OFFSHORE WIND TURBINE VESSEL CHARGING

Design, Simulation and Full-scale Trial

ENGINEERING REPORT

AUTHOR // Will Brindley

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Document History

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Nomenclature

CMDC	Clean Maritime Demonstration Competition
CO_2e	Carbon dioxide equivalent"
COG	Centre of Gravity
CTV	Crew Transfer Vessel (with any form of propulsion)
eCTV	Electric Crew Transfer Vessel
GPS	Global Positioning System
QTF	Quadratic Transfer Functions
RAO	Response Amplitude Operators

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1 Summary

This report details the design and build of an offshore charging solution for an electric Crew Transfer Vessel (eCTV). The eCTV's on-board battery is plugged into a charging cable, which is deployed from the wind turbine or substation platform. The vessel then taps into the renewable power generated by the offshore turbines, providing a system that is low cost, easily maintained and operated, and highly scalable. The cable also functions as the mooring line, making use of the turbine structural foundations.

Lessons learned on the technical design and build are shared at a high level. The focus of the report is on the safe performance of the cable as a mooring line. Mooring simulations using OrcaFlex software are presented, which are used to predict the loads in the system, and thereby define the safe operating limits to maintain connection between the CTV and the wind turbine.

Physical test and real-world field trial data is compared to the simulation models and design expectations, in order to better understand the modelling uncertainties. The next steps for large scale deployment across the North Sea and beyond are outlined.

2 Introduction

2.1 Background

It typically takes 6 months to 1 year for the renewable energy produced by an offshore wind turbine to displace the carbon emissions required to build and maintain the wind farm [1]. Whilst an offshore wind turbine designed for a minimum 20 year lifetime offsets far more emissions than it produces, there is a drive within the industry to make offshore wind a truly zero-emission source of electricity.

Offshore wind turbines are maintained using marine gas oil powered vessels, which can contribute 10-20% of the project life cycle carbon emissions [2]. For closer to shore projects, which make up the majority of installed capacity in the UK, Crew Transfer Vessels (CTVs) support turbine through-life operations and maintenance activities, with an estimated 4000 hours of CTV time producing 2000 Tonnes of CO_2e per year for a single 180MW wind farm [3]. A candidate to reduce the carbon footprint of offshore wind maintenance activities is to use electric Crew Transfer Vessels (eCTVs). However, the limited energy density of battery storage severely reduces the operating capability and range of eCTVs, which limits the adoption of such vessels. Having a method to charge batteries in the field – ideally during offshore downtime – would be a key enabler for the large-scale deployment of eCTVs to unlock carbon emission reductions.

There are multiple viable options available for transferring power from offshore turbines to a CTV, most of which have a well proven pedigree in the oil and gas industry [4]. Of all the available approaches, three feasible options were shortlisted for the project, with a high-level assessment of the relative advantages and disadvantages summarized in Table 1.

Table 1: Comparison of methods of power transfer between a wind turbine and CTV

Assessment Criteria	Seabed located Connector [1]	Floating Buoy Connector [2]	In-Air Connector [3]
Purchase & installation cost	Neutral	Negative	Positive
Maintenance cost & complexity	Negative	Neutral	Positive
Vessel interface cost & complexity	Negative	Neutral	Positive
Vessel mooring capability	Neutral	Positive	Negative

Note 1 Equivalent to an oil and gas submerged loading system or Single Anchor Loading (SAL) riser
Note 2 Equivalent to an oil and gas Catenary Anchor Leg Mooring (CALM) mooring buoy
Note 3 Equivalent to an oil and gas Fixed Tower Single Point Mooring (FTSPM), with the assumption that the offshore structure provides the necessary mechanical interfacing.

2.2 Turbine-Mounted Charging Solution Overview

The "in-air connector" solution was selected, which places the bulk of the battery charging infrastructure on the transition piece deck of an offshore wind turbine – out of the waves, and in an accessible location for maintenance. The eCTV can then be charged from the offshore wind turbine output power (or the grid if wind power is unavailable) when convenient between crew transfers. To keep the connection and disconnection operation as simple and efficient as possible, vessel mooring capability is integrated within the power transfer cable.

The strength of the concept lies in the ability to integrate the critical system components within existing structural and electrical power infrastructure. This offers substantially lower system deployment and maintenance costs over a standalone system. The technology can be scaled to be deployed on any fixed-bottom turbine where CTVs are used for maintenance activities. Once proven for fixed offshore wind maintenance vessels, the technology could potentially be applied for other applications such as larger service operation vessels, floating offshore wind, oil and gas, fishing and maritime craft.

The on-turbine electrical vessel charging project was led by MJR Power and Automation. Vessel operator Tidal Transit, vessel designer Artemis technologies, wind farm operator Xceco, and the Offshore Renewable Energy (ORE) Catapult were project partners. The project is part of the Clean Maritime Demonstration Competition (CMDC), a program funded by the UK Department for Transport that is used to support the research and development of zero emission technology and infrastructure solutions for the maritime sector.

The most technically challenging aspect of the project is to ensure that the charging cable can be safely connected, used as a mooring line for the charging period, and then safely disconnected. This paper focusses on the simulation and testing of the performance of the cable as a mooring line, which governs the operability of the system as a whole. The findings of the mooring assessment, and challenges to overcome and still to solve are discussed.

2.3 Offshore Charging System Design Basis

The charging system was designed around the following core requirements, with a focus on a robust and scalable system:

- Provide 250kW of charging capacity at demonstration scale.
- Have the principal components be installed and accessible for maintenance in-air, using existing infrastructure and low cost installation vessels.
- Allow the CTV to rotate around the turbine (weathervane) in different weather conditions without cable damage
- Perform the connection, charging and disconnection operation without people near the charger.
- Be strong enough to keep the vessel in position with equivalent or better performance than the CTVs conventional moorings.
- The design produced to meet the above requirements in the 7-month project time is outlined in the next section.

3 Offshore Charging System Mechanical Design Summary

3.1 Charging Location

The first offshore trial location for the offshore charging system is targeted at the Inner Dowsing offshore wind farm. The candidate 3.6MW turbine is located at the North-East corner of the Inner Dowsing array, 5km of the coast of Skegness. The characteristics of the site are summarized in the Table 2.

Table 2: Inner Dowsing Site Characteristics

Property	Value
Water Depth (Lowest Astronomical Tide)	9.0 m
Water Depth (Highest Astronomical Tide)	16.5 m
Mean spring tidal current	1.1 m/s
Mean wind speed at hub height	7.2 m/s
Mean significant wave height (Hs)	0.80 m

3.2 Charging System Overview

The designed cable charging system is pictured in Figure 1 below, with each element described in more detail in the following sections.

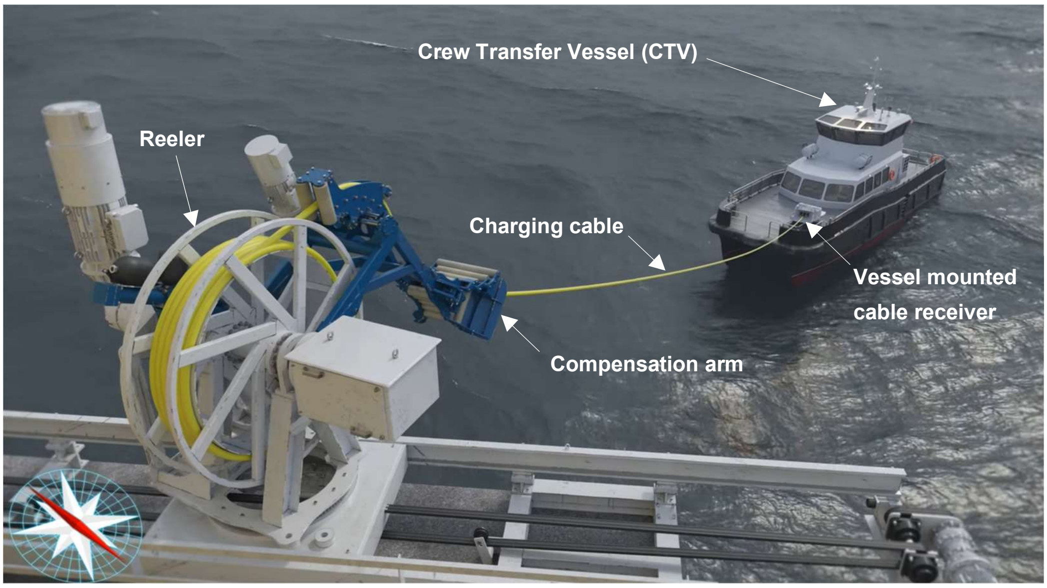
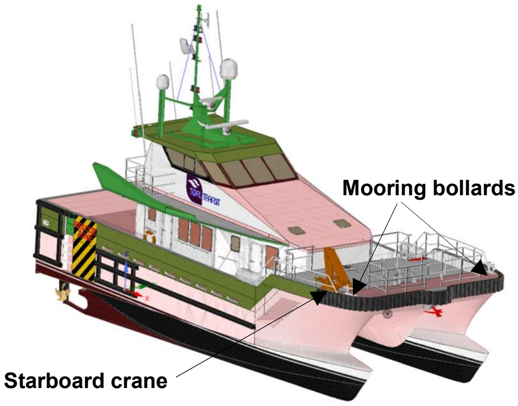


