March 2022

Application of the New IEC International Design Standard for Offshore Wind Turbines to a Reference Site in the Massachusetts Offshore Wind Energy Area

Samuel C. Roach
University of Massachusetts Amherst

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APPLICATION OF THE NEW IEC INTERNATIONAL DESIGN STANDARD FOR OFFSHORE WIND TURBINES TO A REFERENCE SITE IN THE MASSACHUSETTS OFFSHORE WIND ENERGY AREA

A Dissertation Presented

by

SAMUEL CHILMAN ROACH

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

FEBRUARY 2022

Mechanical Engineering
APPLICATION OF THE NEW IEC INTERNATIONAL DESIGN STANDARD FOR OFFSHORE WIND TURBINES TO A REFERENCE SITE IN THE MASSACHUSETTS OFFSHORE WIND ENERGY AREA

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SAMUEL CHILMAN ROACH

Approved as to style and content by:

Professor Matthew A. Lackner, Co-Chair

Professor James F. Manwell, Co-Chair

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Graduate Program Director
Mechanical Engineering
DEDICATION
This thesis is dedicated to my fiancé Kaylie. Your support and love means the world to me. Thank you for everything that you do.
ACKNOWLEDGMENTS

I would like to thank Professor Lackner for his continuous support throughout my time here at UMass. My graduate career would not have gone nearly as smoothly without your dedication to teaching and understanding. I would also like to thank Professor Manwell for the many hours of discussion both related to this project and about wind energy in general. Your passion for the subject and for educating new generations makes the UMass Wind Energy Center what it is today. I would also like to thank Professor McGowan for his support on thesis feedback as a committee member. Thanks also to the University of Massachusetts Graduate School, Pecos Wind Power, and Siemens Gamesa Renewable Energy for their support of me throughout my time as a graduate student.
ABSTRACT

APPLICATION OF THE NEW IEC INTERNATIONAL DESIGN STANDARD FOR OFFSHORE WIND TURBINES TO A REFERENCE SITE IN THE MASSACHUSETTS OFFSHORE WIND ENERGY AREA

FEBRUARY 2022

SAMUEL CHILMAN ROACH, B.S., THE UNIVERSITY OF TEXAS AT AUSTIN

M.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Matthew A. Lackner and Professor James F. Manwell

This thesis summarizes the simulation and analysis performed for the MassCEC project described herein. The intent was to perform a “dry run” of the new IEC offshore wind turbine design standard, IEC 61400-3-1 and to illustrate the use of that standard in the Massachusetts Offshore Wind Energy Area. IEC 61400-3-1 is a design standard used to ensure wind turbine structural performance over the design life of the machine. Each installed wind turbine must be certified by a Certified Verification Agent using this standard before installation. The certification process typically uses a structural dynamics model to predict a turbine's structural response in the presence of a range of operational conditions and meteorological oceanographic conditions, which are codified into Design Load Cases. The area in question is located approximately 24 km of south of Martha’s Vineyard with an assumed water depth of 40 m. The National Renewable Energy Laboratory's FAST software (V8.12) was used to perform simulations of a large subset of the DLCs. Wind data files were generated using NREL's TurbSim and IECWind.

This thesis discusses the instructions of the standard, preparation for simulation of Design Load Cases, and analysis of results. Results from simulations show the application of the standard in detail as applied to a reference turbine. Limitations and ambiguities of the standard in the simulation of control failure cases are analyzed. The application of the standard to hurricane loading is also analyzed alongside an example case for a Category 5 hurricane. The standard is found to be fundamentally reasonable in application to a reference turbine in the Massachusetts Offshore Wind Energy Area.
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CHAPTER 1
INTRODUCTION

1.1 Context and Motivation

In the early days of modern wind energy (the 1970s), design standards were relatively primitive and were not necessarily even considered. As a result of experience both in the United States, primarily in California, and in Europe, the decision was made in the mid-1980s to develop wind turbine design standards under the auspices of the International Electrotechnical Commission, Technical Committee 88 (TC 88).

Figure 1: Abandoned wind farm, San Gorgonio Pass, CA (Walden)
The first edition of the fundamental design standard, IEC 61400-1, was published in 1994 (IEC, 1994). This fundamental standard has been updated a number of times since the first edition, with the fourth edition issued in 2019. At the present time there are 31 TC 88 standards or guidelines concerning wind turbines (van Dam, 2017). IEC 61400-3-1 covers design requirements for fixed offshore wind turbines.

The intent of this thesis described herein is twofold: 1) to perform a “dry run” of the new IEC offshore wind turbine design standard, IEC 61400-3-1 and 2) to illustrate the use of that standard in conditions of the United States where offshore wind energy projects are presently being developed. IEC 61400-3-1 is a design standard used to ensure wind turbine structural performance over the design life of the machine. Each installed wind turbine must be certified by a Certified Verification Agent (CVA) using the guidelines of the IEC standard before installation. The certification process typically uses a structural dynamics model to predict a turbine’s structural response in the presence of a range of operational conditions and meteorological oceanographic conditions, which are codified into Design Load Cases (DLCs).

This thesis is intended to illustrate aspects of the IEC 61400-3-1 standard as they apply to a hypothetical site in the Bureau of Ocean Energy Management (BOEM)’s Massachusetts Offshore Wind Energy Area. The area in question is located approximately 24 km of south of Martha’s Vineyard. The site is assumed to have a water depth of 40 m. The National Renewable Energy Laboratory’s (NREL) FAST
software (V8.12) was used to perform simulations of a large subset of the DLCs. Wind data files were generated using NREL’s *TurbSim* and *IECWind*. The study is intended to be similar to the “Guidelines for Design of Wind Turbines” developed by DNV GL and Riso national laboratory for offshore wind turbines in 2002. This report lists detailed design concerns and the process for design of an onshore wind turbine. (DNV 2002).

The research presented in this thesis was conducted as part of a larger project funded by the Massachusetts Clean Energy Center in 2018 in anticipation of a developing offshore wind energy industry in the state. The project was intended to benefit multiple constituencies, in the state, region, country, and internationally in several ways. In Massachusetts and the region, applying the new design standard using actual data from the BOEM areas should be directly useful. It will help to elucidate how the site-specific conditions found off Massachusetts are likely to affect the design of installed wind turbines. The availability of case studies will help interested parties understand the issues. The results also provide guidance into the types of data that will be of relevance going forward. The larger project includes metocean data sets developed and described by Semyung Park and a turbine model implemented and described by Evan Gaertner. This thesis presents work conducted by the author, and when building upon other work, it will be noted. Other reports created for this project are listed in Appendix B.
1.2 Overview of Research

The focus of this research is to run a test case of the IEC 61400-3-1 offshore wind energy standard using a reference model in the Massachusetts Offshore Wind Energy Area. The readability and applicability of the new standard to the simulation software, FAST v8.12 is explored. Issues unique to the application of the standard to the Massachusetts Offshore Wind Energy Area are also explored.

The simulation software used in this research is FAST v8 developed by the National Renewable Energy Laboratory (NREL). This software is certified to be used for wind turbine certification using the IEC standard. The research will explore simulation capabilities of the software in context of the requirements for certification according to the standard.

The wind turbine model used in this research within FAST v8 is the DTU 10MW Reference Wind Turbine, referred to as the DTU 10MW (Bak et al). This model was developed as an open-source tool for researchers to approximate the loading on the next generation of offshore wind turbines (at the time of its development). This research will explore the limitations of this model in simulating the requirements of the standard, as well as the general applicability of the standard to a reference turbine model in a simulation software.
CHAPTER 2
LITERATURE REVIEW

2.1 History of Engineering Design Standards

Formalized design standards in engineering first arose in the 19th century in
the shipbuilding industry. One of the earliest classification societies, known today as
the American Bureau of Shipping, was started in 1861 as the American Shipmaster’s
Association, with the original goal of certifying qualified ship’s officers. After the end
of the Civil War, the association moved into classifying ships in order to benefit both
insurers and shipowners who wanted lower insurance rates (American Bureau of
Shipping). Ships were classified into different classes and formal definitions of
specifications began to be codified. Standardization soon spread outside of the
shipbuilding industry to other facets of engineering industries. As electricity became
integral to industrial society at the beginning of the 20th the century, the
International Electrotechnical Commission was founded at the International
Electrical Congress [IEC] in 1904. The goal was “that steps should be taken to secure
the cooperation of the technical societies of the world by appointment of a
representative Commission to consider the question of standardization of the
Nomenclature and Ratings of Electrical Apparatus and Machinery” (International
Electrotechnical Commission). The first president of the society was the famed Lord
Kelvin. An even wider selection of design standards come from the organization
known as the International Organization for Standardization (ISO), which was
founded as the International Federation of the National Standardizing Associations
in 1926 (Martincic). The majority of modern industrial design standards are codified by either ISO, the IEC, or both organizations in some way.

