreme wind speed with a recurrence period of 50-years at hub height is equal to or less than V_{ref}. The foundation loads generally include inertia, mass and aerodynamic forces acting on the rotor and hub. They also include forces caused by accelerations or other dynamic reactions.

The three main methods of representing dynamic loads utilised on onshore wind power sites are damage equivalent loads, damage equivalent load spectrums and Markov matrices. All data formats are a statistical approximation of extremely complex variable dynamic wind and machinery loadings. These dynamic loads are utilised for the foundation design to determine the fatigue performance and are generally presented in the fatigue loading section of the foundation loading document.

2.2 Reliability definitions

Structural reliability is defined according to the ISO standard 2394:2015 General Principles on Reliability for Structures [4] as the " ability of a structure or structural member to fulfil the specified requirements, during the working life, for which it has been designed."

A **target** or **design** reliability level is the reliability level (safety critical failures per year) that the structure is designed to be at, or above, for the duration of its design life. This can be expressed as the inverse probability of failure: the lower the probability of failure, the more reliable the structure, and the higher the reliability level.

A target reliability level is determined through consideration of various factors including the consequences of failure (impacts to people, the environment, economic loss and social impacts) balanced against the cost of measures that would reduce the risks of failure. Various industries have worked to establish target reliability levels that are acceptable to stakeholders - regulatory, financial, owners, and the public. These are often communicated in the form of standards and/or regulatory requirements, but are also implied in design, siting or operating requirements.

The ISO 2394 standard provides some general guidance on target reliability levels for a vast range of engineering structures. More specifically for wind turbines, the DNV-OS-J101 standard [6] presents an interpretation of the IEC 61400-1 edition 2 standard in terms of target reliability:

"a wind turbine is designed to a reliability level expressed as a nominal annual probability of fatigue failure of one in ten thousand (10^{-4})"

i.e. the design lifetime is the year at which the expected annual probability of failure (Pf) reaches 10^{-4} if the site conditions perfectly reflect the IEC design inflow conditions which equates to a 1 in 10,000 chance of a failure occurring over the course of a year.

2.3 Structural design life

Structural design life is the number of operating years after which the attained reliability level is expected to drop below the target design reliability level, given the specified design conditions for the turbine class. Design life of wind turbines is stipulated by the design standards as a minimum of 20 years (with some turbines now being designed for 25 years).

Stated differently, if a wind turbine is designed to a reliability level expressed as a nominal annual probability of fatigue failure of one in ten thousand (10^{-4}), then the lifetime is the year at which the expected annual probability of failure reaches 10^{-4}.

Because no site will conform perfectly to the wind turbine class wind regime, it is useful to define the term **structural site life,** which can be used to represent the calculated number of years to reach the design structural reliability level under site conditions. In other words, the structural site life is the number of years a turbine can operate in site-specific wind conditions before the expected fatigue damage on the structural components exceeds the fatigue damage that would be expected in the design wind conditions over the design lifetime.

Figure 2.1 displays an example graph plotting annual nominal probability of failure vs year for a site where the site conditions are not as severe as the IEC conditions resulting in a 'nominal lifetime result' greater than 20 years. This is displayed as the point whereby the failure curve crosses the 10^{-4} y-axis intersect.

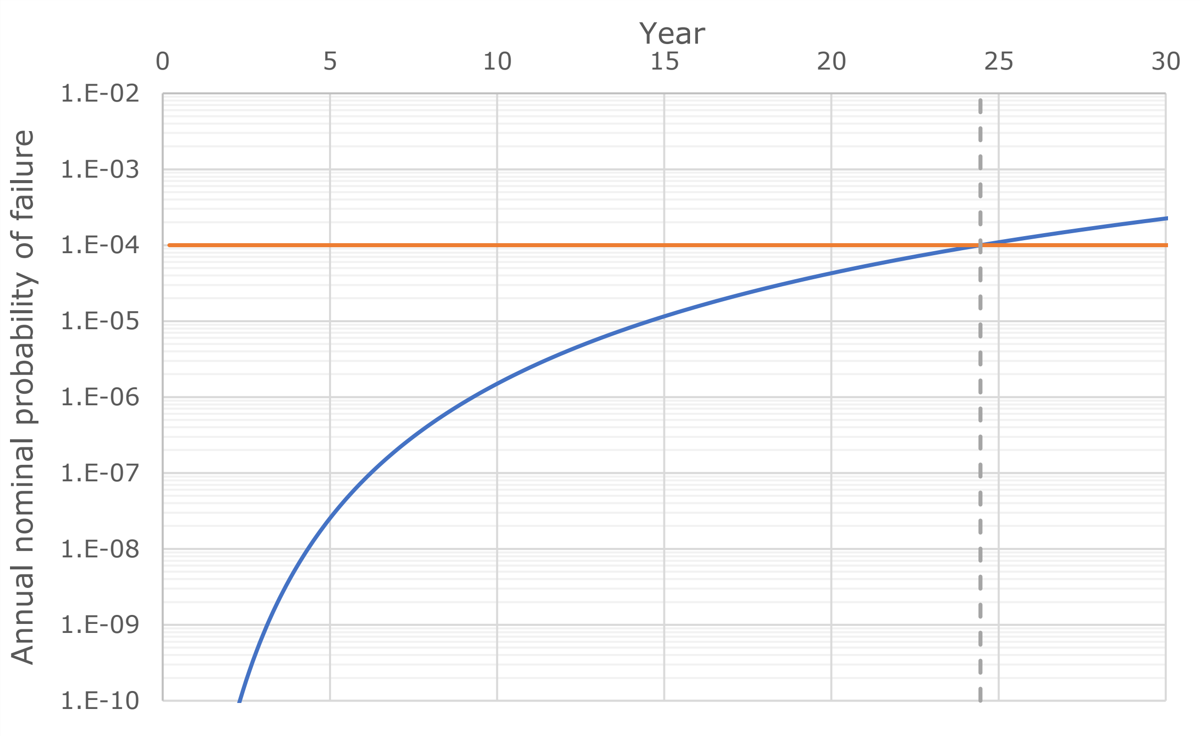

Figure 2.1 Example visualisation of a failure rate curve for a life extension project. The dotted vertical line represents the year after which the probability of failure exceeds the reference value of 1e-4. This gives the nominal lifetime.

Design margin and site load margin refer to ratios of strength and load. Design margin is the ratio between the designed component strength and the load it was designed to withstand. Site load margin is the ratio of design load to site load. For fatigue loads, site load margin is typically calculated as the design damage equivalent load (DEL) derived from load cases provided in design standards—divided by the corresponding DEL imparted by the site conditions over 20 years, minus 1.