Figure 1: Charging system overview in deployed position

3.3 Vessel System

3.3.1 Vessel Particulars

The Kitty Petra CTV, operated by Tidal Transit, was modelled to assess the performance of the charging system. The Kitty Petra has functionally the same main particulars as the three other 20m length vessels in Tidal Transit's fleet, and it is assumed that this analysis is representative of all four vessels. The vessel is pictured in Figure 2, and the principal particulars are given in Table 3 for the fully loaded condition. The vessel mounted cable receiver will replace the starboard crane of similar mass. Mooring lines used offshore are normally attached to the port and starboard bollards.



(**a**) (**b**)

Figure 2: The Kitty Petra CTV: (**a**) Vessel pictured in service; (**b**) 3D model of the hull

Table 3: Kitty Petra CTV Principal Particulars

Property	Valuex	Data Sourcex
Length Overall	20.3 m	General Arrangement
Beam	8.0 m	General Arrangement
Width of each hull	2.4 m	General Arrangement
Draft Amidships	1.68 m	Stability booklet
Displacement	81 Tonnes	Stability booklet
Vertical center of gravity from keel	2.65 m	Stability booklet
Roll moment of inertia	1131 Tonne.m^2	Calculated
Pitch & yaw moment of inertia	3278 Tonne.m^2	Calculated

3.3.2 Vessel Mounted Battery System

Due to the unavailability of an electrically powered vessel for demonstration purposes, a conventional crew transfer vessel with a modular deck mounted battery pack carried as temporary deck cargo was specified for the trials. This battery was specified with a 250kWh capacity and 973 VDC nominal voltage and of the same chemistry (Li-IonNMC) and charging profile as a typical battery system that would be specified for an electric vessel. The 250kWh battery capacity was necessarily limited due to the space and weight restrictions for cargo on the foredeck of the crew transfer vessel, and the demonstration was designed around a '1C' 250kW charging converter.

For example - a charging converter rated at 250kW, charging a 250kWh battery at '1C' rate results in charge time of around an hour. In practice the battery is not discharged fully and not charged fully, with typical states of charge down to a minimum of 20% and up to maximum of 90% therefore charging time is actually less than an hour. This so called '1C' charging rate (where 'C' is the kWh rating of the battery) may be increased to 3C for example, providing that the battery is specified correctly and capable of being cooled sufficiently to allow charging at the higher rates. A 250kWh battery with a 3C rating can be safely charged at 750kW, reducing charging times to less than 20 minutes.

The design intent of the system is that the vessel battery can be charged in around one hour if required, although slower charge rates are available to the operator if, for example the vessel is idle and required to loiter for several hours in the field. As the system is scaled towards the necessary higher battery capacities of around 2MWh for a practical vessel, the charging system can also be scaled accordingly.

With a real world eCTV the charging system may charge the vessel battery directly, or preferably connect to the vessels' common DC bus system and act as an 'offshore power supply' to the vessel, in the same way that shore power connections are used for 'cold ironing'. In this case the vessels DC/DC converter that is part of the electric propulsion system controls the battery charging. In the former case where direct battery charging is used, the DC/DC converter in the turbine charger takes control of vessel battery charging. The system was designed to cover both cases and includes full flexibility of DC output voltage up to 1000 VDC to cater for all possible vessel common DC bus and battery voltage specifications.

3.3.3 Vessel Mounted Cable Receiver and Connector

The charging cable is terminated into a bespoke high performance wet mateable electrical connector that is used for both electrically and mechanically connecting the turbine to the vessel. A wet mateable self-sealing connector system is used due to the aggressive environment, the need for durability and reliability and the requirement to eliminate any manual intervention during connection and disconnection – for example having to remove and refit sealing caps and/or having to clean or dry a contaminated connector. Another critical consideration is during an emergency disconnection whereby the connector may be ejected from the vessel and become submerged. In this case manual operations such as stripping, rinsing, cleaning and drying the connector before reuse must be avoided.

The connector is lowered from the turbine under remote control from the vessel bridge and docked into the vessel receiver bellmouth and connector stabbing system. Prior to connection and before the vessel approaches the turbine, the bellmouth is moved into the vertical position in preparation for connector insertion. Both the cable reeler on the turbine and the bellmouth on the vessel receiver have several powered degrees of freedom to enable the boat crew to carry out rough alignment of the connector with the vessel prior to it entering the bellmouth.. The connector and bellmouth geometry ensure that once the connector is roughly aligned it can be lowered into the bellmouth and aligns and orientates itself automatically during docking. The design intent is such that connection and disconnection can be done 'hands free' without crew having to handle connectors or cables on deck. The cable block and receiving bellmouth is shown in the Figure 3.

(**a**) (**b**)

Figure 3: Vessel connection system **(a)** wet mateable connector block; **(b)** test fit into the bellmouth.

Once the connector is docked into the bellmouth it is locked in position using a locking pawl that is actuated via a hydraulic cylinder. This is powered from a small electrically operated HPU on the rear of the vessel receiver. In a commercial application the HPU would be located inside the vessel in a machinery space and may even be shared with the vessel crane for economy. Once the connector is mechanically locked, a pair of hydraulic 'stabbing' cylinders move upwards to electrically mate with the connector. The vessel is now connected electrically and mechanically to the turbine, although power remains isolated until the vessel reaches the mooring and charging position.

Once connected, the boat pulls away from the turbine with the cable reeler paying out umbilical automatically under constant tension control. If necessary, the reeler can be controlled in other modes, for example manually or in position control, whereby the reeler follows the boat position relative to the turbine. As the vessel moves away from the turbine the bellmouth is lowered to the horizontal position, either manually or automatically to ensure that the cable load path is straight.

Once the vessel has reached the mooring and charging position, power can be fed to the vessel. The bellmouth is mounted on a gimbal frame, that can be hydraulically operated or left to move in 'float mode'. This allows the boat to take up a natural position relative to the turbine whilst keeping the umbilical load path as straight as possible to avoid excessively bending the cable under tension. An important point is that the vessel receiver designed for the demonstration will be dissimilar from the design that will be used in a commercial application. It was designed to interface to the only hard point available on the demonstration vessel deck, which is the crane foundation, with the crane being removed and replaced with the vessel receiver for the trial. The position of this was quite far aft and to starboard resulting in the mooring load path not being in the vessel centre line and the vessel receiver presenting an obstruction on deck. For a commercial design the vessel receiver would fully forward along the vessel center line and recessed such that its top is flush with the vessel deck, allowing personnel to transfer over it unobstructed.

An emergency release system is provided at the vessel receiver to disconnect the vessel in the event of an emergency or a high-tension condition due to increasing weather conditions and where normal disconnection is not possible. This can be activated manually by the crew using a push button on the bridge, or automatically by the control system when the system is approaching its safe working load and is predicted to move into overload, in effect both a Manual and Automatic Overload Protection System (MOPS/AOPS) similar to an offshore lifting appliance. In the event of failure of power or control a passive release system is also provided that will allow the pressure in the locking pawl cylinder to be relieved/vented enabling the connector release from the bellmouth. During emergency release the power is disconnected prior to the connector un-mating.