2.1.1 Offshore Wind Energy Standards

Although offshore wind turbines had been conceptualized in the early 1970s (Heronemus, 1972), the first offshore wind turbines were not installed until 1991. With increasingly significant differences between offshore and onshore wind turbines it became clear that specific guidelines for the design of offshore wind turbines and their support structures were needed. Work began on a new standard for offshore wind turbines in 2000; it was published in 2009 (IEC, 2009). The second edition was issued in 2019.

The International Electrotechnical Commission standard for bottom-fixed offshore wind turbine design (IEC 61400-3) has been significantly updated to reflect advances in offshore wind turbine technology and the increase in offshore wind experience gained by the industry since the standard was first published in 2009. The second edition has been renamed IEC 61400-3-1 to distinguish it from a companion Technical Specification for floating offshore wind turbines, IEC 61400-3-2.

In contrast to land-based wind turbines, offshore turbines have a range of different support structures, and in order to facilitate focusing on the applicable requirements, the turbine is conceptually divided into a rotor–nacelle assembly (RNA) and a support structure, as illustrated in Figure 2. The RNA consists of the rotor (blades and hub) together with the generator, gearbox (if any) and associated
machinery that are housed in the nacelle. The support structure consists of the tower, the sub-structure, and foundation. The tower connects the sub-structure to the rotor-nacelle assembly and raises the latter to a sufficient height about the water surface. The sub-structure extends upwards from the seabed and connects the foundation to the tower; the foundation transfers the loads acting on the structure into the seabed. Substructures may take a variety of forms, depending primarily on water depth and soil characteristics. The main options for fixed offshore wind turbines are the monopile, gravity base structure and multi-member structures, such as jackets or tripods.

![Diagram of Fixed Offshore Wind Turbine Components](image)

**Figure 2: Components of a Fixed Offshore Wind Turbine (IEC 61400-3-1)**

The offshore wind turbine design standard is intended to be augmented by other relevant standards, such as the International Standards Organization (ISO) 19901 series developed for the offshore oil and gas industry.
CHAPTER 3

DESIGN EVALUATION

The intent of the design standard is that the designer follows the process outlined in Figure 3. As shown, there are five major steps: 1) selection of suitable meteorological – oceanographic (“metocean”) conditions for the design basis, 2) design of the RNA, primarily with reference to IEC 61400-1, 3) design of the support structure with reference to the present standard, 4) selection of suitable design load cases (DLCs) to represent the types of conditions for which the turbine must be adequate, 5) verification that the design of the entire structure is adequate. The verification process is done via the use of a structural dynamic computer model, using inputs that correspond to the DLCs. Examples of such models include DNV GL’s BLADED (DNV GL 2017) and NREL’s FAST software (NWTC 2017).
The RNA is normally designed according to classes as summarized in Table 1 (see below). The support structure is designed according to site specific conditions. In any case, it must subsequently be verified that the combined structure is adequate for the site-specific conditions.

The assessment of the turbine structure is initially performed using a preliminary design, which would typically be defined based on previous experience on turbines of a similar nature. As previously noted, the design assessment requires the use of a structural dynamics model of the preliminary design to predict design
load effects. The load effects to be determined are for all relevant combinations of external conditions and design situations.

Safety class refers to the set of conditions to which the wind turbine is designed. As shown in Table 1, there are 3 possible classes for a normal wind turbine (I, II or III), depending on the mean wind speed. Additionally, there are subclasses that depend on the turbulence intensity. In point of fact, the classes apply to the RNA; the support structure is to be designed according to site specific conditions.

**Table 1: Wind turbine class definitions (IEC 61400-1, 4th Ed.)**

<table>
<thead>
<tr>
<th>Wind Turbine Class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>S</th>
</tr>
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<tr>
<td>$V_{ave}$ (m/s)</td>
<td>10</td>
<td>8.5</td>
<td>7.5</td>
<td>Values specified by the designer</td>
</tr>
<tr>
<td>$V_{ref}$</td>
<td>50</td>
<td>42.5</td>
<td>37.5</td>
<td></td>
</tr>
<tr>
<td>Tropical (m/s)</td>
<td>57</td>
<td>57</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>$V_{ref,T}$ (m/s)</td>
<td>57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A+</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.12</td>
<td></td>
<td></td>
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</tbody>
</table>

As stated, IEC 61400-3-1 “provides additional requirements for assessment of the external conditions at an offshore wind turbine site and specifies essential design requirements to ensure the engineering integrity of fixed offshore wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime.”

Neither the design standard nor the type and certification scheme spell out in detail all the steps involved in proper design and evaluation of an offshore wind turbine. There is one document, however, which provides comprehensive guidance for the design of conventional wind turbines, and that guidance is directly relevant to
at least the RNA and tower of an offshore turbine. This document is Guidelines for Design of Wind Turbines (DNV, 2002). It discusses in some detail safety and reliability, external conditions, loads, as well as the most important wind turbine subsystems, including the rotor, nacelle, tower and foundation. In the context of the present exercise, the important topic has to do with the loads. Within this topic important considerations include: load cases (including design situations, wind events, design load cases), load types (such as inertia and gravity loads, aerodynamic loads, functional loads), aeroelastic load calculations (including model elements, aeroelastic models for load, prediction, aerodynamic data assessment, and special considerations), load analysis and synthesis (fatigue loads, ultimate loads), load calculation methods (parametrised empirical models, the simple load basis, quasi-static method, peak factor approach for extreme loads, parametrised load spectra), site-specific design loads, and loads from other sources than wind (such as wave loads, current loads, ice loads, earthquake loads).

Load calculations such as are used in design evaluations or certifications now use aeroelastic computer models, which allow detailed meteorological/oceanographic input files. In this thesis NREL’s FAST (Jonkman and Buhl, 2005) was employed, which in turn uses NREL’s other codes TurbSim and IECWind to generate the input files.

The output of FAST consists of time series of forces, moments, and deflections at various locations on the structure. These may be converted to stresses and fatigue
damage using methods from engineering mechanics, including consideration of the
elasticity and fatigue damage susceptibility of the various materials involved.

Offshore wind turbines must be designed to withstand a range of external
conditions. The most significant of these are: 1) wind conditions (see below), 2)
marine conditions (see below), 3) other environmental conditions (temperature,
salinity, etc.), 4) soil properties (including time variation due to seabed movement,
scour and other elements of seabed instability), and 5) electrical network conditions.
External conditions are considered to be either normal or extreme. Normal
conditions are those that recur regularly more than once per year. Extreme
conditions are rare, expected to occur once every 50 years.

The wind conditions specified in 61400-3-1 are similar to those defined in
61400-1, with some exceptions regarding wind shear, inclination of mean flow and
assumptions regarding offshore turbulence.

Marine conditions are assumed to primarily affect the support structure. They
include at least: waves, sea currents, water level, sea ice, marine growth, scour and
seabed movement. A stochastic wave model is assumed. The design sea state is
specified by the wave spectrum $S_h(f)$; significant wave height, $H_S$; peak spectral
period, $T_p$ and mean wave direction, $\theta_{wcm}$. Wind/wave correlations are also
considered, particularly regarding hub height mean wind speed, $V_{hub}$, $H_s$ and $T_p$ as
expressed in Equation (1) (adapted from Manwell et al, 2009).

\begin{equation}
 f_{V_{hub}}(V_{hub}, H_s, T_p) = f_{V_{hub}}(V_{hub}) f_{H_s}(H_s) f_{T_p}(T_p) f_{\theta_{wcm}}(\theta_{wcm})
\end{equation}
It is noted that distributions are to be determined from long-term measurements or hindcasting. Wave conditions are considered for a normal sea state (NSS) by $H_{s,NSS}(V)$ and the normal wave height (NWH) in which $H_{NWH}$ is the expected value of the significant wave height conditioned on the mean wind speed. The range of associated wave periods $T$ is given in Equation (2):

\[
11.1 \sqrt{H_{s,NSS}(V)/g} \leq T \leq 14.3 \sqrt{H_{s,NSS}(V)/g}
\]

Other sea state conditions to be considered include the severe sea state (SSS), modelled with the normal wind speed range for ultimate loading during power production. Extreme sea states (ESS), defined by significant wave heights and individual wave heights with 1-year and 50-year return conditions are also considered. The possibility of breaking waves must also be taken into account. It is noted that special analysis may be required, and additional details are provided in an annex to the standard. Sub-surface currents are generated by tides, storm surge, atmospheric pressure variations, etc. Models are provided in the standard to take these into account. A reasonable range for the sea water level must be considered, taking into account tidal range, storms, etc. See Figure 4.
Sea ice may seriously affect the design of the support structure. Special design features, such as ice cones may be needed. Loads can be created on an offshore wind turbine and its support structure through several mechanisms, including fast ice cover subject to temperature and water level fluctuations, horizontal loads from moving ice, and pressure from hummocked ice and ice ridges. The new edition of the standard provides detailed guidance on designing for such conditions. An annex on sea ice has been significantly revised since the first edition. Marine growth may influence hydrodynamic loads, dynamic response, accessibility and corrosion rate of the structure. Marine growth is classified as “hard” (e.g. mussels and barnacles) and “soft” (seaweeds and kelps). Seabed soil may move due to currents, in some cases requiring scour protection techniques.