When turbines are sited conservatively, there is positive site load margin. For example, if there is an 8% site load margin on the main shaft in bending, this implies that the loads imparted by the site conditions are 8% lower than the design loads. As a simplification, it is normally acceptable to assume that site load margin and design margin are additive; thus, a 5% design margin and 8% site load margin means the main shaft is capable of resisting loads 13% greater than are expected at the site. The impact of margin on fatigue life is non-linear and depends on the material fatigue strength characteristics.

The design standards define guidelines to design a wind turbine following a deterministic approach. The guidelines contain a number of conservative measures (for example the application of partial safety factors) that have been calibrated in order for the turbine design to fulfil the target reliability level, with the aim to account for all the uncertainties associated with the turbine design process. This also applies for the site-specific loads assessment, which is described by the standards following the same deterministic approach. It is feasible therefore to establish an estimate of the structural site life by establishing the number of years necessary to accumulate the type class fatigue level under site specific environmental conditions as shown in **Figure 2.2** below.

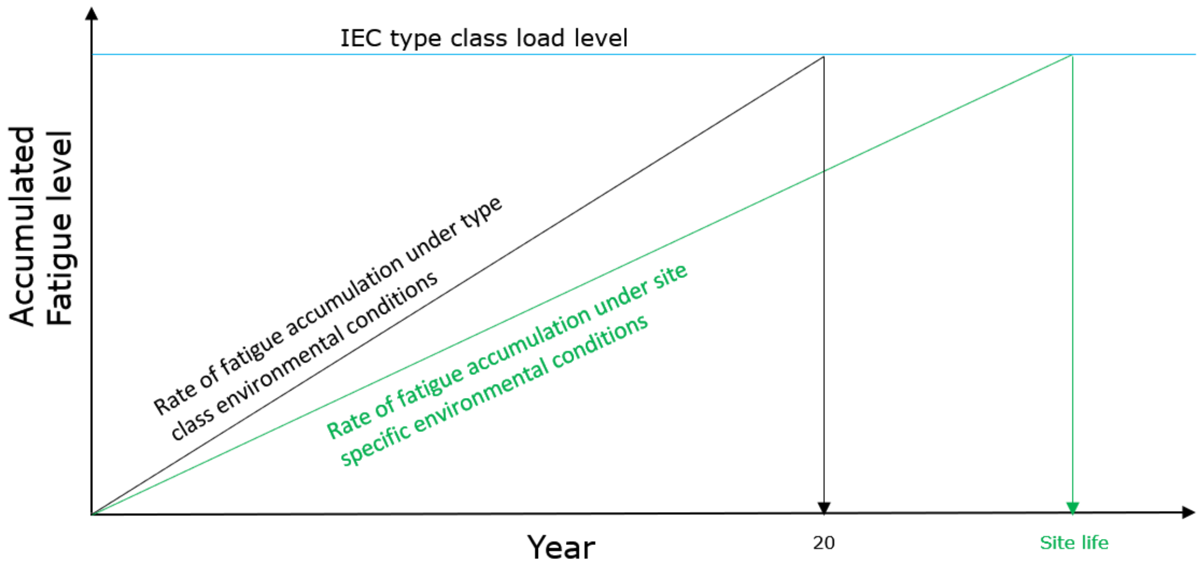

Figure 2.2 Using the deterministic approach to estimate site life

2.4 Structural life assessment

In order to estimate the structural site life, an evaluation of the historical and expected future loading is required. This can be developed from an assessment of the site conditions based on both pre-construction meteorological data as well as data from the operating period. With this data, the site loading can be estimated and compared against the design loading. The loads can be estimated through aeroelastic simulations estimating both site loading and design loading through modelling site and design inflow and operating conditions.

This assessment can be performed by an experienced consultant or by the turbine manufacturer.

The input parameters to the analysis are typically:

- **Wind Speed Distribution**

The wind speed distribution is used to give appropriate weighting to the loading scenarios that occur most often for each turbine. Therefore, it can have a strong influence on fatigue loading as it determines how this loading is accumulated across the many operating states and environmental conditions experienced by a wind turbine.

- **Wind shear exponent**

This is used to describe the wind velocity variations with height. The variation in wind speed across the rotor can lead to an increase in the fatigue loading on the rotor. The wind shear at a site may change over the life of a wind farm due to changes in tree growth/forestry felling.

- **Turbulence**

Fatigue loading on many turbine components is heavily influenced by the turbulence intensity. The turbulence intensity is a measure of the variability of the wind speed and this will be mirrored in the aerodynamic loads on the structure. Within a wind farm, the turbulence intensity is split into the ambient turbulence levels and any additional turbulence that might be generated from the wake of a neighbouring turbine.

- **Air Density**

Aerodynamic loads are proportional to air density and thus can have a strong impact on fatigue load levels.

- **Flow inclination**

Flow inclination describes the angle between the horizontal plane and the direction of wind hitting the turbine. Wind turbines on steep slopes will experience larger inclinations. It has a cyclic effect on the inflow angle of a wind turbine blade which affects its aerodynamic force and so fatigue loading, mainly on the blade itself.

- **Turbine availability**

Availability refers to the ratio of time the turbine can operate vs available hours. The greater the availability the greater the fatigue loading.

The following additional information is useful to inform the analysis:

- **Operating schemes**, such as wind sector management, curtailment, derating or upgrades e.g. power boost etc.;
- **Component failure history** (if available including records from other wind turbines of the same type);
- **Maintenance activity history**;
- **Fault and downtime history** including emergency stop (and start) statistics; and
- Impact of any **historical severe events**, such as hurricanes and earthquakes

3 Wind Turbine Inspections

3.1 Objective

The primary objective of carrying out physical WTG inspections as part of a LTE assessment is to assess the condition of the WTG's critical structural components to determine if they are fit to continue operating safely beyond the design lifetime (i.e. 20 years) and to validate any assumptions made in the analytical analysis. The WTG critical structural components are considered to be the following:

- Tower;
- Blades;
- Pitch System;
- Yaw Ring and Bearing;
- Nacelle frame/bedplate;
- Hub;
- Bolted/welded joints;
- Main bearing;
- Main shaft;
- Safety System; and
- Foundation;

As well as the inspection of structural components, the inspection of non-structural (replaceable) components is desirable in order to feed into the wider analysis regarding the economic case for extending the life of the WTGs. The WTG non-structural components are considered to be the following[1]:

- Gearbox;
- Generator;
- Yaw Drives;
- Transformers;
- Converters; and
- Nacelle housing and external fixtures.

[1] Electrical elements such as control and SCADA systems, electrical cables, transformers etc. were omitted from the scope of this document.

3.2 Lifetime Extension Inspection Pre-requisites

3.2.1 Inspection Personnel

To ensure that the LTE inspection campaign fulfils its objectives, it is important that those carrying out inspection work:

- are sufficiently qualified and experienced to identify the issues they are inspecting for and can take appropriate measurements required to interpret the condition of the WTG's structures and components;
- Accurately record the condition of critical components and report findings in a consistent format (in line with the requirements set out in Annex 1 – Reporting Requirements).