3.4 Charging Cable and Bend Stiffener

The charging cable contains both the electrical power conductors and aramid tension members to provide both power transfer and mooring functions. The cable, manufactured by Fibron, consists of:

- 4 sets of 35mm^2 copper power cores rated to 1kV
- 6 sets of 4mm^2 screen wire bundles
- Vectran fibre and steel wire braid for tensile capacity
- 3mm thick polyurethane inner and outer sheath for mechanical protection

The mechanical properties of the cable are summarized in Table 4 for modelling the vessel mooring performance. The complete reeler, cable and receiver system is shown in Figure 4 below.

Table 4: Charging Cable Mechanical Properties

Property	Assumed Value	Data Source
Outer diameter	47 mm	Manufacturer
Unit in-air mass	3.3 kg/m	Manufacturer
Bending stiffness	0.027 kN.m^2	Estimate [1]
Axial stiffness	9076 kN	Test data
Minimum dynamic bend radius	0.63 m	Manufacturer
Minimum breaking load	10 Tonnes	Manufacturer [2]

[1] Based on physical tests for a 3 second cycle from 1 to 3 Tonnes.
[2] Physical break load testing indicated the sample tensile capacity was in excess of 17 Tonnes.

Figure 4: Charging system setup in the MJR workshop

The bellmouth gimbal system will not perfectly align with load direction for small side loads; to prevent local cable bending damage at the bellmouth connection, a polyurethane bend stiffener is fitted at the cable end.

3.5 Safe System Design Loads

An acceptable safe working design load for the cable system was taken to be 2 Tonnes, which gives a safety factor of 5 on the manufacturers' minimum breaking load. This approach is likely to be conservative, and will be reassessed when a full suite of fatigue and tension-bend test data is available. At present, the cable breakaway system is designed to release at 2.5 Tonnes. The cable tension-bending fatigue capacity is planned to be determined as part of a future test program.

The integrity of the vessel and wind turbine structure was checked against a 2.5 Tonne design load, including appropriate DNV and Eurocode safety factors. For example, the wind turbine external platform primary support structure was checked against ultimate strength (Figure 5), buckling, deflection, and fatigue. All checks were within allowable limits; ultimate strength utilization increased by a maximum of 1% and the contribution to fatigue was negligible.

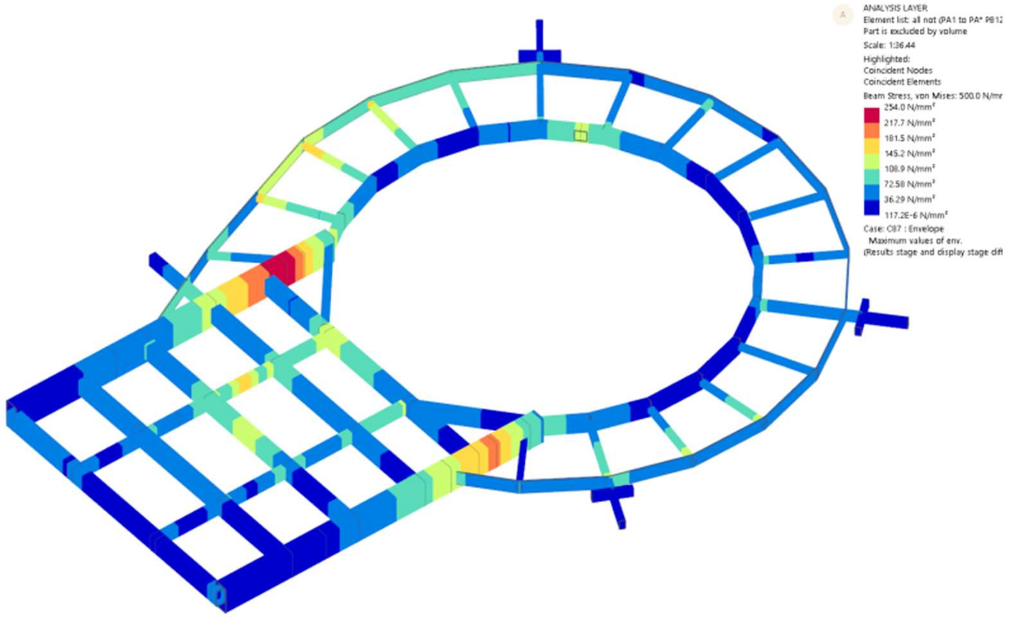


Figure 5: Wind turbine support structure ultimate limit state Von-Mises stress

3.6 Reeler and Compensation System

3.6.1 Reeler

The reeler is designed to accommodate 80m of cable when fully retracted. For charging the vessel at the deployed position, 50m of cable is spooled out by the reeler control system.

3.6.2 Motion Compensation System

When acting as a mooring line, the cable system must be stiff enough to keep the vessel in position when subject to winds and currents, yet compliant enough in waves to keep loads within acceptable limits for the cable, as well as the vessel and turbine support structure. For a conventional mooring line this would be achieved by changing the axial stiffness of the rope; for example by using stretchy nylon segments. This is not an option for the charging cable, where high axial stiffness is required to protect the power cores from excessive strain. Whilst some compliance is available in the weighted catenary formed by the cable at the 50m standoff distance, this is insufficient to reduce loads in moderate wave conditions.

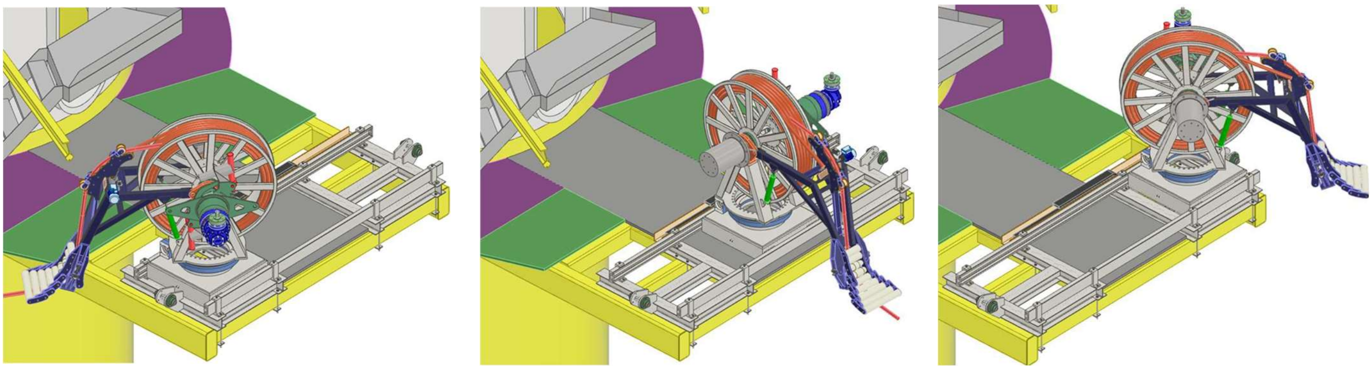
To solve this challenge, a motion compensation system has been designed to offer enhanced compliance. The motion compensation system comprises of two main passive compensation methods: the compensation arm and the reeler drum. The arm moves up and reacts against two hydraulic cylinders to provide a targeted level of stiffness. The reeler drum rotation is compensated through two horizontal cylinders. Active compensation is also provided through a planetary gearbox on the reeler, which rotates the reeler to pay out line when a threshold of line tension is exceeded.

3.6.3 Skid and Heading Tracking System

In addition to the motion compensation system, a slewing and skidding system enables the reeler to track the vessel position relative to the charger. The slew and skid system includes three main functionalities:

- Allows the reeler to manually orientate to the CTV push-on or standoff position.
- Automatically follows the CTV movements due to changing weather conditions to allow the CTV to naturally weathervane around the turbine.
- Provides cable side load protection.

Figure 6 shows how the reeler system automatically slews and skids along the skidding frame to allow the reeler to follow the vessel movements.