Other environmental conditions that may need to be considered include the following: humidity, air density, solar radiation, rain, hail, snow, ice, chemically active
substances, mechanically active particles, salinity causing corrosion, lightning, seismicity causing earthquakes, water density; water temperature and ship traffic.

External electrical conditions must also be considered. The recommendation is to follow the guidance of IEC 61400-1, but in the absence of site data the extreme condition to be considered is the loss of electrical connection for a continuous period of 3 months.

Design standards themselves are only useful to the extent that they are actually applied in the design. In order to ensure that is the case, designs are certified. The certification process normally involves an entity distinct from the designer undertaking a detailed evaluation of the design. This entity is referred to as the Certified Verification Agent (CVA). The CVA in turn is guided by a certification guideline. In the case of wind turbines, guidelines have been prepared by the IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE). The fundamental document for this process is the Type and Certification Scheme IECRE OD-501 (IECRE, 2019). The guidelines in this document are rather general, and the CVA will take into consideration other documents as well as good engineering practice. For offshore wind turbines in particular, a complete certification is quite complex, since there are many sub-systems and components to evaluate, not the least of which are the support structures.
4.1 Design Load Cases

Structural loads may be categorized in three ways: 1) ultimate or fatigue loads, 2) normal or extreme external conditions, 3) operating or non-operating turbine state. There are also three types of turbine state, or "design situation." These include: 1) Normal design situations, considered with appropriate normal or extreme external conditions, 2) Fault design situations, considered with appropriate external conditions; and 3) Transportation, installation and maintenance design situations, considered with appropriate external conditions.

Based on the above, eight types of load case situations have been identified: 1) power production, 2) power production plus occurrence of fault, 3) start-up, 4) normal shut down, 5) emergency shut down, 6) parked (standing still or idling), 7) parked and fault conditions, 8) transport, assembly, maintenance and repair. For each design situation it is necessary to consider appropriate external conditions. Some of the loads that may need to be considered in the design include: 1) gravitational and inertial loads, 2) aerodynamic loads, 3) actuation loads, 4) hydrodynamic loads, 5) sea ice loads and 6) other loads such as wake loads, impact loads, ice loads, etc.

There are two main types of design loads: 1) Ultimate (U) loads (which include normal (N), abnormal (A), or transport and erection (T) and for which it is necessary to consider (i) material strength, (ii) blade tip deflection and (iii) structural stability
(e.g. buckling) and 2) Fatigue (F) loads for which it is necessary to consider fatigue strength. Within those types are sub-categories to be considered. The result is that for all fixed offshore wind turbines there are 27 DLCs to be considered. In addition, for locations where there may be tropical cyclones or hurricanes, there are two additional DLCs and for locations where there may be significant sea ice, there are eight additional DLCs.

4.1.1 Metocean Conditions for the Massachusetts Offshore Wind Energy Area

Metocean conditions for each Design Load Case consist of some combination of winds, waves, and currents. Data from buoy 44008 (SE of Nantucket, Figure 5) of the NBDC database was the primary source of the metocean data for this project, and various post-processes were conducted on that data by Semyung Park (Manwell et al. 2018). Historical data is available on the NDBC’s website, but pre-2007 data does not include wave directional data. Also, data for 2013 and 2014 are excluded because there is too much data missing. As a result, from 2007 to 2016 except 2013 and 2014 year (total 8 years), data was post-processed. Figure 5 shows the location of the data buoy.
Figure 5: Location of buoy 44008, SE of Nantucket

The wind speed data (from NDBC) for a typical offshore wind turbine hub height of 119 m needed to be extrapolated since the buoy anemometer is installed at 5 m above sea level. The power law wind shear equation (Eqn. 3) with an exponent of 0.14 was utilized to extrapolate this data. Previous work by Semyung Park discusses the use of LIDAR data by AWS Truepower. (Manwell et al 2018).

\[ V = V_{hub} \left( \frac{z}{z_{hub}} \right)^{0.14} \]

Figure 6 shows the histogram of wind speed at hub height and the Weibull distribution at the site selected.
Based on the extrapolated data from the site and according to the standard, wind turbulence models for power production were used as model inputs, including the Normal Turbulence Model, Extreme Turbulence model, as well as cases of extreme wind shear and extreme operating gusts. Turbulence intensity and wind shear exponent were determined from AWS Truepower (now UL Renewables) anemometer data and LIDAR data. Wave data was determined from the National Data Buoy Center’s (NDBC) buoy 44008, 54 nautical miles SE of Nantucket.

### 4.1.2 Turbine Specifications

Detailed data for a real offshore turbine was not available. As an alternative, the DTU 10 MW reference turbine was selected as the reference turbine for this exercise.
Figure 7 shows a 3D rendering. The tower itself, assumed to be of steel, is tapered at the top. The model has realistic, detailed data available for load and deflection predictions. However, details of the blade construction which would be needed for stress evaluation are not available. The turbine model is supported by a monopile in 40 m water depth. The FAST model of the turbine was downloaded from DTU’s web portal. The monopile design was chosen as state of the art for fixed bottom offshore wind turbines. The water depth at the modelled site was representative of the conditions in the Massachusetts Offshore Wind Energy Area. Full descriptions of the turbine model can be found in (Bak, 2013).

<p>| Table 2: Parameters of the DTU 10MW Reference Turbine |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
</table>
Wind Regime | IEC Class 1A
Rotor Orientation | Upwind; Clockwise rotation
Control | Variable speed; Collective pitch
Cut in wind speed | 4 m/s
Cut out wind speed | 25 m/s
Rated wind speed | 11.4 m/s
Rated power | 10 MW
Number of blades | 3
Rotor diameter | 178.3 m
Hub diameter | 5.6 m
Hub height | 119.0 m
Minimum rotor speed | 6.0 rpm
Maximum rotor speed | 9.0 rpm
Maximum tip speed | 90 m/s
Hub overhang | 7.1 m
Shaft tilt angle | 5.0 deg
Rotor precone angle | -2.5 deg
Blade prebend | 3.332 m
Rotor mass | 227,962 kg
Nacelle mass | 446,036 kg

Table 3: Dimensions of DTU 10MW turbine’s baseline tower

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>115.6 m</td>
</tr>
<tr>
<td>Diameter, top</td>
<td>5.5 m</td>
</tr>
<tr>
<td>Thickness, top</td>
<td>20 mm</td>
</tr>
<tr>
<td>Diameter, base</td>
<td>8.3 m</td>
</tr>
<tr>
<td>Thickness, base</td>
<td>38 mm</td>
</tr>
<tr>
<td>Tower mass</td>
<td>605,000 kg</td>
</tr>
</tbody>
</table>
Figure 8: Schematic of DTU 10MW on monopile in 40m water depth (not to scale)

Monopiles are the most common offshore support structure type. As of 2016, they represented 80% of the global installed capacity (REF 2?). This is due to relatively low manufacturing and installation costs compared to other foundation types. A monopile consists of a cylindrical steel tube driven into the seafloor. A transition piece above the influence of waves connects the monopile to the tower.

Several existing studies have designed monopiles for the DTU 10MW at different water depths (REFS 4, 5, 6?) The BOEM MAWEA and RIWEA have depths
ranging from approximately 15 m to 35 m. A water depth of 40 m was assumed for this study. The geometry of the monopile design is summarized in Table 4. Site soil properties and the embedded length of the pile have not been considered; FAST assumes rigid connections at the seafloor. A penetration depth of 5 meters below the mudline was assumed. The natural frequency shown is calculated inclusive of the effect of the tower and RNA.

Table 4: Monopile Support Structure Geometry

<table>
<thead>
<tr>
<th>Water Depth [m]</th>
<th>Transition Piece Height [m]</th>
<th>Pile Diameter [m]</th>
<th>Pile Thickness [m]</th>
<th>Penetration Depth [m]</th>
<th>Natural Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>10</td>
<td>9</td>
<td>0.15</td>
<td>45</td>
<td>0.27</td>
</tr>
</tbody>
</table>

4.2 Load Cases Run

It was originally intended to run all of the IEC 61400-3-1 DLCs with the FAST code. As it turned out, some DLCs are outside of the scope of FAST capabilities and were thus impossible to simulate. In some cases DLCs were simulated by changing control parameters as described in Table 5. These parameters were set according to the cases described in the FAST User's Guide (Jonkman and Buhl 2005).