3.2.2 Review of relevant documentation

The WTGs will be inspected at regular intervals during their life as part of scheduled maintenance, for end of warranty inspections and at owner-specified periods. It is generally recommended that independent inspections (i.e. inspections by someone other than the entity carrying out the operations and maintenance (O&M)) of WTGs are carried out at 5-year intervals in order to track the condition of the turbines. Planning for LTE inspections should take place in the period up to five years before the end of the design life (years 15 to 20 for a 20-year design life). All available material relative to previous inspections and maintenance carried out over the lifetime of the WTG (including the scope of maintenance activities under third-party O&M contracts) should be collated and made available to the Inspector at least 4 weeks prior to the scheduled commencement of inspections. This would include information such as recent inspection reports, monthly asset manager or Original Equipment Manufacturer (OEM) reports, Root Cause Analyses (RCA) reports, the detailed history of major component failures at the site and oil and grease sample results. This will inform the LTE inspections and ensure that the findings between successive reports are linked and any specific defects or concerns are monitored.

3.3 Lifetime Extension Inspections

Set out below are the recommended inspections to be undertaken as part of the LTE assessment. The schedule of inspections assumes there are no existing pre-eminent faults identified on the turbine prior to the LTE inspections; however, where the inspector's preliminary review of available documentation (as described above) identifies particular issues, these should be included in the scope of the inspections as required.

The inspections are divided into two categories:

- **Primary Inspections**; and,
- **Secondary Inspections**.

Primary inspections make up the majority of the scope of work and generally entail detailed visual inspections of components with some invasive techniques also utilised. The primary inspections will be scheduled and undertaken by the inspector. Following the primary inspections, it is likely that the inspector will identify particular areas such as potential defects for further investigation during the secondary inspections. The secondary inspections may necessitate the procurement of specialist third parties to execute the tests/checks required. Therefore, there may be a number of weeks between the primary and secondary inspection tests and this should be factored into any programme for LTE assessment.

3.4 Non-Destructive Testing (NDT)

Where required, secondary inspections generally consist of some form of NDT. This form of testing can be used to determine length and depths of weld defects or areas of corrosion for example. Where NDT is recommended in the inspections within this report, it can refer to any number of individual or combined techniques. A non-exhaustive list of methods that can be used in NDT (either alone or in combination) of suspected structural weld faults, e.g. on tower or hub section, are listed below:

- Phased Array Ultrasonic Testing (UT);
- Time of Flight Diffraction (ToFD);
- Alternating Current Field Measurement (ACFM);
- Magnetic Particle Inspection (MPI);
- Dye Penetrant Inspection (DPI);
- Eddy Current Inspection (ECI);

Due to the time and costs associated with NDT, it may be completed as a follow-up activity by a specialist third-party after areas of concern have been identified. Alternatively, it may be completed in-house if the resources, equipment and expertise are available.

Typically, NDT is used when visual inspections reveal any areas of concern, or if the owner becomes aware of any common failure areas which require a more thorough assessment.

- Where visual inspection does not identify any cracking, the owner should evaluate an appropriate period to repeat inspections based upon the output of the analytical assessment, and the results of inspections at all the WTGs at the wind farm site.
- Where minor cracks[2] are found, a repeat inspection at a six-month interval is recommended.

When assessing cracks, note should be taken of the crack width, depth, length and directions, for comparison with future investigations. Staining around the crack should also be noted. If any cracks are identified, it is recommended that an expert is consulted to determine the risk associated with the defects.

[2] While it can be difficult to quantify, 'minor cracks' may refer to cracks of a very minor length on or near high stress areas which show no progression over repeated inspections or cracking of greater length on non-critical or low stress areas. If it is believed that the structural integrity of the component is at any risk where cracks are identified, then suitable repair options should be considered.

3.5 Structural Inspections

Inspection of the structural components of the WTG are considered essential. **Table 3.1** is provided as a guideline for inspections to be undertaken as part of any LTE assessment. Primary inspections listed in the table are considered essential. Secondary inspections are also considered essential in the event that a potential defect/issue has been identified during primary inspection.

Guidelines on inspection techniques to be employed are provided later in this section.

Table 3.1 Guideline for structural inspections to be undertaken as part of any LTE assessment

Element/Component	**Primary Inspection**	**Secondary (Enhanced) Inspection**
Tower		
Structural welds	100% visual inspection (internal and external)	NDT of surface cracks to determine length and depth
Tower corrosion	Visual inspection (internal and external)	Measure loss of corrosion protection (if possible)
Tower verticality	Measure	
Deflection	For embedded can type WTGs only	
Blades		
Aerofoil surfaces	100% visual inspection of aerofoil, particularly leading edge and trailing edge	
Blade roots	Visual inspection	NDT (if possible)
Blade interior	Visual inspection	
Pitch System		
Blade bearings	Visual inspection of high stress areas	NDT of cracks/damage (if possible)
Grease	Grease analysis	Detailed visual inspection of blade bearings
Emergency system	Functional test	
Yaw Ring and Bearing		
Teeth	Visual inspection	
Bearing	Visual inspection	
Grease	Grease analysis	
Nacelle frame/bedplate		
General structure	Visual inspection of all visible areas	

Element/Component	Primary Inspection	Secondary (Enhanced) Inspection
Structural welds	Visual inspection	NDT of cracks/damage
Bolted/welded joints		
Corrosion of bolts	Removal of sample for inspection	
Torque markings	Visual inspection for any movement	Torque check
General	Tap test	
Hub		
General structure	Visual inspection of all visible areas & NDT of any pre-existing casting defects	
Mounted ancillary components	Visual check of integrity of components	
Main bearing		
Main bearing	Visual inspection	
Seals	Check integrity of seals	
Grease	Grease analysis	
Housing	Visual inspection	NDT
Main shaft		
Main shaft	Visual inspection	NDT
Foundation		
Grout	Visual inspection	
Holding down bolts	Visual inspection Torque check	
Visible areas of the foundation (incl. surrounding ground conditions and drainage)	Visual inspection	Invasive inspections, e.g. core sampling, if determined necessary
Safety System		
Safety system	Functional check	

3.5.1 Tower

Primary Inspection

The inside of the tower (welds, tower cables, lighting etc.) should be inspected from the ladder and platforms and the outside should be inspected by drone for corrosion, cracks, spalling in the supporting steel/concrete structures, deformation, gaps etc. The tower doorway welds should be a focus area due to the stress concentration on the doorway. The tower inspection should also identify loose, corroded or missing bolts. Tower verticality can be carried out using a theodolite or inclinometer.

Secondary Inspection

The towers may require enhanced visual inspection or, where appropriate, NDT may also be necessary. Tower movement relative to foundation can be established using a dial gauge as part of a pause test.