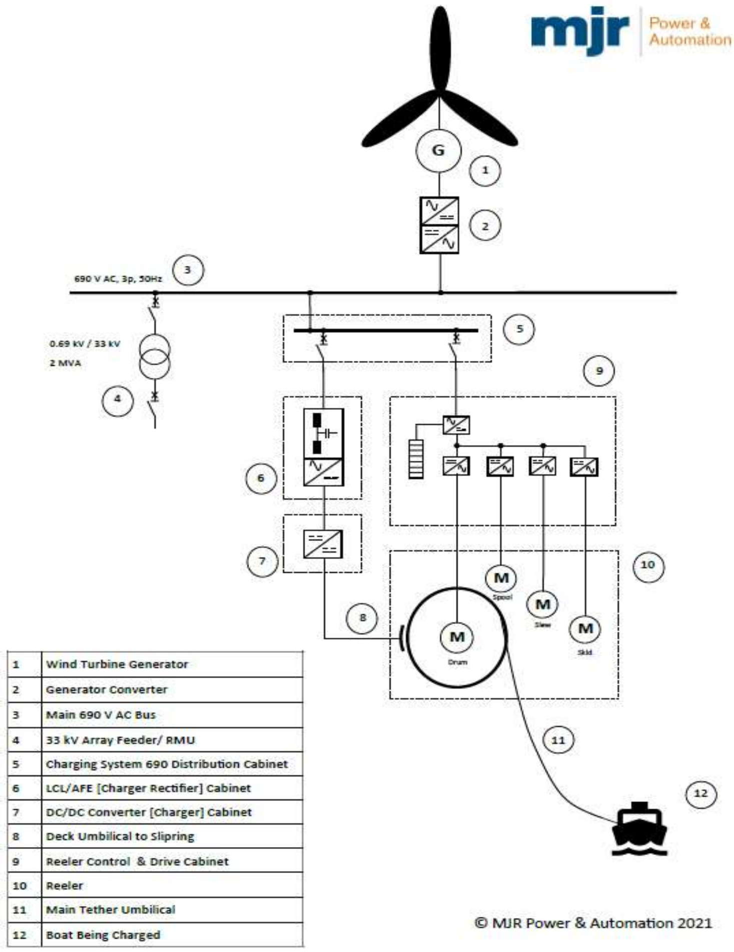
(a) (b) (c)

Figure 6: Reeler system slew and skidding (a) CTV heading North-West of reeler (b) CTV heading South of Reeler (c) CTV heading South-East of reeler

4 Electrical power, control and monitoring system design summary

4.1 Electrical system architecture

Figure 7 illustrates the general electrical architecture of the charging system and how it is intended to integrate with both the turbine electrical system at the test site and the eCTV.



1	Wind Turbine Generator
2	Generator Converter
3	Main 690 V AC Bus
4	33 kV Array Feeder/ RMU
5	Charging System 690 Distribution Cabinet
6	LCL/AFE [Charger Rectifier] Cabinet
7	DC/DC Converter [Charger] Cabinet
8	Deck Umbilical to Slipring
9	Reeler Control & Drive Cabinet
10	Reeler
11	Main Tether Umbilical
12	Boat Being Charged

Figure 7: Power system overview

4.2 Turbine Side Power Supply

4.2.1 Source of Supply

The prototype offshore charging system in this case is connected to the wind turbine low voltage generator at the primary side of the 0.69/33 kV LV/MV step up transformer. In another embodiment, the system could be connected to the 33 kV (or 66 kV) MV array side via suitable switchgear and a separate MV/LV step down transformer or a tertiary winding on the main array step up transformer.

At the trial site a new charging system distribution enclosure (Figure 7, item 5) is installed and connected to the existing wind turbine 690 V distribution (Figure 7, item 3) to provide two feeds:

- Feed 1 – to the active front end (AFE) enclosure.

- Feed 2 – to the reel drives enclosure.

4.2.2 Power Transmission Philosophy

The primary design intent of the system is to provide charging for electric and hybrid electric crew transfer vessels with the ultimate aim of being able to rapidly charge a battery of up to 2 MWh in a conveniently short time, for example 1 hour or less. This will require a scale-up of the 250kW prototype system.

In order to achieve a 2MW power transfer using a conveniently sized umbilical cable, medium voltage AC is a convenient transmission medium. However the vessels in question are relatively small, circa 20 m long, and do not have the space or weight capacity to house the power conversion gear required to convert MV AC to DC that would be compatible with the vessel batteries or common DC bus distribution.

It is for this reason that the system is designed to transfer DC power at a compatible level to be able to directly supply either a) the common DC distribution bus of the electric vessel; or b) to be able to connect to the vessel battery directly.

4.2.3 Power Conversion Philosophy

The 690 VAC 50 Hz, 3 phase supply available at the turbine (via the new charging system distribution enclosure) is connected via a suitable distribution circuit breaker to the charging converter (AFE Enclosure). A suitable distribution switchgear will be installed on the turbine as part of the installation of the prototype system. The charging converter comprises the following main items of hardware:

- A low harmonic IGBT Active Rectifier (Active Front End) which rectifies the 690 VAC 50 Hz, 3 phase supply to a fixed DC voltage (Figure 7, item 6) ; and
- A DC/DC converter that converts the fixed voltage DC produced by the rectifier into a compatible DC voltage to feed either a) the common DC bus of the vessel; or b) the vessels battery directly (Figure 7, item 7).

The charging converter equipment is located in the turbine foundation and is split into two standalone cabinets (split to allow lifting and handling during installation), one for the IGBT Active Rectifier (Active Front End), another for the DC/DC converter.

4.2.4 Electrical Connection Philosophy

The DC output from the charging converter (Figure 7, item 6 & 7) is connected to a cable reeler (Figure 7, item 10) located on the deck of the turbine foundation. The feeder cable or deck umbilical (Figure 7, item 8) is routed inside the turbine foundation and through an existing transit out of the turbine foundation and onto the turbine weather deck. The cable then passes through a drag chain to allow the reeler to skid and slew (to cope with vessel movement), and then finally on to the fixed (non-rotating part) of a slipring assembly that is connected to the drum. The rotating part of the slipring assembly is connected to the main cable which is spooled onto the reeler drum.

4.3 Control and Monitoring System

A real time control system is provided to enable safe control of the charging system. Control is available from both the vessel and turbine operating locations and is designed to embed safety throughout the charging process. The control software has been developed for full operational control of the charging system, reeler system and vessel connection system. The three high level cable catenary control modes are summarized in the text below. More details on the control sequence and user interface are provided in Appendix B.

4.3.1 Manual control

In this mode, all movement of the reeler and vessel side equipment is manual, operated from a bridge located control unit onboard the vessel. The vessel will be the master in terms of control, and if communication is lost, the system will be left in a safe mode. The vessel crew remotely controls the turbine reeler to deploy (or recover) the connector to the vessel connection system, latch it (or unlatch it) and connect it (or disconnect it).

4.3.2 Follow mode

The control system automatically will pay-out the reeler when the vessel moves back from the turbine - there are multiple sensors that are used to monitor and control line-load, mechanical arm position and yaw direction. As the vessel moves away from (or back towards) the turbine the reeler operates in constant tension to pay out (or in) the umbilical automatically and maintain/limit tension.

4.3.3 Mooring mode

This is the main mode that is used to charge the batteries. When the vessel has moved away from the turbine to the mooring and charging position, the reeler will stop paying out umbilical and compensate for vessel motion using its passive compensator system. The reeler is still active and in the cases of extreme vessel motion the reel drive motor and control system can assist the passive compensators to limit line tension until the vessel can be safely disconnected.

Throughout the process of charging the vessel battery system, the vessel crew has full visibility of the status of the charging and deployment system with the operator control station situated on the bridge of the vessel. The interactive touch screen interface of the charging system is shown in Appendix B.

4.4 Web Portal Monitoring and Booking System

Booking and monitoring of the wind turbine charging system can be performed via a web portal system – either from the vessel, the windfarm control room, or via desktop access. The web portal supplements the real time control system and allows asset owners and operators to access live real time monitoring data together with fiscal data and billing. It also shows live information on vessel traffic, positions and the status of the wind farm turbine chargers.