Table 5: Set of Design Load Cases in IEC Standard

<table>
<thead>
<tr>
<th>Design Situation</th>
<th>Design Load Case</th>
<th>Type of Analysis Specified</th>
<th>Partial Safety Factor</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Production</td>
<td>1.1</td>
<td>Ultimate</td>
<td>Normal</td>
<td>Used for Ultimate Load Extrapolation</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>Fatigue</td>
<td>Fatigue</td>
<td>Contains wind and wave conditions for evaluating fatigue over the lifetime of normal power production for the turbine</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>Ultimate</td>
<td>Normal</td>
<td>Ultimate loading from extreme turbulence during normal power production</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>Ultimate</td>
<td>Normal</td>
<td>Potentially critical coherent disturbances/wind shear during normal power production</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>Ultimate</td>
<td>Normal</td>
<td>Severe sea state during normal turbulence and normal power production</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>Ultimate</td>
<td>Normal</td>
<td></td>
</tr>
</tbody>
</table>

34
<table>
<thead>
<tr>
<th>Power production plus occurrence of fault</th>
<th>2.1</th>
<th>Ultimate</th>
<th>Normal</th>
<th>Control function failure events with expected failure mode return period of less than 50 years. A fault in the collective pitch system is simulated, with a single blade going to a set point of 0 degrees. The emergency stop is activated soon after this occurs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>Ultimate</td>
<td>Abnormal</td>
<td>Normal</td>
<td>Control function failure events with expected failure mode return period of greater than 50 years. These abnormal control systems faults or secondary layer protection function related fault are outside the scope of FAST capability and should be met by manufacturer specifications.</td>
</tr>
<tr>
<td>2.3</td>
<td>Ultimate</td>
<td>Abnormal</td>
<td>Abnormal</td>
<td>The extreme operating gust combined with loss of one or more phases in a three-phase electrical network connection, timing chosen to achieve the worst loading. The emergency stop function of the turbine is activated 1 second after the generator torque is set to 0, approximating a loss of the electrical network. At the same time as the generator torque loss, the extreme operating gust wind event occurs.</td>
</tr>
<tr>
<td>2.4</td>
<td>Fatigue</td>
<td>Fatigue</td>
<td>Fatigue</td>
<td>Fatigue damage of an event like that in DLC 2.3 over the lifetime of the turbine. This was not performed due to lack of information about the likelihood of this failure over the turbine life.</td>
</tr>
<tr>
<td>2.5</td>
<td>Ultimate</td>
<td>Normal</td>
<td>Normal</td>
<td>A Low Voltage Ride Through is considered as normal, specified by voltage drop and duration. This is treated in simulation as the generator torque going to zero.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Start Up</th>
<th>3.1</th>
<th>Fatigue</th>
<th>Fatigue</th>
<th>Normal startup analyzed for fatigue damage over the life of the turbine. This was not performed due to lack of information about the number of startups over the turbine life.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>Ultimate</td>
<td>Normal</td>
<td>Normal</td>
<td>An Extreme Operating Gust startup event. Timing was chosen such that the beginning of the gust occurs when the power production reaches 95% of the maximum power, 50% of the maximum power, and at least two additional timings evenly distributed within the interval from 50% to 95% maximum power.</td>
</tr>
<tr>
<td>3.3</td>
<td>Ultimate</td>
<td>Normal</td>
<td>Normal</td>
<td>An extreme coherent disturbance occurring during startup. Disturbances refer to a direction change of up to 180 degrees accompanied by an increase in wind speed. The direction change magnitude $\Theta$ decreases in higher mean wind speeds.</td>
</tr>
</tbody>
</table>

| Normal Shut Down                          | 4.1 | Fatigue | Fatigue | Normal shut down case, analyzed for fatigue damage over the life of the turbine. This was not performed due to lack of information |
about the number of shutdowns over the turbine life.

| 4.2 | Ultimate | Normal | An Extreme Operating Gust normal shutdown event. Timing was chosen for the beginning of the gust with a minimum of six events evenly distributed from 10 seconds before the beginning of the shutdown until the time at which the power reaches 50 percent of the initial power production level. |
| Emergency Stop | 5.1 | Ultimate | Normal | Loads due to activation of the emergency stop button loads during normal operation. |
| Parking | 6.1 | Ultimate | Normal | Combination of extreme wind and wave conditions such that the global extreme environmental action has a combined return period of 50 years. This results in a wind speed of 40 m/s. |
| 6.2 | Ultimate | Abnormal | Loss of electrical power network at an early stage in the storm containing the extreme wind situation shall be assumed. Effect of a wind direction change of up to 180° shall be assumed. FAST v8.12 was unable to simulate this condition for an idling turbine. |
| 6.3 | Ultimate | Normal | The environmental conditions of DLC 6.1 with an extreme yaw misalignment of up to +/- 20°. |
| 6.4 | Fatigue | Fatigue | The expected number of hours of non-power production time at a fluctuating load appropriate for each wind speed where significant fatigue damage can occur to any component. |
| Parking with fault | 7.1 | Ultimate | Abnormal | Outside of the scope of FAST simulation capabilities. |
| 7.2 | Fatigue | Fatigue |  |
| Transport, assembly, maintenance and repair | 8.1 | Ultimate | Normal | Outside of the scope of FAST simulation capabilities. Certification for these load cases would come from transportation and installation information. |
| 8.2 | Ultimate | Abnormal |  |
| 8.3 | Fatigue | Fatigue |  |
| 8.4 | Fatigue | Fatigue |  |
| Hurricane Loads | I.1 | Ultimate | Normal | See “Stopped Rotor in Hurricane Conditions”. |
CHAPTER 5

SIMULATION PROCEDURE

5.1 Preparations for Simulations

Due to the large number of simulations anticipated (approximately 3500), special preparations were undertaken to facilitate running the simulations and storing the output files in an organized manner. This was accomplished via the preparation of scripts in the Python computer language, an example of which is found in Appendix A.

Python scripts were written for each design load case to run the FAST simulation for each wind speed and sea state. These scripts automatically create a time-stamped subfolder for each design load case (DLC). Inside each subfolder is a set of master input files for the DTU 10 MW turbine model, created from the input files report (Manwell et al 2018b). The scripts run multiple simulations of the turbine and edit the FAST input files for each condition needed in the runs contained in the load case. Figure 9 shows a flowchart of the simulation process.
Figure 9: Loop Code for running an example DLC

NREL’s TurbSim (NWTC Information Portal (TurbSim), 2018) was used to generate full-field wind inflow files for the DLCs that use the Normal Turbulence Model (NTM) and the Extreme Turbulence Model (ETM), as well as the Extreme Wind
Model (EWM). NREL's *IECWind* was used to generate inflow files for the DLCs that specified extreme events, such as the extreme coherent gust with direction change (ECD), and extreme wind shear (EWS). Wind inflow time series were generated at a resolution of one second.

Sea states generated during the metocean part of this project by Semyung Park were used as inputs to *HydroDyn*, the hydrodynamics module of *FAST*. Normal sea states come from the joint probability distribution for each wind speed. For the wind-wave misalignment cases in DLCs 1.2, 6.4, and 7.2, the joint probability distribution of wind speed, wave height, and wave period was used. This distribution report can be found in the metocean report (Manwell et al 2018).

The control failure cases were run using the assumptions stated in (Jonkman, 2007) of a “worst case” scenario of a blade pitch runaway followed by an emergency stop of the turbine. The loss of electrical network and low voltage ride through events were simulated by setting the generator torque to 0 during the simulation, as specified in the *FAST User’s Guide*. Start up and shut down events were simulated by modifying the cut-in and cut-out times set in the controller input file. The applicability of this to a real turbine is questionable. The standard itself allows the manufacturer or the certifier to decide which cases of control failure are truly critical. The author’s experience working at Siemens Gamesa showed the discrepancy between the minimum required by the standard and the reality of the complex cases needed for certifying a turbine. Real turbines require many different sub-cases per control failure DLC.
5.1 Output Files

The output files contained 108 variable values with a time resolution of 0.0125 seconds. Each case was simulated for 10 minutes, with an extra 30 seconds at the beginning for initial transients to reach a steady state. As a result, there were 50,400 lines of output in each output file.