3.5.2 Blades

Primary Inspection

Visual inspections of the blades should identify any new damage and monitor known damage (identified in previous reports). Effects of lightning strikes should be inspected where applicable. The visual inspection should cover all parts of the blade including the leading edge, trailing edge, the pressure side, the suction side, the root, the lighting protection system, retrofits (or aerodynamic hardware such as vortex generators or serrated edges) and repairs. Blade inspections can be undertaken using drones, ground-based high-definition cameras or manual rope-access as long as the level of blade erosion can be determined, i.e. has the erosion penetrated (i) top coat, (ii) laminate, (iii) core material.

The blade root is a particularly critical location given the high cyclic stresses it is subjected to over the operational life of the WTG.

An internal inspection of the root, laminate and main spar (to the extent possible) should also be carried out to identify any damage of the laminate. Where internal blade inspections cannot be undertaken, the recommended frequency of external blade inspections may increase in order to compensate for any uncertainty in blade LTE estimates due to inaccessibility of the internal blade.

Secondary Inspection

NDT of the blade root can be carried out using Phased Array UT.

3.5.3 Pitch System/Blade Bearings

Primary Inspection

The blade bearings will require thorough visual inspection and grease sampling. Grease analysis will identify particles of iron or chromium if present. This may indicate excessive wear and tear.

Secondary Inspection

MPI or UT should be performed on any suspect areas.

3.5.4 Yaw Ring and Bearing

Primary Inspection

Checks for cracks and excessive wear and tear in gear-rim and pinion teeth to be undertaken including a check in general integrity of the yaw system.

Grease analysis should be undertaken and excessive grease leakage from the yaw bearing should also be recorded if identified.

Secondary Inspection

NDT to be undertaken on any cracks in gear-rim and pinion teeth to understand dimensions of the cracks.

3.5.5 Nacelle Frame/Bedplate

Primary Inspection

The WTG machine frame should be subject to a thorough visual inspection to confirm its integrity with key focus on locations where major components are mounted. All structural welds should be identified and inspected for defects. This inspection should look for cracking, corrosion or other damages as well as any modifications that have been made to the original design.

Secondary inspection

A non-exhaustive list of methods that can be used in NDT (either alone or in combination) of suspected structural weld defects are listed below:

- UT;
- ToFD;
- ACFM;
- MPI;
- DPI;
- ECI;

NDT may be necessary if the visual inspections reveal any areas of concern, or if there is awareness of pre-existing common modes of failure which require a more thorough assessment.

3.5.6 Bolted Connections

Primary Inspection

Bolted connections that are subject to fatigue loads should be subject to checking. The maintenance history of these bolted connections should also be reviewed if possible, to identify if there is a history of bolts not having been maintained correctly or other issues.

Review of the bolt torque markings when initially tightened (if possible) and tap testing of bolts should be carried out.

Secondary inspection

Torque checks on an appropriate sample of bolts should be carried out. A sample of bolts may also be removed and inspected for corrosion with bolts replaced.

3.5.7 Rotor Hub

Primary Inspection

The rotor hub should be visually inspected to identify any visible cracking or damages. This inspection should cover bolting, castings, shaft connection, spinner and slipring. Particular care should be taken to ensure that castings are properly inspected.

Secondary inspection

Where visual inspection identifies any areas of concern, NDT may be completed by performing MPI or UT on any suspect areas.

- If minor cracks are identified, a minimum inspection interval of six-months or less is recommended, depending on the severity of the cracks.
- If progressing cracks are found, repair works should be initiated, with regular periodic inspections. The length of time between inspections should be evaluated based on the severity and rate of progression of cracking.

3.5.8 Main Bearing

Primary Inspection

The WTG main bearing (including main bearing housing) should be visually inspected to identify any damage. In particular, inspection of the housing mounting points onto the nacelle bedplate is required. Grease sampling and checking of integrity of seals should be undertaken. Borescope inspections of bearing condition should be carried out where possible.

- Where these inspections find no significant damages beyond wear-and-tear, the owner should evaluate an appropriate period to repeat inspections based upon the output of the analytical assessment and the results of inspections at all the WTGs at the wind farm site, with a two-year interval recommended as a minimum.
- Where progressing but non-critical damages are detected, grease flushing and monitoring should be considered, and an annual inspection interval is recommended.
- Where critical damages are found, replacement works should be initiated, and enhanced inspections at three-month intervals are recommended when no other monitoring means exists. Where other suitable monitoring means exist (i.e. CMS) close supervision should be maintained and alarm thresholds set to interrupt operation whilst awaiting a replacement part.

3.5.9 Main Shaft

Primary Inspection

The main shaft should be visually inspected for surface corrosion, fretting or other damage such as scoring, particularly at the rotor side of the main bearing. If there is evidence of forging defects in the main shaft within the manufacturing documentation for the asset, it is recommended that NDT is undertaken.

Secondary inspection

None specified. Further inspection at discretion of asset owner.

3.5.10 Foundations

Primary Inspection

Tower to Foundation interface checks to be undertaken are as follows:

- Waterproof seals should be inspected for wear, cracking or disintegration;
- The grout interface should be checked for visible signs of damage, cracking or deterioration which may permit water ingress;
- Inspection of Anchor bolts and tensioning/torquing should be carried out to confirm any potential rate of pre-load drop off. Check for distortion including thread damage and corrosion; and
- Condition check of visible portion of the embedded can for any signs of corrosion, distortion or indications of loss of watertightness. Checks should also be undertaken for vertical differential movements and any remedial works undertaken (e.g. evidence of grouting).

Concrete surface checks:

- Check for signs of spalling/delamination;
- Map structural cracks (if any) along with crack widths;
- Crack movement monitoring using Linear Variable Displacement Transducers (LVDTs);
- Check for surface deposits (i.e. rust staining, efflorescence etc.).

Surrounding Ground conditions:

- Check of line and level of foundation to determine movement (i.e. settlement, rotation, or slip);
- Inspect for slip, settlement, subsidence, or deformation of adjacent embankments;
- Look for foundation overburden material loss (if any); and
- Check for signs of ground movement or distress (cracks, heave, depressions, pumping of fines etc.).

Drainage:

- Inspection of installed drains condition and performance to ensure water remains at an appropriate level to ensure stability (e.g. camera surveys); and
- Groundwater monitoring (for e.g. standpipes) and installed drainage inspection works.

Secondary Inspection

In the case of secondary inspections of foundations, these are at the discretion of the asset owner due to their invasive nature. Such inspections may include core sampling or tower deflection measurements for example.

3.5.11 Safety System

Primary inspection

A functional check and condition check of all safety and protection systems is required including but not limited to the following:

- overspeed detection (injection testing to test system response and testing of the sensor);
- primary braking;
- pitch actuation;
- secondary braking;
- fall arrest on the elevator; and
- fall arrest on the ladder;

Secondary Inspections

Not applicable. All checks included in primary inspection.