The vessel books a charging slot at a turbine charger which appears on the windfarm control room operators screen as a reservation to authorise. The windfarm control room operator can then authorise or decline the booking or divert the booking to anther turbine. An alternative auto-authorization system could be set up, similar to land based electric vehicle charging. Once authorized the vessel can approach the turbine, is authenticated automatically, and can begin to charge. Communication with the wind farm control room can be done via a live chat function or VHF radio.

As the vessel approaches the turbine it connects wirelessly to the on-turbine control system. In a future development we also plan to use power line communication over the charging umbilical once the vessel is connected.

When the vessel is charging, real time data showing the vessel charging can be viewed by the vessel crew and the wind turbine operator who both have full visibility of the status of charging.

Figure 8 shows the display of live data of vessel positions and turbine availability. Note that this is real AIS data from Teesport via our office located AIS receiver. The windfarm shown is Redcar and the turbines with chargers (in green) are simulated.

Figure 9 shows the screen with the vessel connected to the turbine charger. This screen displays real time data on the vessel position, charging status, and system performance parameters. More details of the booking and control system user interface are provided in Appendix B.

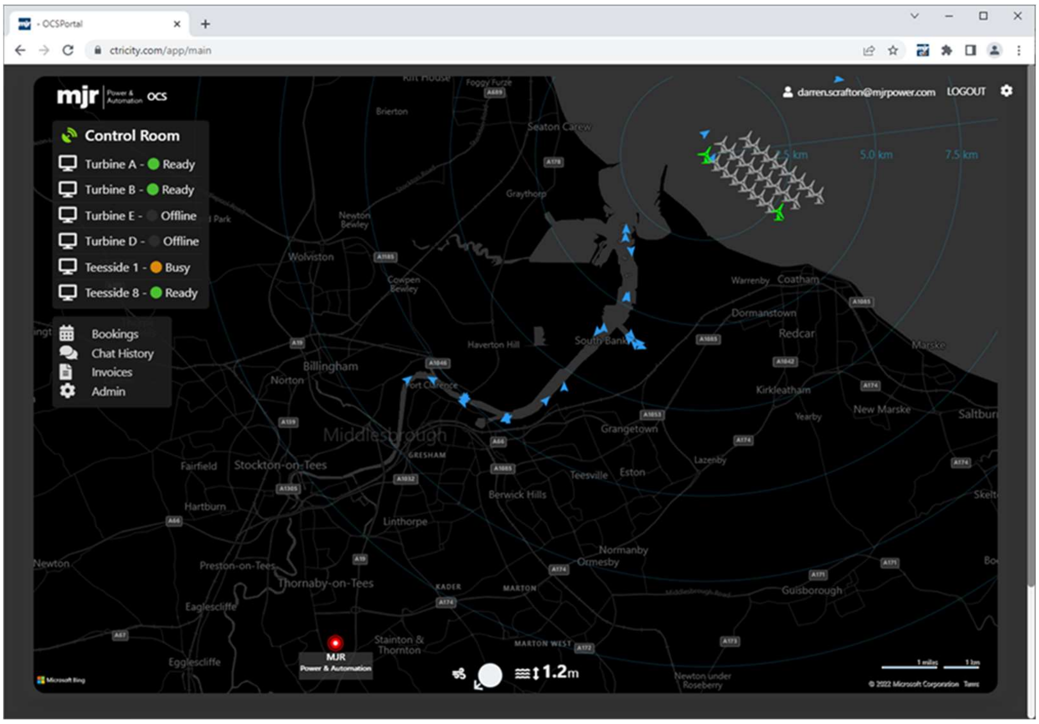


Figure 8: Live marine data – Control Room view

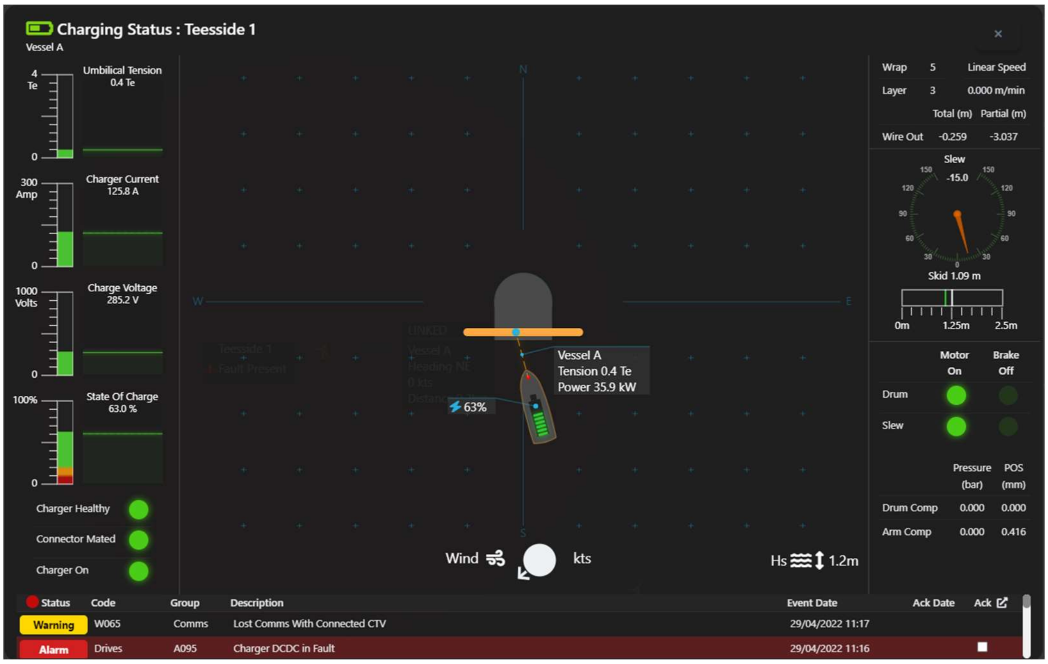


Figure 9: Charging screen

5 Stationkeeping Performance Modelling

5.1 Vessel Hydrodynamic Response

5.1.1 Wave Frequency Response

A hydrodynamic model of the CTV hull was developed to predict the vessel performance in waves. The underwater hull geometry was meshed in the ANSYS AQWA software [5], resulting in a mesh with 8232 diffracting elements (see figure 10). The mesh was imported into the OrcaWave diffraction analysis software [6], and the wave diffraction data was finally imported into the dynamic marine system analysis package OrcaFlex [7]. Potential and source formulations were used to solve the diffraction analysis. Water depth was set to a depth of 10m; a sensitivity check showed little change in the vessel response with water depth changing within the tidal range at typical operating wave periods.

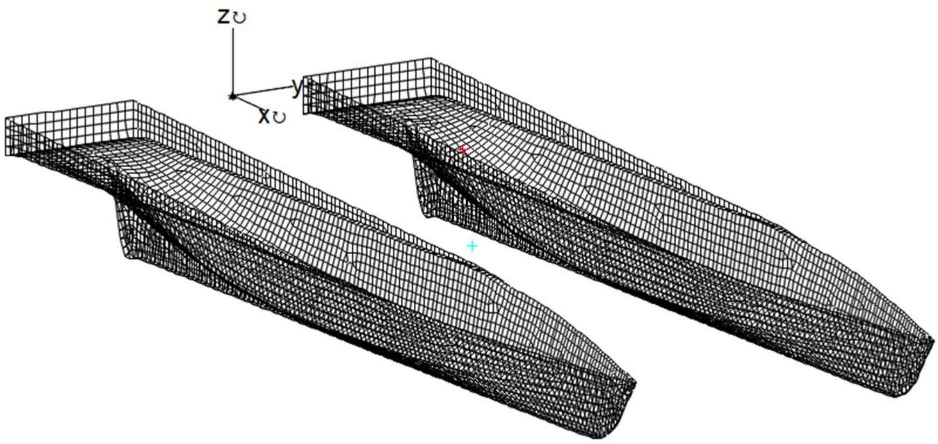


Figure 10: Vessel Hydrodynamic Mesh

In addition to the added mass and damping calculated by the diffraction software, wave loading was applied using load Response Amplitude Operators (RAOs), where wave forces and moments are applied at the vessel origin. Load RAOs were used in preference to displacement RAOs, because the vessel response is influenced by the cable loads. The vessel RAOs are provided in Appendix A. The roll natural period from decay tests is 3.7 seconds; however there is a second peak present in the roll RAOs at a wave period of 1.8 seconds. This peak corresponds to the wave length matching the 5m distance between the two catamaran hulls. Wave diffraction data was generated for wave periods down to 1 second to properly capture this effect.

