FLOATING WIND JOINT INDUSTRY PROGRAMME

Fatigue analysis of high voltage electrical equipment in floating structures

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Cover image courtesy of Jose Vega-Lozano, taken at Sheringham Shoal Windfarm ©Equinor.

Introduction

Deployment of floating wind turbines and floating substations creates various challenges, including how electrical equipment is designed for fatigue, and how test procedures will be developed to provide an adequate representation of the fatigue damage experienced over the design life of the equipment while operational on floating structures. This is complicated by the accelerations electrical equipment will endure in floating structures being dependent not only on the local metocean characteristics but also the different motion characteristics of varying types of floating structures.

To date, only pre-commercial designs for floating wind turbines have been developed. An example of this is the 50 MW Kincardine Offshore Floating Wind Farm, which consists of five 9.5 MW and two 2 MW turbines based on semi-submersible substructures. The only floating substation deployed to date was in support of the Fukushima FORWARD programme, which supported a pilot-scale floating wind demonstrator farm. The substation was positioned on an advanced spar substructure, with a helipad and met-mast installed.[1]

Figure 1: 66kV substation "Fukushima Kizuna", Courtesy of Fukushima Offshore Wind Consortium.[1]

This Fatigue Analysis of High Voltage Electrical Equipment in Floating Structures (HVEF) project, delivered by Petrofac for the Floating Wind Joint Industry Programme (JIP) set out to better understand high voltage electrical equipment design and its suitability for operation in offshore floating structures.

This summary report outlines the project's key findings based on the objectives and highlights future requirements and needs for the industry.

Project objectives

1. Obtain a greater understanding of fatigue analysis of electrical equipment in floating structures through the identification of relevant forces and weak points of electrical equipment sensitive to acceleration stress;
2. Advise on potential design changes required and a type-test program for floating wind applications;
3. Determine a basis of feasibility for the application of electrical components in floating wind, identifying the associated risks and costs incurred.

[1] (PDF) Construction of Phase 1, Fukushima FORWARD, available at http://www.fukushima-forward.jp/

Methodology

A combination of simulations was conducted with varying motion characteristics and floating foundation solutions for both the wind turbine generators and offshore substations. This enabled a better understanding of the accelerations electrical equipment would have to endure under the specified conditions and parameters outlined below. It is important to highlight that the high voltage elements in the offshore substation operate at significantly higher voltages compared to those found in the offshore wind turbine.

This analysis was performed in the time domain using the mooring analysis programme OrcaFlex. The simulations were modelled considering the following designs and environments:

Wind turbine generators (WTGs)

- 15 MW turbine on a spar hull;
- 15 MW turbine on a semisubmersible hull.

Substations

- 250 MW substation on a semisubmersible hull;
- 800 MW substation on a semisubmersible hull;
- 250 MW substation on a TLP hull;
- 250 MW substation on a barge hull.

Environments

- 'Benign' similar to a Mediterranean Sea deployment;
- 'Moderate' similar to offshore California or Japan;
- 'Harsh' similar to that found in the North Sea.

Damage Equivalent Load (DEL) Calculation & Comparison

1. Acceleration parameters for each design and mooring system were obtained and simplified to a Damage Equivalent Load (DEL), which enabled comparison between different fatigue environments via a common metric which can be quantified;
    - Electrical components of the wind turbine are concentrated in the nacelle, and so a single set of acceleration data was extracted for this location.
    - Within the substation, the electrical equipment is more distributed and therefore the acceleration data was extracted for the centre of the transformer, reactor, HV switchgear and auxiliary transformer.
2. The frequency content of each simulation was calculated by performing a Fourier transform and used to produce a combined Power Spectral Density (PSD) plot to determine where the energy was concentrated in the frequency spectrum;
3. Vibration test standards were investigated for qualifying electrical equipment and DELs were calculated from the defined parameters in DNV-CG-0339;
4. The test standard DELs were then compared with the simulated and calculated acceleration levels from the varying designs and environments;
5. A more applicable test specification methodology was developed, and the practical considerations were discussed.