3.6 Non-structural inspections

Inspection of the non-structural components of the WTG are not considered essential but are recommended. While these components do not affect structural integrity, they may affect reliability and any findings from associated testing would add value to the LTE assessment.

Table 3.2 is provided as a guideline for inspections to be undertaken as part of any LTE assessment. Primary inspections listed in the table are considered essential. Secondary inspections are also considered essential in the event that a potential defect/issue has been identified during primary inspection.

Guidelines on inspection techniques to be employed are provided later in this section.

Table 3.2 Guideline for non-structural inspections to be undertaken as part of any LTE assessment.

Element/Component	Primary Inspection	Secondary Inspection
Gearbox		
Gear Teeth	Borescope inspection	
Oil	Oil analysis	
Sump	Check of swarf magnet (if present)	
Generator		
Mounting and bolt torquing	Visual inspection and torque check	
Alignment with gearbox	Measure	
Grease (from bearing)	Visual inspection	Grease analysis
Air gap	Visual check	
Slip ring and brushes	Visual check	
Cabinets	Visual check	
Yaw Drives		
Pinion	Visual inspection and functional check	NDT of cracks/damage (if possible)
Transformer		
Transformer	Visual inspection (and oil sampling if applicable)	Thermographic survey and partial discharge testing
Converter		
Cabinet	Visual inspection	Thermographic survey
Nacelle		
External fixtures and fittings	Visual inspection	

3.6.1 Gearbox

Primary Inspection

The gearbox and its housing and/or supports should be subject to a visual inspection which should look to identify any cracking, corrosion or other damage. Borescope inspections of the gearbox internal condition (teeth, bearings, shafts) should also be completed to identify cracking, pitting, scoring etc. Lubricant sampling and analysis of gearbox oil should also take place to identify particles, corrosion, moisture levels and any other contamination. If there is a swarf magnet in the sump, a visual check for particles should be undertaken.

Secondary Inspection

There are no secondary inspections specified. Further inspections of gearbox are at the discretion of asset owner.

3.6.2 Generator

Primary Inspection

The generator should be visually inspected. The mounting point and bolt tightness should be checked. The air gap must be checked for dirt. The slip ring and brushes to be checked for dust and/or carbon build-up. Cabinets should be checked for general cleanliness and to ensure all cables and components are secure and in good condition.

This inspection should look to identify any wear, corrosion, leakage of grease/lubricants or other damage. A visual check of the grease discharge should be undertaken to identify particles or any variance in colour.

Generator electrical testing and generator alignment testing should take place in line with manufacturer's recommendations.

Secondary Inspection

In the event that the visual inspection of grease discharge identifies potential issues such as presence of particles, bearing grease sampling should also take place.

3.6.3 Yaw Drives

Primary Inspection

A functional check of the yaw drives should be undertaken in conjunction with a visual inspection of the condition of the pinions, particularly the pinion teeth.

Secondary Inspection

If cracks are identified, NDT can be carried out to determine crack length and depth if viable or alternatively replace.

3.6.4 Transformer

Primary Inspection

The transformer should be visually inspected to identify issues with the insulation. Other potential issues include leakage, over temperature, moisture or dirt. Oil sampling is also recommended.

Secondary Inspection

In the event that the visual inspection identifies areas of concern thermographic inspection and partial discharge tests can be performed.

3.6.5 Converter

Primary Inspection

Visual inspection of the converter cabinet for general cleanliness and any loose cable connections or discolouration around terminations.

Secondary Inspection

In the event that the visual inspection identifies areas of concern, thermographic inspection can be undertaken to detect any loose connection or excessive resistance.

3.6.6 Nacelle

Primary Inspection

A visual inspection of the fixtures and fittings on the outside of the nacelle to ensure they are secure is recommended. This includes access hatches, bolts, anemometry fixings.

Secondary Inspection

None specified. Any further inspections are at the discretion of the asset owner.

A sample WTG Inspection Checklist Template is included in Annex 2 – Sample WTG Inspection Checklist Template.

3.7 Follow on actions from the Lifetime Extension Inspections

Following completion of the inspections the following actions should be carried out:

- Compare the results of the LTE inspections to the analytical analysis to confirm whether the input assumptions were correct or if some assumptions to the analysis need to be varied and the analyses rerun.
- Immediately risk assess any major issues identified during the inspection in order to safeguard life and asset integrity.
- Implement corrective actions within the timeframe recommended in the inspection report and otherwise as soon as reasonably practicable in accordance with good industry practice.
- Retain all pertinent findings and record these on an active Risk Register with asset designation clearly referenced. This register should be reflective of the asset's operational history and of any LTE assumptions.
- Assess any future inspection schedule and any individual inspection requirements which may be appropriate for that asset and the condition observed. Such assessment will be risk based and in line with industry best practice.

4 Lifetime Extension Assessment of Onshore Wind Turbine Foundations

4.1 Background

Wind turbine foundations are a critical support structure for wind turbines. The failure of the foundation could result in the wind turbine partially or fully collapsing and being rendered inoperable. Therefore, it is recommended that the condition and integrity of wind turbine foundations is continually assessed during service and prior to LTE to avoid unexpected issues developing.

When designing WTG foundations, a design lifetime of 20 to 25 years is generally assumed as a basis for dimensioning or sizing the foundations. Similar to turbine components, the probability of failure of wind turbine foundations increases with operating time. When foundations are operated beyond the original design lifetime, they will eventually reach a level of reliability below that intended by the original design. Whilst in some cases it may be many years before this happens, continuing to operate beyond the design lifetime exposes the owners and other stakeholders to risks associated with the possibility of catastrophic failure such as injury to people, costly unplanned repairs, loss of income, property damage, environmental damage or negative impacts to public relations and reputation. Therefore, in late life, careful consideration of both the foundation design life and actual condition of the foundations will need to be taken in order to operate the foundation beyond its design life safely.

The design of onshore wind turbine foundations is typically done on a site-specific basis taking into account the geotechnical properties at the site, the expected loading from the wind turbine over the design lifetime based on the measured site conditions or design (IEC) conditions and the material properties of the construction materials used.

Assuming that there are no latent problems in the original design or construction works and that operational conditions have not been more onerous than design conditions, the service life of foundations may generally be extendable. This expectation, however, should be evidenced through analysis and ongoing monitoring.

4.2 Analytical foundation life assessment approach

Where information is available, it is advised that an analytical foundation life assessment is performed to estimate the lifetime of the foundation, i.e. the calculation of the reference period of time for which the foundation (or component of the foundation) is expected to perform safely, with the level of reliability associated with the selected design standards (in the European market, the standards adopted by the designers when designing for fatigue are Eurocode and IEC 61400-1 standards). The analytical foundation life assessment is also useful to inform critical areas to focus on during foundation inspections and maintenance activities.