5.1.2 Wave Drift Response

Low frequency wave drift loading was applied using Quadratic Transfer Functions, which apply a mean force, and a second order wave force, based on the difference in period between waves. From a number of different options available within OrcaFlex for applying wave drift forces, Newman's approximation was selected as the most robust and reflective of measured vessel response from trial data. Wave drift response is one of the most challenging problems in the analysis of moored floating systems, and conventional engineering diffraction analysis tools have been demonstrated to give poor correlation for mooring problems [8]. As such, it is important to compare the calculated response with physical test data where possible. The choice of wave drift method is discussed in more depth later in the paper with respect to comparison to full-scale trial data.

5.1.3 Current and Viscous Drag

OrcaFlex is based on potential flow theory, which means that viscous effects are not captured without the introduction of additional damping, drag coefficients, or Morison elements. Morison elements were used to capture the combined effects of current drag and viscous damping in all degrees of freedom. Morison elements of 18.5m length were positioned at the centerline of each hull, and discretized into 20 segments longitudinally to capture varying fluid velocity and moment along the hull. The drag diameter was equal to the vessel draught of 1.68m, with the center of the cylinder positioned at the half draught below the waterline.

Most of the non-wave making damping is likely to be due to eddy making damping from vortices generated at the hard chine hull and skeg [9]: therefore the damping physics are consistent with the Morison element drag formulation, in that the force is proportional to the relative fluid velocity squared [10].

A vertical (heave) drag coefficient of 2.2 was used for each catamaran hull, based on the drag of a square section in similar Reynolds number regime as the hull [11].

To find the level of damping produced by the model, the vessel was heeled to 10 degrees and released in a roll decay test. The Morison elements were found to give an equivalent linear damping of 4% of critical, giving a total of 9% critical damping including wave radiation damping. The level of overall damping is aligned with typical expectations for vessel roll damping of 10%, and the proportion of eddy making to wave making damping of 1:3 matches well with catamaran model test data at zero speed [9].

The lateral (sway) drag coefficient was taken from the average drag coefficient for two plates in tandem [11], where the ratio of separation distance to depth (E/D) was taken as 3.

The longitudinal (surge) drag coefficient for slender hulls is largely due to skin friction. The drag coefficient value used was based on OrcaFlex default vessel coefficients with similar length to breadth ratio.

There is a high level of uncertainty associated with the Morrison drag coefficients shown in Table 5, and these should ideally be calibrated against model tank test data for the specific hull used to improve confidence in the calculated vessel response.

For reference, the model was initially built with current coefficients and a linear damping input. Whilst this is a more conventional approach to vessel modelling, it was found to produce unrealistic excessive vessel motions in roll and yaw. In consultation with Orcina, the developer of OrcaFlex, these unrealistic motions were understood to be due to a numerical issue where the damping is unable to suppress a feedback loop between wave loading and vessel roll motions. Using Morison elements solves this problem.

Table 5: Morison element drag data

Direction of Motion	Drag Area	Drag Coefficient
Vertical (heave)	62 m²	2.200
Lateral (sway)	62 m²	1.100
Longitudinal (surge)	194 m²	0.014 [1]
[1] Gives a coefficient of 0.04 when taking length times draught as the drag area.		

5.1.4 Wind Loading

Wind forces were calculated using the vessel's above water projected area of 82m² beam-on and 37m² head-on. Representative wind drag coefficients for a vessel with similar above water shape profile were taken of 0.85 in sway and 0.55 in surge [12]. Wind loading is a small component of mooring loads in typical operating conditions compared to waves and currents at the Inner Dowsing site.

5.2 Vessel Conventional Mooring Analysis and Full-Scale Trial Validation

5.2.1 Trial Setup

The greatest uncertainty in the prediction of cable loading is the vessel hydrodynamic response. To validate the vessel motion response at full scale, the Kitty Petra CTV was moored to an Inner Dowsing wind turbine between 09:30 and 13:15 UTC on 30 March 2022.

The trial arrangement is shown in Figures 11, 12 & 13. A total length of 74m of 22mm diameter Oceanmoor polypropylene rope [13] was passed around one of the turbine's J-tubes. The rope was connected to a 5 Tonne load link manufactured by cyclops marine, which in turn was connected to the vessel's bollard via strops. The critical property for the rope is the axial stiffness of 1049kN, which was derived from laboratory test data cycling between 1 and 3 Tonnes at a period of 10 seconds, performed by TTI for the project. The load link continuously measured rope tension throughout the trial at a sampling period of 1 second.

A video was recorded from a GoPro Max mounted on the bridge port-forward window throughout the trial. GPS position was recorded on the GoPro Max.

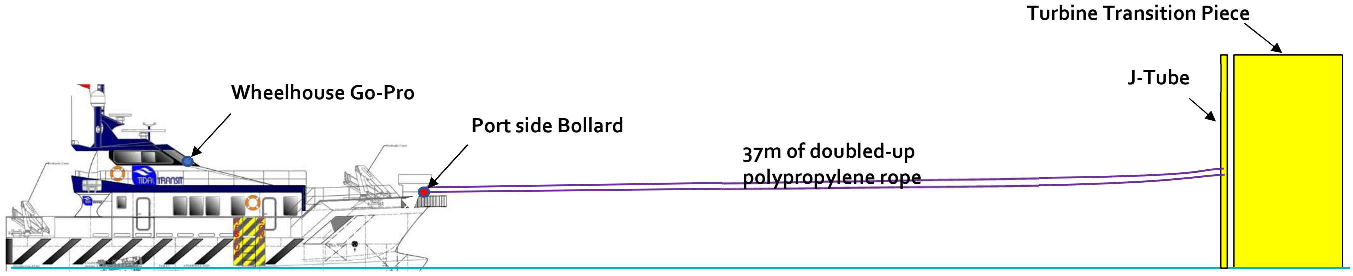
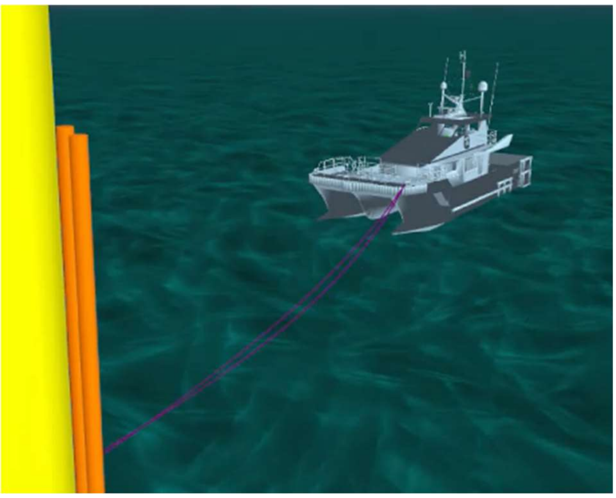


Figure 11: Offshore trial high-level setup



(a)

(b)

Figure 12: OrcaFlex model of offshore mooring trial **(a)** looking from transition piece **(b)** plan view