5.1.1 Simulation “Sanity Checks”

A normal step in undertaking simulations such as described here are “sanity checks”, in which tests are undertaken to verify that the results are plausible. This is particularly important in situations, such as here, where a considerable number of simulations are being performed, and the output of the simulations will be used in subsequent studies. For the sanity checks here the detailed outputs of a range of simulations, from those with very low wind speeds and those with very high wind speeds were examined. The following outputs were focused on: wind speed, blade pitch angle, blade out-of-plane tip deflection, forces at the root of a blade, rotor thrust, tower base force, and generator power. In all cases the averages of the outputs were examined, and in some cases the time series output was examined. These results are available in the MassCEC simulation report (Manwell et al 2020).
CHAPTER 6

RESULTS

6.1 Ultimate Load Case Results

Results are shown from the set of design load cases run with FAST. Full certification of the reference turbine was not possible since certain physical parameters of the turbine were unavailable. Ultimate load cases in order of worst to best are shown below. The highest in-plane blade root bending moments for the simulations of the reference turbine under the given metocean conditions occurred at the extreme wind and wave cases while the turbine was parked. Evaluation of the acceptability of these results is not possible without detailed blade structural data. If these data were available, maximum stresses for each component could be calculated in detail.
Figure 10: Blade Root In Plane Bending Moments

The highest out-of-plane blade root bending moments for the simulations of the reference turbine under the given metocean conditions occurred at the control failure case simulating a blade pitch mechanism failure followed by an emergency stop. The magnitude of this load is approximately double that of the maximum in-plane blade root bending moment.
The three highest in-plane tip deflections for the simulations of the reference turbine under the given metocean conditions occurred at the same design load cases as the blade root out of plane bending moments. This highest load cases, DLC 6.3 involves yaw misalignment. The “in-plane” loads are therefore out of plane with the incoming wind.
Figure 12: In Plane Tip Deflections

The highest out of plane tip deflection for the simulations of the reference turbine under the given metocean conditions coincides with the tower strike analyzed below.
Figure 13: Out of Plane Tip Deflections

Maxima for tower base fore-aft bending moments for the simulations of the reference turbine under the given metocean conditions are highest for the operational cases, including several startup and shutdown DLCs.
Maxima for tower base side-side bending moments for the simulations of the reference turbine under the given metocean conditions are about half of the values of fore-aft bending moments. The extreme parked case is highest followed by the control failure case which resulted in a tower strike.
6.2 Tower Base Ultimate Loads

Loads on the tower base were investigated for two types of situations: normal operation at rated wind speed where the thrust is typically highest and stopped rotor during a hurricane, results are shown in Figure 14 and Figure 15.

6.2.1 Extrapolation of Ultimate Operating Loads

The ultimate operating load is estimated according to the standard by finding the maximum load during operation for a number of independent situations and extrapolating from those to a load with a return period corresponding to 50 years. To calculate this value, 50 ten-minute simulations were executed during which time the
average wind speed was approximately rated wind speed of the reference turbine, 11.4 m/s. Different randomizing “seeds” were used in each case so that the instantaneous wind speed characteristics differed. The maximum value of the tower base bending moments $M$ during each of those 50 simulations was then identified. The results of those simulations are illustrated in Figure 16. The average maximum value was $M_{av} = 1.31 \times 10^5$ kNm, the standard deviation was $\sigma_M = 19,227$ kNm and the maximum of those maxima was $1.73 \times 10^5$ kNm.

![Maximum F-A Tower Base Bending Moments](image)

**Figure 16: Maximum Tower Base Bending Moments**

A Gumbel distribution was then fit to the 50 maxima. The probability density function $p(x)$ for the Gumbel distribution is shown below:

$$p(x) = \frac{1}{\beta} \exp\left(\frac{-(x-\mu)}{\beta}\right) \exp\left(-\exp\left(\frac{-(x-\mu)}{\beta}\right)\right)$$

Where

$$\beta = \frac{\sigma \sqrt 6}{\pi} \quad \text{(here, } \sigma = \sigma_M)$$
\[ \mu = x_{av} - 0.577 \beta \text{ (here, } x_{av} = M_{av}) \]
Performing the calculations yields \( \beta = 14,992 \) and \( \mu = 122,655 \).

Next, the Weibull distribution was used to account for the fact that the wind speed is only within this rated range for a small part of the operational life, assuming the average wind conditions remain the same over the 50-year period for which the ultimate load is sought. A long term mean wind speed of 9.7 m/s and a Weibull shape factor of \( k = 1.83 \) were assumed, such that the Weibull scale factor is \( c = 10.9 \) m/s (Manwell, Lackner, Park, 2018)

The probability of the wind speed \( U \) being between \( U_i = 11 \) and \( U_{i+1} = 12 \) m/s is given by the following equation:

\[ p(U_i < U \leq U_{i+1}) = \exp \left( -\left( \frac{U_i}{c} \right)^k \right) - \exp \left( -\left( \frac{U_{i+1}}{c} \right)^k \right) \]

The probability of the wind speed being in the range of 11 to 12 m/s is equal to 0.064. Over a 50-year period there are 167,185 ten-minute periods when the moment could reach an extreme value. This number of intervals corresponds to the “return period” of the extreme event. Applying the Gumbel distribution yields an estimated extreme value of \( 3.03 \times 10^5 \) kNm, or approximately 1.75 times as high as the largest value observed in the 50 simulations. Figure 17 illustrates the predictions together with the data from the simulations (note that the x axis is logarithmic). It may also be observed that the last few data points from the simulations suggest that the ultimate extreme may not be as high as the Gumbel predicts, so using the Gumbel is likely conservative. However, few simulations are performed compared to the
timescale of the required return period, making it difficult to say anything more definitive.

![Ultimate Load Extrapolation]

**Figure 17: Ultimate Load Extrapolation**

### 6.3 Stopped Rotor in Hurricane Conditions

Two separate hurricane scenarios were simulated to illustrate the effect of hurricane loading on the reference turbine when stopped. These scenarios are intended to represent cases when the turbine is shut down and parked to minimize damage from the incoming winds.

### 6.3.1 Annex I Tropical Cyclone Criteria

In Annex I of the IEC 61400-3-1 standard, “Recommendations for alignment of safety levels in tropical cyclone regions,” a hurricane load is treated as the Extreme Wind Model with a wind and wave condition with a 500-year occurrence. From the table of wind return periods generated during the metocean phase of this project, this
results in a wind speed of 52.7 m/s at a hub height of 120 m. From the table of wave return periods generated during the metocean phase of this project, the extreme wave height with a 500-year return is 18.6 m.

6.3.2 Category 5 Hurricane without 3d Effects

Another sample load case was created with files using an idealized Category 5 hurricane from (Kapoor et al., 2019). The characteristics of the simulated storm are based on Hurricane Felix, which was representative of small Category 5 hurricanes. The simplest of the hurricanes simulated without veer or gust conditions was run for the DTU 10 MW turbine on a fixed monopile support structure.

The ultimate stress limit for the tower in bending is assumed to be 235 MPa. The tower is steel, with a base diameter of 7.42 m and wall thickness of 0.0349 m. The 2nd moment of inertia about an axis perpendicular to the primary direction of thrust

\[ I_{yy} = \frac{\pi}{4} \left( R_{out}^4 - R_{in}^4 \right) \]

The moment of inertia is calculated to be 6.47 m^4.

\[
M\text{allowable} = \frac{\sigma_{\text{yield}} I_{yy}}{R}
\]

For the tower in bending, the maximum allowable tower base bending moment is 388,667 kNm. Figure 18 illustrates the maximum tower base bending moments magnitudes.
Figure 18: Tower Base Bending Moment

Bending magnitude at the tower base is increased in the hurricane cases due to the extremely high wind speeds. The moment still falls within the yield stress threshold for the tower. Hurricane inputs as specified by the IEC standard do not require explicit consideration of 3D effects of hurricane loading.

6.4 Tower Strike Event

The acceptable value for tower clearance calculation is specified in the IEC 61400-1 Standard. For the DTU 10MW turbine, the undeflected blade tip clearance without loads from Bak et al. (2013) is 18.26 m. Using the combined partial safety factors for loads, materials, and consequences of failure, the allowable clearance was calculated from the undeflected tip clearance using the equation shown below.
Allowable Clearance = (Undeflected Clearance) \* \left( \frac{\gamma_f \gamma_n \gamma_m - 1}{\gamma_f \gamma_n \gamma_m} \right)

For tip deflection, the partial safety factor for loads $\gamma_f$ is 1.35 for normal design load cases and 1.1 for abnormal design load cases. The consequence of failure factor $\gamma_n$ is 1.0. The material safety factor $\gamma_M$ is 1.1. This leads to an allowable tip clearance of 5.96 m for the normal design load cases and 3.17 m for the abnormal design load cases.

The control failure design load case (DLC 2.1) was run using the assumptions stated of a “worst case” scenario of a blade pitch runaway followed by an emergency stop of the turbine. With the current setup of the controller input file, this resulted in a tower strike by the blade tip as indicated by analysis of FAST outputs.