Key findings

1 **Fatigue accelerations are higher in wind turbine nacelles than in all substation vessel types, however the extent is dependent on floating structure type, environment and mooring design.**

It was found that the DELs in the wind turbine nacelle for both the assessed spar and semisubmersible designs were generally higher than those anywhere on any of the substations, as the motions generated in the nacelle due to pitch and roll of the floating WTG structure were amplified by the tower height. In general, the DELs for components in the wind turbine nacelle were approximately three times those seen in the substations.

The exception to this was the substation TLP design, where high-frequency vertical accelerations were seen to result in a significantly higher DEL compared to the other substation hull designs. This was most noticeable in the benign environment, where interaction between the wave frequency and the vertical natural frequency was responsible for an amplified response. This was not the case for the harsh environment, where the DEL was comparable to the other three substations. Tuning of the hull form and tendon stiffness specifically to the deployment location would be an effective way to reduce this effect.

The semisubmersible substations demonstrated the lowest DELs across all sites due to their resistance to wave-induced motion and the separation between the wave frequency loading and the hydrodynamic natural periods.

2 **Existing vibration test standards are not designed to perform as fatigue tests for floating offshore substation environments.**

The review of DNV-CG-0339 and similar standards found that these existing standards are designed to identify problematic areas of resonance at the types of forcing frequencies seen in shipping environments. The fatigue environment that the reviewed standards are intended for is not representative of a substation environment due to the absence of significant sources of vibration including marine diesel engines, rotating machinery or compressors, therefore making the existing standards unsuitable. The wind turbine nacelle will see high-frequency vibration from the rotor and gearbox, but the mechanical vibration is a similar environment to that experienced in existing fixed-bottom turbines and hence does not represent a new feature of a floating structure.

Adopting the test methodology of the existing standards, which focus on identifying resonance, has the potential to create misleading test results. This is due to the floating structure vibration environment relating to wave frequencies, and the test frequency would be higher than experienced in the real-world environment.

The DELs calculated from the test accelerations were compared to the DELs obtained from the wind turbine and substation designs, assuming a 20-year design life. It was determined that the DEL for the test acceleration defined in the standards was not certain to exceed 20 years of life as per the simulations conducted in this study and therefore the test specification was not suitable for use without modification.

3 **The fatigue test specification should be developed to match the required DEL accelerations calculated through simulations.**

A methodology was presented to determine a target test DEL from the DELs established within the simulations for each floating structure type and environment, including adjustments to be made to allow for design life and design fatigue factor. This enables various combinations of acceleration, frequency and duration to be assessed to determine if a feasible test programme can be developed.

A constant sinusoidal test is considered to be the most appropriate method to apply for testing equipment in the offshore environment due to the dominance of the energy at the wave frequency and the absence of rotating machinery. Using this method, it can be demonstrated that the fatigue damage incurred during the test will be an acceptable match for the fatigue damage accumulated in service, provided various constraints are met.

4 **There are currently limited test facilities for equipment weighing over 20 tonnes; planning the fatigue strategy should account for further specific constraints.**

When determining the test frequency, acceleration and duration for a given target DEL, further limitations should be considered which may arise from:

- Structural resonance
- Nonlinearity of response
- The non-propagating stress limit
- The test facility capabilities

Satisfying all of these constraints becomes increasingly difficult as the equipment under test (EUT) mass and physical dimensions increase. An investigation into test facilities available in Europe showed that the choice was limited beyond an EUT mass of 20 tonnes. Beyond 50 tonnes, physical testing may not be feasible, depending on the acceleration level and test duration required.

5 **Design by analysis approach should be adopted for testing larger items of equipment**

Full physical testing offers the most clarity for validating design life and identification of failure points which may potentially lead to improved future design, however for larger items of equipment, the acceleration that a test facility is able to generate can become the limiting factor. Extending the test duration to accumulate a sufficient number of cycles is of limited use, as the nonlinear relationship between stress and damage means that the time required to complete the test rapidly increases with a reduced acceleration input. In addition, the high capital cost for large items of equipment produced in small quantities also reduces the attractiveness of performing a physical destructive test.

In this case, a design by analysis method should be considered to demonstrate the fatigue performance of the electrical equipment via finite element analysis, or even via hand calculations if the structure is suitably uncomplicated. The potential of adopting a hybrid approach between physical testing of subassemblies coupled with analysis of the complete equipment should be considered as a means by which the benefits of both methods can be obtained.