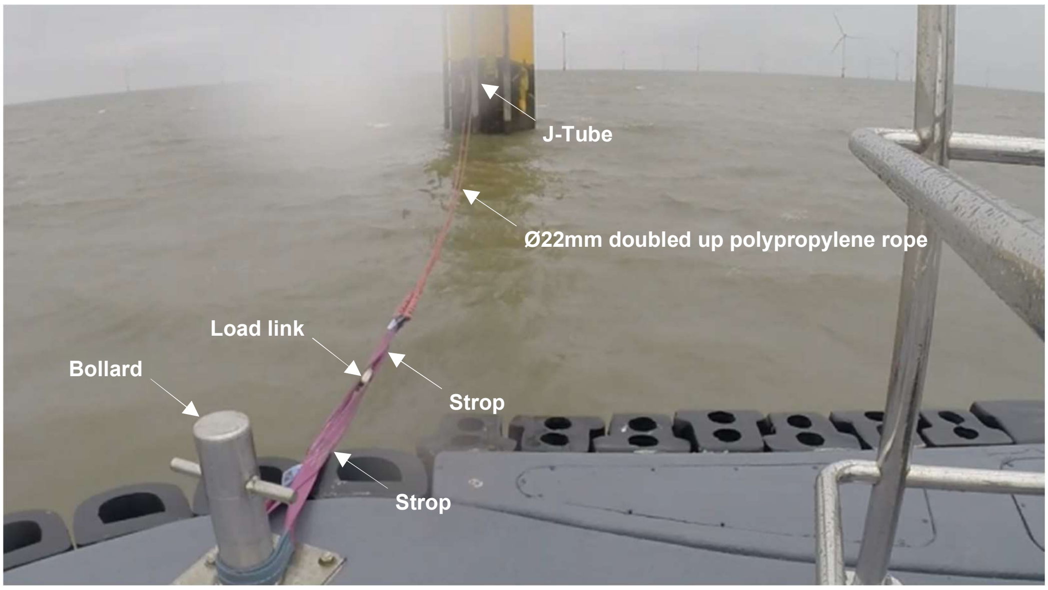


Figure 13: Mooring line arrangement for the trial

5.2.2 Weather Data

Directional wave time series data with a sample period of 0.8 seconds was recorded at the Chapel Point wave buoy [14] located 1.5km West-North West of the trial turbine. The wave time series was input directly into OrcaFlex as a table of wave height and simulation time.

Wind speed and direction was extracted from the target turbine. The wind speed measured at the turbine hub height was adjusted for a 10m reference height [11]. Wind was applied with an NPD gust spectrum.

Current was predicted by scaling measured current speeds during spring and neap tide cycles with the tidal levels recorded during the trial. Current was applied as a time series with speed varying over the simulations.

The trial covered an ideal range of wave conditions, which ramped up from low (0.4m Hs) to the extreme operating limit for mooring operations (1.7m Hs). This drove the measured mooring tensions to increase from less than 0.5 Tonnes to a peak of 3.7 Tonnes at the end of the trial. Three characteristic time periods were selected for detailed analysis, each lasting for 10 minutes as shown in Figure 14 and Table 6: a low, moderate, and extreme environment case. Waves were predominantly from the North-North East, and wind was predominately from the East-North East. Current was coming from the South before 11:00 and from the North after 11:30, with a period of slack tide from 11:00 to 11:30.

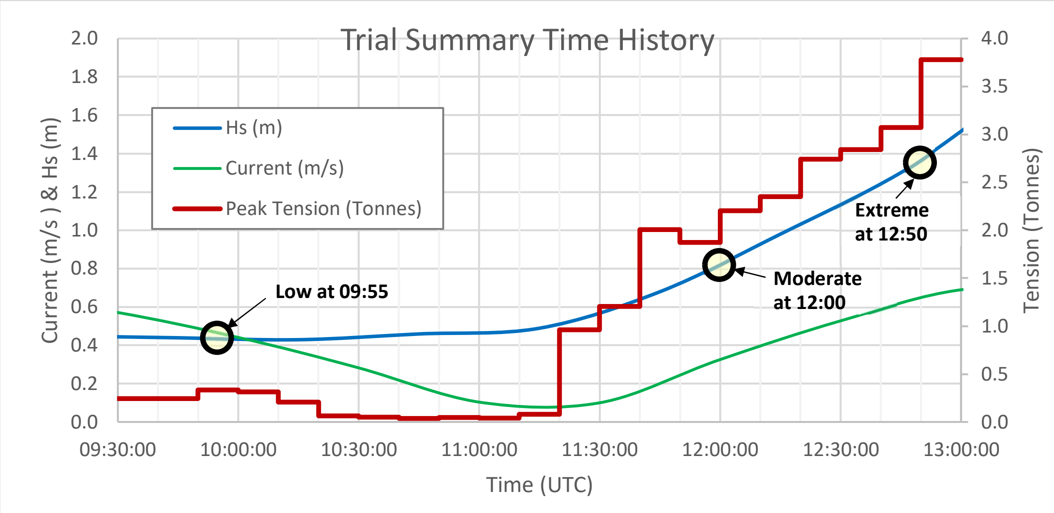


Figure 14: Trial weather time history. Tensions are plotted as the peak over each 10 minute period.

Table 6: Average weather conditions over characteristic periods

Parameter	"Low" period	"Moderate" period	"Extreme" period
Wave Hs	0.43 m	0.80 m	1.30 m
Wave Tz	6.3 seconds	3.3 seconds	3.7 seconds
Wave Direction	34° (from North)	33° (from North)	17° (from North)
Current Speed	0.47 m/s	0.34 m/s	0.63 m/s
Current Direction	180° (from North)	0° (from North)	0° (from North)
1-Hr wind speed at 10m	2.0 m/s	8.0 m/s	8.7 m/s
Wind Direction	165° (from North)	61° (from North)	59° (from North)
Start Time (UTC)	09:50	11:55	12:45
Period duration	700 seconds	700 seconds	900 seconds

5.2.3 Motion Response Comparison

Several options are available in OrcaFlex for how to include wave drift response, all of which could be used in an engineering design context. It was found that the mooring response in terms of motions and extreme tensions was very sensitive to the selected method. The trial gives the opportunity to select the method that gives the best fit to the observed response.

There are two main choices available: whether to use full QTFs or Newmans approximation, and whether to use a filtering or modification method. Newmans approximation simplifies the full QTF matrix to only the diagonal data. Note that the full QTF model required a separate diffraction mesh to be setup around the free surface of the hull. Filtering and modification are both methods of manipulating the QTF data to avoid double counting wave drift loads. The different wave drift methods are compared in figure 15 below, where the extents of each box are the extreme Northing and Easting points. Using Newman's QTFs with filtering gives the best match to the observed vessel GPS position, heading, yaw motions, and measured tension data. The excessive yaw and sway motions predicted by the other methods are not considered realistic.

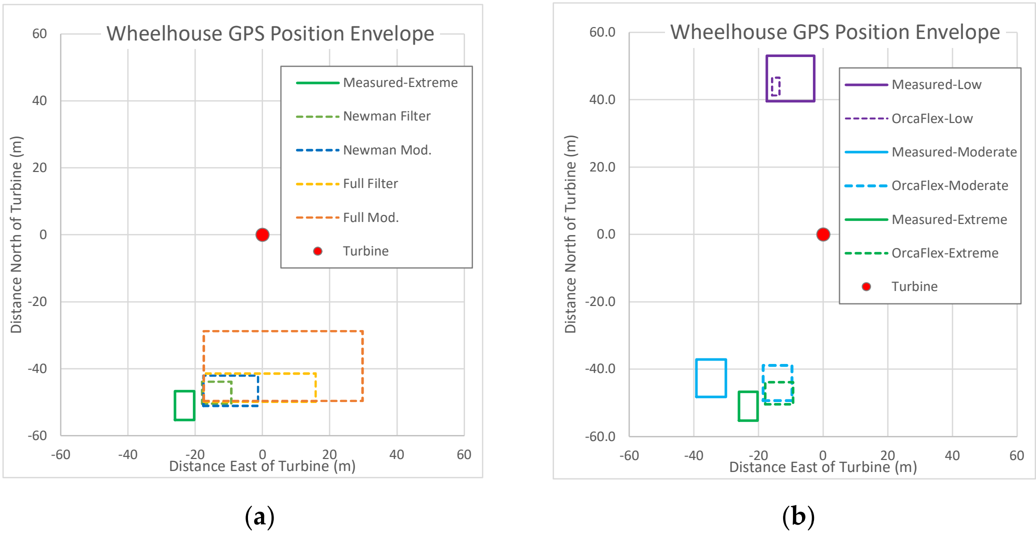


Figure 15: GPS envelope measured from the port side wheelhouse for the extreme sea state case (**a**) Comparison of vessel position for the different QTF methods; (**b**) comparison of measured GoPro GPS coordinates and calculated vessel position (using filtered Newman's QTFs)

The selected method for further analysis reported in this paper is Newman's QTFs with filtering. It should be noted that no other data was calibrated within the model to achieve a better match with the measured response.