The tower clearance output from the FAST simulations was analyzed as follows. This detailed time series output gives the distance from the tip of each blade to the tower centerline. The minimum value of this output during a control failure during normal operation at 24 m/s was 2.51 m. The true tower clearance is equal to this value reduced by the tower radius. The tower radius when a blade passes the tower can be estimated from the tower top and tower base diameters, and scaling by the ratio of the rotor radius minus the height of the rotor above the tower top to the tower height. That value is 3.74 m and occurs when the tip of the blade is 29 m ASL (above sea level). The true tower clearance for this load case is a value of -1.23 m; in other words, there is less than no clearance.
This failure would indicate a need for control adjustment and engineering redesign of the proposed turbine before certification. As noted previously, the allowable tip clearance for this load case taking into account safety factors is 5.96 m.

However, this case reflects the limitations of using the DTU 10MW reference turbine in the FAST v8 environment.

6.5 Fatigue Load Results

Fatigue can be assessed to estimate the damage accumulated over the life of a turbine due to normal operating load cycles. A Wöhler exponent value of 10 is standard to calculate “Damage Equivalent Loads” in composite materials, and exponents of 3 or 3.5 are commonly used for steel.

The wind speed can be divided into \( i = 1 \) to \( NB \) ranges. The ranges when summed are assumed include all possible wind speeds of relevance. The tower base under operational conditions is the area of interest.

FAST is run for each range for a 10-minute period multiple times and with different wind speed files to randomize the inputs. NREL’s TurbSim is used to generate input files to do this. The method uses different “seeds” to generate each wind speed file.

The tower base bending moment for each bin is selected. Damage comes from the stress on the material and in order to estimate damage the bending moment must be converted to stress and an appropriate relation between damage and stress (S-N curve) must be applied.
An example of evaluating fatigue for the tower base of the DTU 10 MW turbine follows. For this example, the fore-aft tower base bending moment, $TwrBsMyt$ was used. FAST was run 6 times using data generated by TurbSim for wind speed bins 2 m/s wide beginning at 4 m/s and going to 24 m/s. Figure 19 illustrates the bending moment data for the six 10 m/s cases, which had an average of $1.14 \times 10^5$ kNm.

![Figure 19: Sample Tower Base Bending Moment Time Series](image)

The stress at the tower base was found using the diameter of $D = 7.82$ m and wall thickness of 0.0349 m, yielding an area moment of inertia of $I = \frac{\pi}{4} \left( R_{out}^4 - R_{in}^4 \right) = 6.47 \text{ m}^4$. Using $R = c$ in the maximum stress equation $\sigma_{\text{max}} = \frac{Mc}{I}$ the stress is 0.603 times the moment. Thus, the average stress in this case is 68,700 kPa.

The moment data was processed using a rainflow counter (Manwell, McGowan, Rogers, 2009) with sub-bin width of 2,500 kNm for all wind speeds. The
number of occurrences is illustrated in Figure 20 for the six runs of the 10 m/s bin. (The moments were converted to stresses after the counting.)

Figure 20: Sample Moment Ranges and Number of Occurrences

The cumulative distribution function for this data was found and the Weibull $c_i$ and $k_i$ values for the moments were estimated. For stress, the ratio of $R/I = 0.603 \times 0.001$ was used to convert to the moment in kNm to equivalent stress in MPa.

For fatigue life estimation an S-N curve was used. Figure 21 below shows a typical S-N curve. First the approach was verified by duplicating the calculations summarized in ABS' Table 4 Parameters for Class 'T' ABS Offshore S-N Curves (ABS, 2003) reproduced here as Table 6. Using $A = N S^m$, assuming $m = 3$ and reading 36 MPa at $1.0 \times 10^7$ cycles gave $A = 4.87 \times 10^{11}$ as expected.
Figure 21: Sample S-N Curve (from ABS, 2003)

Table 6: Parameters for Class T S-N Curves (from ABS, 2003)

<table>
<thead>
<tr>
<th>S-N Curve</th>
<th>A (For MPa Units)</th>
<th>A (For ksi Units)</th>
<th>m</th>
<th>C (For MPa Units)</th>
<th>C (For ksi Units)</th>
<th>r</th>
<th>N₀</th>
<th>S₀ (For MPa Units)</th>
<th>S₀ (For ksi Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T(A)</td>
<td>1.46×10¹³</td>
<td>4.46×10⁸</td>
<td>3.0</td>
<td>4.05×10¹¹</td>
<td>2.61×10¹¹</td>
<td>5.0</td>
<td>1.0×10⁷</td>
<td>52.7</td>
<td>7.64</td>
</tr>
<tr>
<td>T(CP)</td>
<td>7.30×10¹¹</td>
<td>2.23×10⁸</td>
<td>3.0</td>
<td>4.05×10¹¹</td>
<td>2.61×10¹¹</td>
<td>5.0</td>
<td>1.77×10⁸</td>
<td>74.5</td>
<td>10.8</td>
</tr>
<tr>
<td>T(FC)</td>
<td>4.87×10¹¹</td>
<td>1.49×10⁸</td>
<td>3.0</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Note: For service in seawater with free corrosion (FC), there is no change in the curve slope.

Data from ABS' Table 1 Class Curve C (here Table 7) and ABS' Figure 1 ABS-(A) Offshore S-N Curves for Non-Tubular Details in Air (here, Figure 22) was used. This curve is conservative for the case but does serve to illustrate the method.
Table 7: Parameters for ABS (A) Offshore S-N Curves for Non-Tubular Details in Air (from ABS, 2003)

<table>
<thead>
<tr>
<th>Curve Class</th>
<th>A ( \text{MPa Units} )</th>
<th>B ( \text{ksi Units} )</th>
<th>m</th>
<th>C ( \text{MPa Units} )</th>
<th>D ( \text{ksi Units} )</th>
<th>r</th>
<th>( N_0 ) ( \text{MPa Units} )</th>
<th>( S_0 ) ( \text{ksi Units} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1.01 \times 10^{13}</td>
<td>4.48 \times 10^{13}</td>
<td>4.0</td>
<td>1.02 \times 10^{13}</td>
<td>9.49 \times 10^{13}</td>
<td>6.0</td>
<td>1.0 \times 10^{5}</td>
<td>100.2 \text{ksi}</td>
</tr>
<tr>
<td>C</td>
<td>4.33 \times 10^{12}</td>
<td>4.93 \times 10^{12}</td>
<td>3.5</td>
<td>2.59 \times 10^{12}</td>
<td>6.35 \times 10^{12}</td>
<td>5.3</td>
<td>1.0 \times 10^{5}</td>
<td>78.2 \text{ksi}</td>
</tr>
<tr>
<td>D</td>
<td>1.52 \times 10^{11}</td>
<td>4.65 \times 10^{11}</td>
<td>3.0</td>
<td>4.33 \times 10^{11}</td>
<td>2.79 \times 10^{11}</td>
<td>5.0</td>
<td>1.0 \times 10^{5}</td>
<td>53.4 \text{ksi}</td>
</tr>
<tr>
<td>E</td>
<td>1.04 \times 10^{11}</td>
<td>3.18 \times 10^{11}</td>
<td>3.0</td>
<td>2.30 \times 10^{11}</td>
<td>1.48 \times 10^{11}</td>
<td>5.0</td>
<td>1.0 \times 10^{5}</td>
<td>47.0 \text{ksi}</td>
</tr>
<tr>
<td>F</td>
<td>6.30 \times 10^{11}</td>
<td>1.93 \times 10^{11}</td>
<td>3.0</td>
<td>9.97 \times 10^{11}</td>
<td>6.42 \times 10^{11}</td>
<td>5.0</td>
<td>1.0 \times 10^{5}</td>
<td>39.8 \text{ksi}</td>
</tr>
<tr>
<td>F2</td>
<td>4.30 \times 10^{11}</td>
<td>1.31 \times 10^{11}</td>
<td>3.0</td>
<td>5.28 \times 10^{11}</td>
<td>3.40 \times 10^{11}</td>
<td>5.0</td>
<td>1.0 \times 10^{5}</td>
<td>33.0 \text{ksi}</td>
</tr>
<tr>
<td>G</td>
<td>2.50 \times 10^{11}</td>
<td>7.64 \times 10^{10}</td>
<td>3.0</td>
<td>2.14 \times 10^{11}</td>
<td>1.38 \times 10^{11}</td>
<td>5.0</td>
<td>1.0 \times 10^{5}</td>
<td>29.2 \text{ksi}</td>
</tr>
<tr>
<td>W</td>
<td>1.60 \times 10^{11}</td>
<td>4.89 \times 10^{10}</td>
<td>3.0</td>
<td>1.02 \times 10^{11}</td>
<td>6.54 \times 10^{10}</td>
<td>5.0</td>
<td>1.0 \times 10^{5}</td>
<td>25.2 \text{ksi}</td>
</tr>
</tbody>
</table>

Figure 22: Sample S-N Curve for details in air (from ABS, 2003)

In this case, as shown in Table 7, \( A = 4.23 \times 10^{13}, m = 3.5 \)

Damage was calculated using both the direct bin method, and the Weibull method for the single line S-N curve. We also calculated the damage using the two-segment S-N curve with the Weibull method.
The rainflow algorithm was then run for all the tower base bending moment data. The means, standard deviations, Weibull $c$’s and $k$’s and damages are all summarized in Table 8. Note that there are three columns associated with “damage per interval.” They correspond to the Weibull method, the direct bin method and Weibull two-segment method. Each entry is the damage associated with a single 10-minute-long interval during which the wind speed was as indicated in the first column. The last three columns show the cumulative damage over the 20-year life of the turbine, taking into account the amount of time that the wind speed was as in the first column.