The main basis of an analytical foundation life assessment may include geotechnical and structural assessment work using the wind turbine supplier produced static and cyclic loading information. These checks may be utilised to identify potential areas and levels of structural risk associated with each foundation type. The results may indicate that additional measures such as enhanced inspection work, As Low as Reasonably Practicable (ALARP) studies or structural intervention and remediation works will be required.

Provided that the original design is suitable and that there have been no construction or operational issues, the fatigue[3] life of structural components is in most cases the driving factor to foundation life extension.

4.2.1 Analytical assessment scope

The analytical foundation life assessment scope would include:

- A review of the ground conditions to determine susceptibility to cyclic soil degradation[4] and to estimate soil parameters for modelling of the foundation;
- An assessment of the durability of concrete materials[5]; and
- A numerical study to estimate fatigue design life of foundation components.

Typically, a deterministic analysis process will be used to estimate fatigue design life, adopting material properties, loads and partial factors from IEC-61400 supplemented as necessary using European Standards (EN). The reliability level associated with the fatigue design life will be the reliability level inherent to the adopted standards and partial factors.

Fatigue life would be assessed for each of the foundation components (reinforcement, concrete, grout, anchor bolts, etc.), considering all potential failure modes.

4.2.2 Required data

The following information is required to complete the analytical foundation life assessment:

- Cyclic loads at tower bottom in the form of Markov Matrices;
- As-built detailed foundation drawings and specifications;
- Detailed drawings of tower-foundation interface components (embedded can or anchor-bolts cage, as applicable);
- Interpretive geotechnical investigation report; and
- If relevant, records of foundation related issues during construction and operation.

In addition, construction records, quality assurance documentation and inspection reports should be reviewed to confirm the historical condition of the foundation.

It should be noted that codified fatigue checks are extremely sensitive, normally based on logarithmic formula. This means small deviations between estimated stress ranges in specific elements can result in major differences in the estimated fatigue damage accumulations. This is a particular problem in

[3] The term 'fatigue' in structural engineering refers to the progressive and localised structural damage that occurs when a material is subjected to cyclic loading. A fatigue failure can occur at loads and stresses much less than the ultimate strength of the material or structural element.

[4] Long-term cyclic loading can lead to cyclic degradation of the foundation bearing strata in the form of reduction of stiffness and geotechnical resistance. Cyclic degradation can result in a reduction of the turbine natural frequency, an increase in total and differential settlements and a reduction of the overall geotechnical bearing capacity.

[5] Durability refers to the ability of the material to withstand the ambient conditions for which it is designed without deterioration of its engineering properties for a reference period of time. Durability is dependent on project specific ambient and ground conditions, as well as design characteristics and quality of construction. Adequate performance of foundation components is therefore subject to sufficient durability of materials.

reinforced concrete analysis where codified design rules are based on a series of simplifications and approximations. Due to the complexities of fatigue science and the limitations of the structural codes of practice, the provision of quantitative results should be treated cautiously.

In the situation where the outcome of the analytical foundation life assessment is not satisfactory (i.e. foundation life constrains the overall project life extension), a more refined analysis may be an option to improve results, for example by using site-specific fatigue loads instead of IEC class loads, or by investigating the actual materials strength.

For older wind farm sites the original design loading information may be generic instead of site specific. Hence, if obtaining updated site-specific loading information, it may be prudent to compare the revised extreme loading with the generic document. It is generally expected that the generic loading information will be conservative and more onerous. Therefore, some benefit may be achieved due to a reduction in anticipated extreme loading.

Other alternatives to extend the foundation life include; reduction of turbine loading through turbine control strategies, structural health monitoring or foundation remedial works – the latter option is likely to entail significant costs however and may not be economically viable.

Regular inspections and preventative maintenance activities for foundations should be extended to cover any intended extended life. Routine activities may be complemented with condition monitoring, especially where there is a specific concern, for example a structural issue.

4.3 Condition based life assessment approach

In cases where it is not possible to carry out an analytical assessment or there are construction or operational issues such as concrete cracking, embedded can movement etc. then a condition-based life assessment approach will be required.

An enhanced structural health monitoring and inspection plan would be put in place to record the growth or criticality of any defects. The monitoring should be targeted on any known design deficiencies and previous observations of defects. ALARP risk workshops should be held on a regular basis to identify priorities and review the current condition and the acceptability of any non-compliances.

The condition of the foundations would need to be assessed at possibly an increased frequency as age progresses. Using this method, any projection of life may necessarily only be short term, because of the time for a fault to manifest itself and develop into a failure criterion. However, a rolling programme of continual assessment with consequent short-term life prediction could be adopted.

Condition monitoring can be valuable as a complimentary tool as part of this process. Nevertheless, condition monitoring on its own is generally not sufficient to enable the safe life extension of foundations.

It will not be possible to put an exact remnant life on these structures, and in a small number of instances it may not be possible to extend the working life of the foundation safely, however the structural health monitoring process will ensure that risks are managed to optimise the residual life of the foundations and will inform remediation proposals for continued operation or decommissioning where required.

4.3.1 Required data

The following information is required to inform the condition-based life assessment:

- Structural crack widths and crack mapping including any remedial works undertaken (for e.g. sealing);
- Crack movement monitoring using LVDTs;
- Groundwater monitoring (for e.g. standpipes) and installed drainage inspection works to ensure water remains at an appropriate level to ensure stability;
- Tower seals inspection and remediation works;
- Embedded can movements and any remedial works undertaken (e.g. grouting);
- Anchor Bolt Foundation inspection and torquing records in order to study any potential rate of pre-load drop off;
- Sign of ground movement or distress (cracks, heave, depressions, etc) in the vicinity of WTG foundations;
- Check of the foundation slab level to determine movement (if any); and
- Structural remedial/strengthening solution (if any) for the foundations including expected expenditure.

The above list is not exhaustive and only includes some of the most common inspections, techniques and defects known in the onshore wind industry.

5 Information to be gathered to support Lifetime Extension analysis

Below are some recommendations as to important information to be gathered to support LTE analysis. Please note that the list is not exhaustive.

For new build projects, it is recommended that the below information is gathered from the start of operation and stored in a secure manner so that it can be accessed at any period during the operational life of the project. For older projects it is recognised that not all the listed information may be available however it is recommended that as much of the data as possible is gathered to facilitate the analysis.