Industry needs and innovations

1 Development of generalised acceleration bands corresponding to different floating structure types and environments.

For an electrical equipment manufacturer, designing or following test specifications for individual structures types and environments is expensive and time consuming. Minimising the number of tests required to qualify equipment would therefore reduce the cost of developing new designs. Development of electrical equipment suitable for use in multiple projects could be streamlined by testing to an acceleration level that bounds the required project accelerations. Setting criteria based on classes of environment (for instance similar to the IEC wind turbine classes [2]) would enable qualification of equipment by manufacturers without having to re-qualify them for every project.

2 Standards for performing fatigue testing for use in floating offshore wind deployments.

Due to the differences between the fatigue environments considered in the existing vibration testing standards and those experienced by components installed on floating structures, a standard should be developed for performing fatigue testing specifically for use on floating offshore wind structures.

3 Industry would benefit from more test facilities for equipment larger than 20 tonnes equipment.

A survey of testing facilities in Europe found that the number of facilities able to test equipment in excess of 20 tonnes is relatively limited, and testing equipment beyond 50 tonnes may not be feasible, depending on size and acceleration requirements. In this case, testing should be performed using a finite element model or a potential hybrid methodology which physically tests subassemblies of large equipment.

[2] IEC 64100-1. Geneva, Switzerland: International Electrotechnical Commission; 2005.

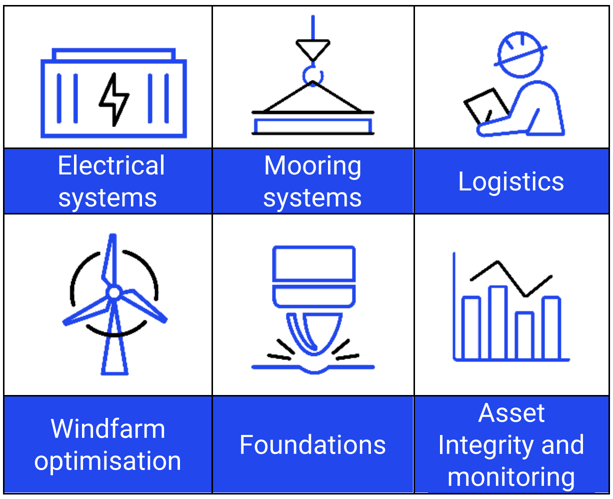
ABOUT THE FLOATING WIND JIP

The Floating Wind Joint Industry Programme (Floating Wind JIP) is a collaborative research and development (R&D) initiative between the Carbon Trust and 17 leading international offshore wind developers: bp, EDF Renouvables, EnBW, Equinor, Kyuden Mirai Energy, Ørsted, Ocean Winds, Parkwind, RWE Renewables, ScottishPower Renewables, Shell, Skyborn Renewables, SSE Renewables, TEPCO, Tohoku Electric Power Company, Total Energies and Vattenfall.

The primary objective of the Floating Wind JIP is to overcome technical challenges and advance opportunities for commercial scale floating wind. Since its formation in 2016, the programme scope has evolved from feasibility studies to specific challenges focusing on:

- Large scale deployment
- Industrialisation
- De-risking technology challenges
- Identifying innovative solutions
- Cost reduction

This fatigue analysis of high voltage electrical equipment in floating structures (HVEF) study was delivered under Stage 2 Phase V of the Floating Wind JIP. Contrasting to previous phases, the Floating Wind JIP partners decided to publish individual project reports for Phase V due to an increased number of projects with different durations. The summary reports for previous Stage 2 phases can be found here: Phase I, Phase II, Phase III and Phase IV.



Research areas

The Floating Wind JIP selected six research areas where further understanding and advancement is required to reach full commercialisation of floating offshore wind projects.

These research areas are explored through different Carbon Trust research mechanisms such as common R&D projects, discretionary projects and industry competitions.

ABOUT THE CARBON TRUST

Who we are

Our mission is to accelerate the move to a decarbonised future. We are your expert guide to turn your climate ambition into impact.

We have been climate pioneers for more than 20 years, partnering with leading businesses, governments and financial institutions to drive positive climate action. To date, our 400 experts globally have helped set 200+ science-based targets and guided 3,000+ organisations and cities across five continents on their route to Net Zero.

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