### Table 8: Sample Damage Calculation

<table>
<thead>
<tr>
<th>Wind speed bin mid</th>
<th>Rainflow av (kN)</th>
<th>Rainflow std dev (kN)</th>
<th>Weibull c (kN/m)</th>
<th>Weibull c (MPa)</th>
<th>Weibull k</th>
<th>Cycles N</th>
<th>Damage per interval Weibull data</th>
<th>Damage per wind speed bin 2 segment data</th>
<th>Damage per wind speed bin 2 segment data</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>54.687</td>
<td>28.177</td>
<td>61.735</td>
<td>37.2</td>
<td>2.05</td>
<td>1047</td>
<td>2.02E-06</td>
<td>1.13E-06</td>
<td>2.62E-01</td>
</tr>
<tr>
<td>6</td>
<td>65.426</td>
<td>31.326</td>
<td>73.876</td>
<td>44.5</td>
<td>2.23</td>
<td>1013.5</td>
<td>2.09E-06</td>
<td>3.40E-06</td>
<td>5.03E-01</td>
</tr>
<tr>
<td>8</td>
<td>54.201</td>
<td>27.628</td>
<td>61.194</td>
<td>36.9</td>
<td>2.08</td>
<td>867</td>
<td>1.59E-06</td>
<td>1.68E-06</td>
<td>8.61E-07</td>
</tr>
<tr>
<td>10</td>
<td>33.547</td>
<td>23.598</td>
<td>37.052</td>
<td>22.3</td>
<td>1.47</td>
<td>648</td>
<td>3.93E-07</td>
<td>4.81E-07</td>
<td>6.49E-02</td>
</tr>
<tr>
<td>12</td>
<td>35.645</td>
<td>31.097</td>
<td>37.545</td>
<td>22.6</td>
<td>1.16</td>
<td>400.5</td>
<td>5.34E-07</td>
<td>5.51E-07</td>
<td>6.19E-02</td>
</tr>
<tr>
<td>14</td>
<td>24.365</td>
<td>20.906</td>
<td>25.793</td>
<td>15.6</td>
<td>1.18</td>
<td>575</td>
<td>2.12E-07</td>
<td>2.57E-07</td>
<td>9.92E-02</td>
</tr>
<tr>
<td>16</td>
<td>24.943</td>
<td>18.485</td>
<td>27.319</td>
<td>16.5</td>
<td>1.38</td>
<td>796.5</td>
<td>2.19E-07</td>
<td>2.48E-07</td>
<td>6.50E-08</td>
</tr>
<tr>
<td>18</td>
<td>26.495</td>
<td>18.141</td>
<td>29.371</td>
<td>17.7</td>
<td>1.51</td>
<td>942.5</td>
<td>2.64E-07</td>
<td>2.69E-07</td>
<td>6.09E-08</td>
</tr>
<tr>
<td>20</td>
<td>30.492</td>
<td>19.247</td>
<td>34.097</td>
<td>20.6</td>
<td>1.65</td>
<td>967.5</td>
<td>3.74E-07</td>
<td>3.85E-07</td>
<td>1.06E-07</td>
</tr>
<tr>
<td>22</td>
<td>33.910</td>
<td>21.658</td>
<td>37.879</td>
<td>22.8</td>
<td>1.63</td>
<td>1032.5</td>
<td>5.92E-07</td>
<td>5.91E-07</td>
<td>2.11E-07</td>
</tr>
<tr>
<td>24</td>
<td>38.284</td>
<td>23.394</td>
<td>42.921</td>
<td>25.9</td>
<td>1.71</td>
<td>1019</td>
<td>8.22E-07</td>
<td>8.15E-07</td>
<td>3.33E-07</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>1.20</strong></td>
<td><strong>1.26</strong></td>
<td><strong>0.71</strong></td>
</tr>
</tbody>
</table>

As can be seen, this example indicates that all of the fatigue life of the tower would have been used up (total greater than 1.0) before the end of 20-year lifetime when the single line S-N curve is used. A more realistic assessment, using the 2 segment S-N curve, indicated significantly less fatigue damage, and the fatigue life was adequate.
Figure 23 illustrates the cumulative density function (CDF) from the data and from the Weibull CDF using $c$ and $k$ values for one of the cases from Table 7 (10 m/s), confirming that the Weibull gives a good fit to the data.

![CDF from Data and Weibull](image)

**Figure 23: CDF from data and Weibull, 10 m/s**

It is of note that Table 7 indicates that there is more damage from cycles at lower wind speeds than those at higher wind speeds. This is surprising on the surface, but it does appear to reflect a consistent interpretation of the data. To illustrate this, consider Figure 24, which shows the time series of the tower base bending moment for wind speed bins of 6 m/s and 22 m/s.
Figure 24: Two bending moment time series

The mean moment at 6 m/s is lower than that at 22 m/s. However, it is visually apparent that the fluctuations are greater at 6 m/s, which would be expected to result in greater fatigue damage. Numerically, the average moment at 6 m/s is 44,363 kNm and its standard deviation is 30,677 kNm, while the average moment at 22 m/s is 59,358 kNm and its standard deviation is 15,299 kNm, so the variability (standard deviation divided by the mean) in the 6 m/s case is nearly 2.7 times as great as that of the 22 m/s case. This observation is also consistent with the histograms which are output from the rainflow algorithm (using six seeds for each), as shown in Figure 25. This figure shows that there are more occurrences of cycles of greater ranges (which are most damaging) at the 6 m/s wind speed than at 22 m/s. This may be reasonable due to higher turbulence at lower wind speeds causing hypothetically higher fatigue. Further work on fatigue is found in the Analysis report for this project (Manwell et al 2020).
Figure 25: Two cycle ranges and occurrences
CHAPTER 7

CONCLUSIONS

Most of the results of the study were reasonable, and consistent with sanity checks taken. Extreme loads and fatigue damage results from model outputs exceed simplified estimates of turbine loads, which is to be expected.

The control failure during power production case (DLC 2.1) produced some of the highest loads but the case of control failure on a physical turbine may have many differing root causes depending on proprietary controller design that the standard fails to address in any detail. Industry-standard assumptions for most severe control failures were made for this analysis but technical details and rationale behind these were lacking.

There is no guidance in IEC 61400-3-1 about buckling. The approach used in other reports for this project was adapted from (Leite, 2015). Results indicated buckling was not a problem for the reference model used in the Massachusetts Offshore Wind Energy Area.

The standard gives little guidance on fatigue calculations. The industry standard method of rainflow counting to find the number of cycles of various ranges was used and then applied a commonly used SN curve to calculate total fatigue damage. Suggestions regarding material property assumptions and modelling approaches to employ would also be useful.
The standard also does not include detailed specification of how to assess soil, and FAST itself has limited capabilities. Future editions of the standard should address this at a higher level of detail.

The results indicate that hurricanes may be a source of significant structural loads, and perhaps the highest loads. This suggests that continued work is needed to study the possible effects of hurricanes on offshore wind turbines, taking into account both their infrequency and the possible compounding effect of associated problems, such as loss of the electrical system or control system failures during such an extreme event. The standard does not specify the inclusion of 3D wind effects (such as veer), but these may indeed be vital to proper characterization of hurricane loads in the offshore environment.

A detailed blade model for the DTU 10MW is not available. If such a model was available, finite element analysis and partial safety factor stress assessment as described in the standard could have been performed and evaluated.