5.1 Turbine information

- Turbine make and model
- Hub height
- IEC design class and type certificate (including special versions, cold weather package, different tower specifications, etc, if available)
- Turbine control system (e.g. constant speed, variable speed-pitch regulated)
- Details of control measures/modes of operation that have been implemented either at specific wind turbines or across the wind farm over the life of the project. Examples include noise curtailment, grid curtailment (both internal due to maximum export capacity (MEC) limits and external due to system constraint and curtailment).
- Any load measurement data for any structural component(s) in the turbine

5.2 Turbine Foundation information

- Geotechnical interpretative report covering foundation locations
- Bottom tower section and foundation interface details (anchor cage or embedded can) dimensions, materials, anchor bolts pre-stressing details.
- Foundation geotechnical and structural design calculations
- Geotechnical and structural specifications
- As-built foundation design drawings, including detailed reinforcement drawings
- Design foundation loads received from turbine manufacturer including Markov matrices
- Details of any foundation defects (and associated repairs) which have occurred over the lifetime of the assets

5.3 Meteorological data

5.3.1 Pre-construction data

It is recommended that the pre-construction energy assessment and site suitability assessment reports for the wind farm are stored for future reference.

Additionally, it is also recommended that the raw data from the pre-construction meteorological masts along with installation and service records, instrument calibration records etc, are stored.

5.3.2 Operational data

If an onsite met mast is present, then it is recommended that the measurement data from the mast(s) are stored along with installation, service records, instrument calibration records etc. If data storage limits are an issue it is recommended that a minimum of two years' data from the start of operations is kept since from experience it is likely that the instruments will be operated and serviced appropriately during the initial period at the start of operations but may not be maintained as frequently after this.

5.4 Operational records

- Details of all structural failures, replacements or refurbishments of all major parts e.g. blade throws, tower section replacements etc.
- Component replacement log and RCA of any major or serial failures
- Monthly operations and maintenance reports for the wind farm – both turbine operator and owner reports
- Any ad-hoc analysis on faults, downtime or grid problems performed to date
- Site specific power curve test report, if available
- Details of operational restrictions to the wind farm during the operational period or planned in the future (e.g. Wind sector management, Noise curtailment, Shadow flicker management, Grid curtailment, etc.)
- Changes in software which are noted to affect the performance of the wind turbine
- Changes in nacelle anemometer settings/calibration factors
- Changes in exposure at the site e.g. changes in forestry, neighbouring wind farms being built
- Groundwater monitoring (for e.g. standpipes) and installed drainage inspection works.
- Anchor Bolt Foundation inspection and torquing records in order to study any potential rate of pre-load drop off.

5.5 SCADA data

There is a significant amount of information provided in modern wind farm SCADA systems meaning storage requirements can be significant over time. Below are the minimum recommended data fields which should be stored for future use in life extension studies.

Timestamp, power, pitch, rpm, wind speed (mean & standard deviation), direction, availability and yaw error.

Turbine normal, emergency stop (and start) statistics and fault code data if available from SCADA.

6 Useful documents and Standards

6.1 Standards

IEC 61400-28: Through-life management and life extension of wind farms

DNVGL-ST-0262 Lifetime extension of wind turbines standard

UL 4143 Wind Turbine Generator – Life Time Extension (LTE) standard

6.2 Useful documents

Strategy for Extending the Useful Lifetime of a Wind Turbine, Report from MEGAVIND, July 2016

“Grundsätze für die Durchführung einer Bewertung und Prüfung über den Weiterbetrieb von Windenergieanlagen (BPW) an Land”, Basic Principles for Performing an Assessment and Verifificatition of the Lifetime Extension of Onshore Wind Energy Converters (BPW), BWE Grundsätze, May 2017

7 References

[1] IEC 61400-1 International standard, Wind Turbine Generator systems, Edition 3 – Part 1: Design requirements, August 2005, Amended 2010

[2] DNV GL Standard: DNVGL-SE-0441 Type and component certification of wind turbines

[3] Germanischer Lloyd, Rules and regulations, IV - Non-marine Technology, Part 1 – Wind Energy, Regulation for the certification of the Wind Energy Conversion Systems. Chapter 1 – 10, 2010

[4] ISO 2394 General principles on reliability for structures, 2015(E) edition

[5] Standard DNVGL-ST-0437 “Loads and site conditions for wind turbines”

[6] DNV-OS-J-101 “Design of offshore wind turbine structures”

Annex 1 – Reporting Requirements

Table 1 - Recommended title information to be recorded for consistent reporting

#	Item	Additional Information
1	Document No#	For doc control purposes
2	Revision #	For doc control purposes
3	Report #	For unique record and ID
4	Report Type	Type of inspection (Category)
5	Report Title	Type of inspection (Local)
6	Prepared by	Inspector
7	Reviewed by	Inspector/Engineer (Validation)
8	Requested by	Optional (Who initiates inspection)
9	Site Name	Name + location
10	Asset Name	e.g. T01, T02, T03
11	Asset Serial #	Unique ID (Manufacturer)
12	Asset Unique ID (CMMS)	Unique ID (Maintenance Management)
13	Asset Type	Make & Model
14	Inspection Date	Date of inspection

Table 2 - Recommended content (report & summary)

#	Item	Additional Information
1	Purpose of Inspection	What was inspected, why and where?
2	Environmental	Time / Temp / Wind Speed / Precipitation / Conditions
3	List of Inspectors	Who carried out the inspection? Provide certification details of inspectors where applicable.
4	Defect Classification	Define damage/risk categories in use for various components.
5	Documentation References	Any linked documentation or references of importance.
6	Asset Nameplate	• Equipment nameplate recorded • Asset info. (Type, rating, construction year, run hours, production to date, rotor diameter, hub height, etc.).
7	Serial Defects / Asset History	Known serial or historic issues with this WTG model or asset should be recorded for reference.

8	Overview of Findings (Graphic)	Summarised graphic representation of the complete findings. Consistent categorisation during reporting is important. Overview should include suitable representation of observations delineated by severity and class. Pareto and pie charts typically useful.
9	Summary of Findings (Text)	Findings should be condensed and summarised according to severity (defect classification)
10	List of Observations (Tabular)	Priority list of observations in condensed tabular form

Table 4 - Recommended Content (Singular recorded observations during inspections)

#	Item	Additional Information
1	Observation Reference ID	Simple #ID
2	Location (Area)	Where on the component was the observation made? What location?
3	Discipline	ELEC, MECH, CIVIL etc.
4	Defect Type	Corrosion, Poor maintenance, Broken, Missing, etc.
5	Observation classification	Observation, Safety Concern, Defect
6	Resolution	Replace, Repair, Inspect, Calibrate etc.
7	Defect Class	Minor, Moderate, Major, Critical
8	Comment	Free text. What is the observation?
9	Recommendation	Free text. What is the recommendation?
10	Equip Unique ID (CMMS)	Unique identifier of the equipment being observed.
11	Action	Fix immediately, fix at next service, consult etc.
12	Picture	Good image of the damage/observation

Table 5 – Recommended storage of records, risk register and further actions

#	Additional Information
Following completion of the inspection the inspector should;	
1	Retain all pertinent findings and record these on an active Risk Register with asset designation clearly referenced. This register should be reflective of the asset's operational history and of any life extension assumptions.
2	Implement corrective actions within the timeframe recommended in the inspection report and otherwise as soon as reasonably practicable in accordance with good industry practice.

3	Following the findings of the inspection the programme manager will assess any future inspection schedule and any individual inspection requirements which may be appropriate for that asset and the condition observed. Such assessment will be risk based and in line with industry best practice.
4	Initiate any major defect notifications through the appropriate internal channels and immediately risk assess any major issues identified during the inspection in order to safeguard life and asset integrity.

Annex 2 – Sample WTG Inspection Checklist Template

Pre-Inspection Checks	✓
Are there any disabled alarms?	
Check service and major maintenance history for items of note	
Record WTG Nameplate (Photo)	
Check for unusual noises before shutting down	

External Observations	✓
Is there any grease escaping from the yaw ring?	
Is there any grease escaping from the blade seals?	
Check tower/tower joints condition	
Check for unusual noises before the WTG is stopped	

Foundation	✓
Pedestal Concrete Structure	
External Foundation Bolts	
External Foundation Bolt Covers	
Pedestal Grout	
Backfill Soil around Pedestal	
Lighting and Signage	
Foundation Drainage	
Check foundation weather seal	
Check for spalling or signs of hydraulic pumping (Externally)	

Basement	✓
Internal Tower Grouting	
Internal Base Bolts	
Lighting	
Tower Welds	
Tower Paint	
Cable Routing (Wear Protection)	
Transformer (Check for overheating, discharge, oil leaks, cooling system damage)	
Switchgear (Check SF pressure, labelling & external condition)	
Check dehumidifying system	
Check for spalling or signs of hydraulic pumping (internally)	

Tower Base Section	✓
Access (Door, Stay, Steps, Lock, Sealing, Vents)	
Tower Ladder	
Lighting, Service Outlets, Accessories	
Tower and Doorway Welds	
Tower Paint	
Cable Routing (Wear Protection)	
Statutory Inspections	

Service Lift	✓
Lift Cubicle	
Lift Doors/Hatches (Interlocking)	
Lift Controls	
Lift Power Cable	
Lift Lighting/Beacons/Sounders	
Lift Limit/Safety Switches	
Lift Motor	
Statutory Inspections	

Bottom Cabinets	✓
Grounding Connections	
Wiring/Cable/Bus Connections	
Wire and Cable Routing	
Controller Components	
Any Extra Connections of Disconnected Cables	
UPS Condition	
Check coolant pressure	
Cabinets	
Cleanliness of Cabinets	
Switchgear	
Platform	
Cooling System	
HSSE (Signage, First aid, Fire)	
Statutory Inspections	

Top Tower Section & Transition Deck	✓
Tower Ladder	
Fall Arrest Safety Cable/Rail	
Lighting, Service Outlets, Accessories	
Tower Cable Routing	
Platform bolts, steelwork and hatches	
Tower Welds	
Cable Loop Assembly	
Cable Routing Protection	
Safety Cable/Slider Top Mount Assembly	
Cable Transition Yaw Deck to Nacelle (Wear Protection)	
Cable Suspension/Support	
Nacelle to Tower Bolts	
Overall Cleanliness and Paint Condition	
Statutory Inspections	
HSSE (Signage)	

Tower Intermediate Sections	✓
Tower Sections	
Tower Welds	
Cleanliness and Paint Condition	
Lighting	
Cable fixings	
HSSE (Signage)	
Platform bolts, steelwork and hatches	

Rotor	✓
External Blade Bearing Seals	
External Blade Greasing System	
Blade to Nose Cone Dust Covers	
Nose Cone Condition	
Nose Cone Entry Hatch	
Nose Cone Mounting Brackets	
Hub Entry Hatches	
Pitch Linkage	
Pitch Bearing Backing Plates and Spindles	
Mechanical Pitch System	
Hydraulic Pitch System	
Check for Loose Objects in Hub	
Internal Blade Bearing Seals	
Cleanliness of Hub Internally	
Blades Root(s)	
Blade Surface	
Statutory Inspections	

Main Bearing	✓
Covers and Protection	
Main Bearing Housing	
Bearing Seals	
Grease Purge from Main Bearing	
Main Bearing Mounting	
Compression Coupling	
Condition Monitoring Sensors	
Check for cracks in the housing	

Nacelle Exterior	✓
Nacelle Tie Off Points	
Wind Speed Sensor	
Wind Direction Sensor	
Sensor Mounting Bracket	
Lightning Protection	
Aviation Lighting System	
Nacelle Top Cover Integrity	

Nacelle	✓
Nacelle Top Cover (Interior)	
Nacelle Bottom Cover	
Nacelle Hatches	
Nacelle Cooling Venting	
Nacelle Heating System	
Nacelle Cover Hardware and Mounting	
Lighting, Service Outlets	
Grounding Straps	
Wiring Harness and Routing	
Tool Hoist and Tag Line	
Bed Plate (including welds and bolted connections)	
Rotor Lock Assembly	
Cleanliness of Nacelle	
HSSE (Signage, Rescue Equipment, Fire Extinguisher, First Aid)	
Statutory Inspections	

Gearbox	✓
Gearbox Housing	
Gearbox Mounting/Torque Arms	
Gearbox Oil Level	
Gearbox Oil Cooling System	
Cooling Lines, Fittings, Pipe Connections	
Breather Filter	
Gearbox Oil Filtering System	
Gearbox Oil Pump Assembly	
Gearbox Heating System	
Nacelle to Hub Slip Ring Power Rotary System	
Condition Monitoring System	
Trigger vibration and over speed sensor if possible	
Seals/Gaskets	

Generator	✓
Generator Mounting	
Generator Grounding to Bed Frame	
Generator Bearings	
Check Grease Traps	
Generator Cabling Routing and Connections	
Generator Cooling System	
Generator Power Collecting Ring	
Generator Phase Brushes	
Generator Ground Brushes	

Yaw System	✓
Yaw Brakes	
Oil/Grease Catch Pans	
Yaw Bearing	
Yaw Ring Gear	
Lubrication	
Yaw Pinion	
Yaw Gear Drives	
Electrical Connections and Motors	
Yaw Drive Oil Level	

High Speed Coupling and Braking System	✓
High Speed Cover Assembly	
High Speed Coupler	
Brake Disc	
Brake Calliper	
Brake Accumulator	
Brake Disc Locking Mechanism	
External Brake Sensors	

Hydraulic Station	✓
Check Oil Level	
Air Breather and Filter	
Hose and Fitting Connections	
Manifold and Valves	
Hydraulic Oil Cooling System	
Accumulators	
External Hydraulic Sensors	

Top Controllers/Cabinets	✓
Controller Heating/Cooling Systems	
Cabinet Mounting and Doors	
Wiring/Cable/Bus Connections	
Controller Components	
Controller Cabinet	
Grounding Connections	
HSSE (Signage)	