The topic of ultimate loads is an important one and could still use additional study, considering both “normal” extreme events and hurricanes. The approach used in DLC 1.1 was to extrapolate to a 50-year event based on 50 simulations with the wind speed near rated and then fit a Gumbel distribution to the maxima of those 50 simulations. Another approach is to use the method of environmental contours to assist in finding the ultimate loads. This method is also recommended in IEC 61400-3-1, but in the case of the present study it did not lead to the extreme load. Extreme structural loads are an important subject in the field of structural reliability.
(probabilistic design) and merit significant additional consideration in the development of wind turbine design standards. It is of note, in fact, that over the course of this project, the IEC itself has developed a proposal for a new working group to undertake a comprehensive study of these methods: PNW TS 88-761: Wind energy generation systems – Part 9: Probabilistic design measures for wind turbines. Such a study is needed.
CHAPTER 8

FUTURE WORK

The exercise explored through this research demonstrates the unique questions that arise when applying the IEC 61400-3-1 standard to a reference turbine model in the Massachusetts Offshore Wind Energy Area using FAST v8.12. Though there are clearly ambiguities of the standard, especially relating to control systems and fatigue, the exercise demonstrated that further pursuit of testing the standard with reference models is a valuable exercise. Future work should use updated models along with updated versions of the standards to elucidate more ambiguities.
import shutil
import subprocess
import os
import datetime
from decimal import Decimal

hubheight = 119
WaveSeed1 = [1718589219, 905725457, 1701252285, 1408192428, 1823491298, 1457572645]
WaveSeed2 = [304698591, 1966527065, 2060494295, 76690245, 2005735225, 1627234539]

BlPitch = [-1, -1, -1, -1, 2, 2, 2, 2, 2, 2]
RotSpeed = [3, 3, 3, 3, 11.5, 11.5, 11.5, 11.5, 11.5, 11.5]
NacYaw = [-8, -8, 0, 0, 8, 8]
WaveHs = [1.8, 1.9, 2.0, 2.4, 2.7, 3.0, 3.4, 4.0, 4.5, 5.0, 5.8]
WaveTp = [7.8, 7.8, 7.5, 7.2, 7.2, 7.5, 7.8, 8.1, 8.5, 9.2]
WavePk = [1, 1, 1, 1.32, 1.99, 2.74, 2.97, 3.42, 3.89, 3.87, 3.90]

Folder = [0, 1, 2, 3]
Winds = [4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24]
WaveDir = [0, 30, 60, 90]
WaveDirLineCounter = 0
WaveDirLoop = 0
numbering = [1, 2, 3, 4, 5, 6]

WindSpeed = [4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24]
TurbInt = [26.0, 20.2, 17.2, 15.3, 14.2, 13.4, 12.8, 12.4, 12.1, 11.9, 11.7]
Powerlaw = (float(((Decimal.from_float(10))/Decimal.from_float(hubheight)))**0.14)
WindSpeedZ10 = [x * Powerlaw for x in WindSpeed]
WindCurrent = [0.01 * x for x in WindSpeedZ10]

now = datetime.datetime.now()
month = str(now.month)
day = str(now.day)
hour = str(now.hour)
minute = str(now.minute)
datelabel = month + '_' + day + '_' + hour + '_' + minute
BigFolder = 'D:\Offshore Batch Results\DLC 1-1\AllSeeds-' + datelabel
command = ['mkdir', BigFolder]
p = subprocess.Popen(command, stdout=subprocess.PIPE, shell=True)
out = p.communicate()
SeedNumber = len(WaveSeed1)
for S in range(0, SeedNumber):  # final range (0, SeedNumber)
    for W in range(0, 11):  # final range (0,11)
        Label = 'DTU_10MW_RWT_W' + str(WindSpeed[W]) + 'Seed' + str(S)
        with open(Label + '.fst', 'w') as GlueFile:
            GlueMaster = open('DTU_10MW_RWT_Master.fst', 'r')
GlueLineCounter = 0
while True:
    line = GlueMaster.readline()
    GlueFile.write(line)
    if not line.strip():
        break

with open('DTU_10MW_RWT_InflowWind.dat', 'w') as InflowFile:
    InflowMaster = open('DTU_10MW_InflowWindMaster.dat', 'r')
    InflowLineCounter = 0
    while True:
        line = InflowMaster.readline()
        InflowFile.write(line)
        if not line.strip():
            break
    InflowFile.write("D:\Offshore Batch Results\Wind\NTMSpeeds\NTM' +
    str(WindSpeed[W]) + \ " TurbSim.bts" + \n"
    MasterDiscard = InflowMaster.readline()
    InflowLineCounter = InflowLineCounter + 1
    while True:
        line = InflowMaster.readline()
        InflowFile.write(line)
        if not line.strip():
            break
    InflowFile.write("D:\Offshore Batch Results\Wind\NTMSpeeds\NTM' +
    str(WindSpeed[W]) + \ " TurbSim.bts" + \n"
    MasterDiscard = InflowMaster.readline()
    InflowLineCounter = InflowLineCounter + 1
    while True:
        line = InflowMaster.readline()
        InflowFile.write(line)
        if not line.strip():
            break

with open('DTU_10MW_RWT_HydroDyn.dat', 'w') as HydroFile:
    HydroDynMaster = open('DTU_10MW_RWT_HydroDynMaster.dat', 'r')
    HydroLineCounter = 0
    while True:  # copying top half of HydroDyn Master File to HydroDyn file for specific
    line = HydroDynMaster.readline()
    HydroFile.write(line)
    HydroLineCounter = HydroLineCounter + 1
    if HydroLineCounter == 12:
        break
    HydroFile.write(str(WaveHs[W]) + \ " WaveHs - Significant wave height of incident
waves (meters) [used only when WaveMod=1, 2, or 3'] + '\n"
    MasterDiscard = HydroDynMaster.readline()
    HydroFile.write(str(WaveTp[W]) + \ " WaveTp - Peak-spectral period of incident
waves (sec) [used only when WaveMod=1 or 2]'+ '\n"
    MasterDiscard = HydroDynMaster.readline()
    HydroFile.write(str(WavePk[W]) + \ " WavePkShp - Peak-shape parameter of
incident wave spectrum (-) or DEFAULT (string) [used only when WaveMod=2] [use 1.0 for
Pierson-Moskowitz]'+ '\n"
    MasterDiscard = HydroDynMaster.readline()
    HydroLineCounter = HydroLineCounter + 3
    while True:  # copying bottom half of HydroDyn Master File to HydroDyn file for specific
    line = HydroDynMaster.readline()
    HydroFile.write(line)
HydroLineCounter = HydroLineCounter + 1
if HydroLineCounter == 22:
    break

HydroFile.write(str(WaveSeed1[S]) + ' WaveSeed(1) - First random seed of incident waves [-2147483648 to 2147483647] (-) [unused when WaveMod=0 or 5] + \n')
MasterDiscard = HydroDynMaster.readline()
HydroFile.write(str(WaveSeed2[S]) + ' WaveSeed(2) - Second random seed of incident waves [-2147483648 to 2147483647] (-) [unused when WaveMod=0 or 5] + \n')
MasterDiscard = HydroDynMaster.readline()
HydroLineCounter = HydroLineCounter + 2
while True:  # copying bottom half of HydroDyn Master File to HydroDyn file for specific simulation instance
    line = HydroDynMaster.readline()
    HydroFile.write(line)
    HydroLineCounter = HydroLineCounter + 1
    if HydroLineCounter == 41:
        break

HydroFile.write(str(WindCurrent[S]) + ' CurrNSV0 - Near-surface current velocity at still water level (m/s) [used only when CurrMod=1] + \n')
MasterDiscard = HydroDynMaster.readline()
HydroLineCounter = HydroLineCounter + 1
while True:  # copying bottom half of HydroDyn Master File to HydroDyn file for specific simulation instance
    line = HydroDynMaster.readline()
    HydroFile.write(line)
    HydroLineCounter = HydroLineCounter + 1
    if not line.strip() and HydroLineCounter > 153:  # End of HydroDyn File, adjust and check command
        break

command = ["FAST_Win32.exe", Label + ".fst"]
p = subprocess.Popen(command)
p.wait()
shutil.copy2(filedirectory, BigFolder)
shutil.copy2(filedirectory, BigFolder)
shutil.copy2(filedirectory, BigFolder)
shutil.copy2(filedirectory, BigFolder)
shutil.copy2(filedirectory, BigFolder)
shutil.copy2(filedirectory, BigFolder)
shutil.copy2(filedirectory, BigFolder)
shutil.copy2(filedirectory, BigFolder)
shutil.copy2(filedirectory, BigFolder)
APPENDIX B
MASSCEC PROJECT REPORTS AND DOCUMENTATION

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition of Meteorological Conditions for Applying IEC 61400-3-1 to an Offshore Wind Turbine in the Massachusetts Offshore Wind Energy Lease Areas</td>
<td>Manwell, Lackner, Park</td>
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<td>Creation of Rotor Nacelle Assembly and Support Structures FAST Input Files for the Application of IEC 61400-3-1 to an Offshore Wind Turbine in the Massachusetts Offshore Wind Energy Lease Areas</td>
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<td>MassCEC Final Report</td>
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<td>NAWEA Conference Paper</td>
<td>Roach, Manwell, Lackner, Park, Gaertner</td>
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</table>

All reports may be found in the project repository, <MassCEC Standards Project>, located on the UMass Amherst Wind Energy Center Website, https://www.umass.edu/windenergy/home.
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NDBC (2018) *Station 44008 (LLNR 827) - NANTUCKET 54 NM Southeast of Nantucket*,
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