With the selected QTF method, the measured vessel surge and sway motion envelope was consistent with the modelled response in OrcaFlex. The captured video (see Figure 16) response visually showed similar vessel behaviour in terms of yaw, pitch and roll motions, and mooring line behaviour. No accelerometer data was available to provide a more in-depth analysis of comparative motions.

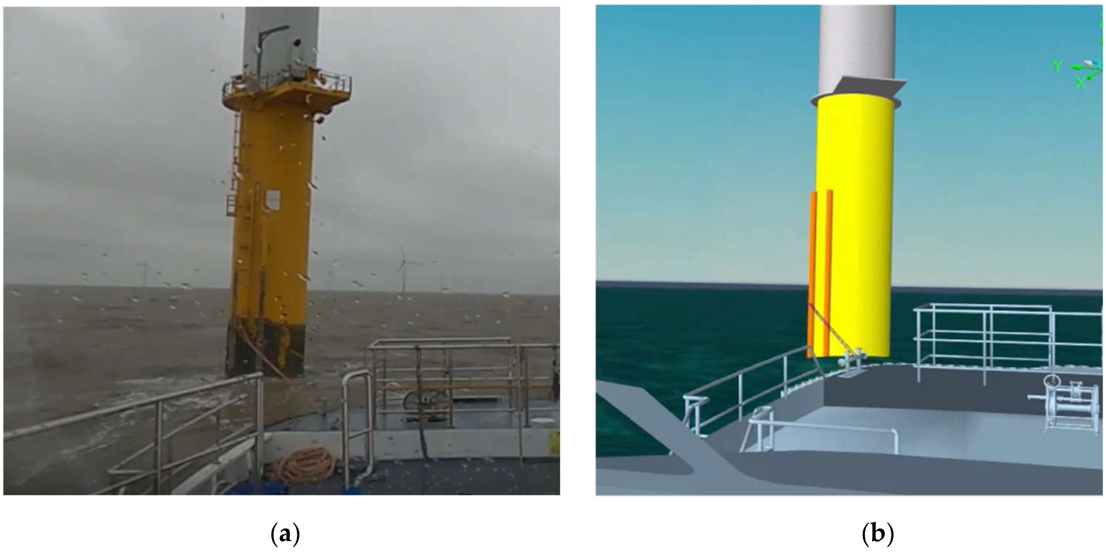


Figure 16: **(a)** Video footage of mooring trial in the extreme period; **(b)** OrcaFlex model of the same

5.2.4 Tension Response Comparison

The measured load cell tension response is compared with the simulated OrcaFlex values in figure 17. Mean tensions are well predicted in all cases, which indicates that we can have confidence that the mean environmental forces calculated in OrcaFlex match reality. The OrcaFlex peak tensions are 30% higher than measured for the moderate and extreme time periods. The potential cause of this difference is discussed below.

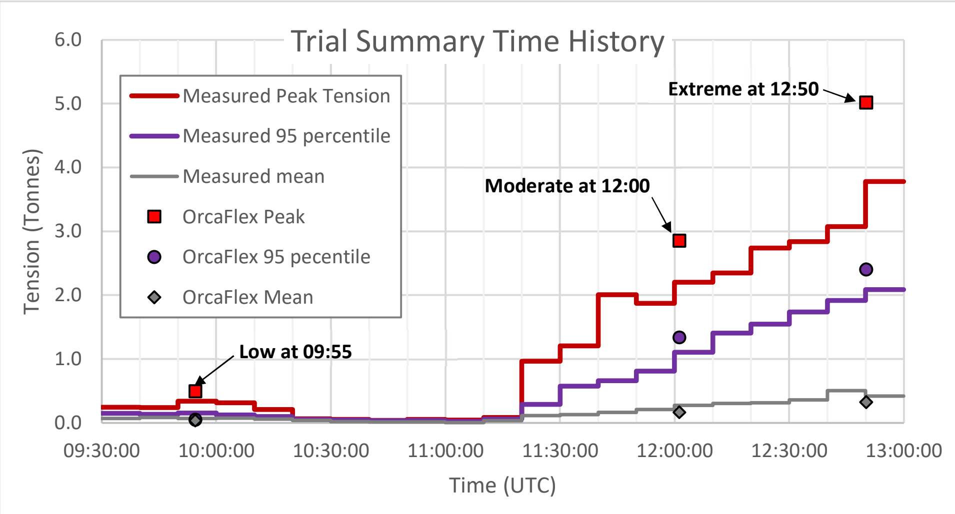


Figure 17: Comparison of measured tension and the simulated tensions in OrcaFlex. Measured tension data taken over each 10 minute period.

The mooring tension response over a time period of 200 seconds is shown in the Figure 18. Both the measured and simulated response show a resonant motion period of approximately 20 seconds. There is negligible wave spectral energy below a 10 second period; therefore this response is indicative of low frequency surge motion, where the wave drift forces are exciting the mooring system natural frequency.

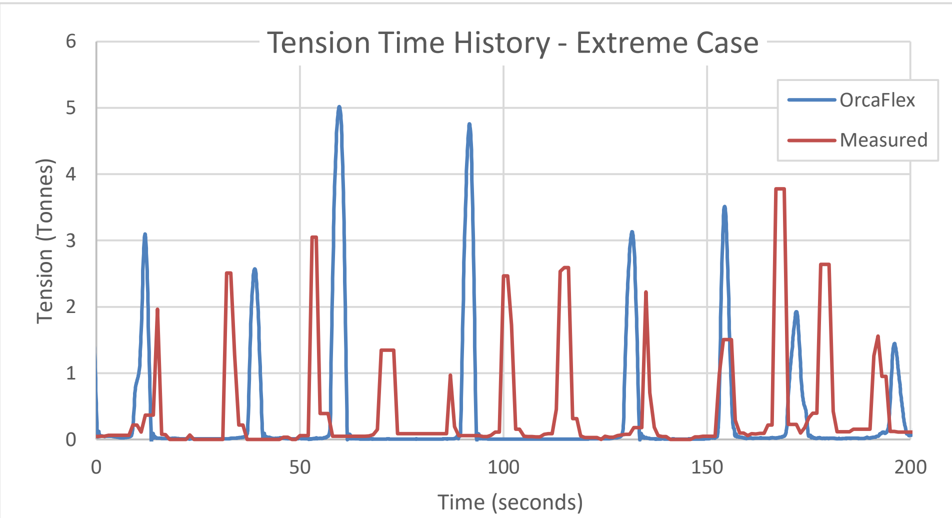


Figure 18: Comparison of measured tension over 200 seconds during the extreme time period (12:43:00 UTC)

Potential sources of uncertainty in the modelled and measured tensions were explored to further understand the difference in measured and simulated response:

- *The accuracy of load measurement*: the load link was tested at the TTI laboratories when subject to load cycles from 1 to 3 Tonnes at a period of 10 seconds and 3 seconds. At the longer period, the load link was found to correlate very well with an independent load cell. At short periods down to 3 seconds, some load peaks were missed by the load link due to hysteretic effects, indicating peak loads may be underestimated by approximately 10%.
- *The rope properties*: A sample of the mooring rope was tested at the TTI laboratories for axial stiffness, and used throughout the analysis. Note that using the OrcaFlex lookup formula for the polypropylene rope stiffness gave half the stiffness value and 30% lower tensions.
- *Measured wave data*: time series data was available from a wave buoy only 1500m distant, on a bearing parallel to the wave direction. Therefore the measured wave data input to the analysis should be highly representative of the waves seen by the vessel.
- *Vessel hydrodynamic modelling*: whilst it is difficult to separate the cause and effect of the vessel motion and mooring loads, the tension response is clearly indicative of a wave drift driven phenomenon. This is known to be the most uncertain and difficult to predict response using existing engineering tools, and has previously been show to be highly sensitive to somewhat arbitrary user input options.

Based on the above, the most obvious explanation for the difference in predicted peak tensions is uncertainty in wave drift response prediction. No further model calibration was performed to adjust the wave drift response; the level of conservatism was deemed acceptable for the project demonstration phase. Further refinement may be possible with more controlled model testing, or a longer period of high fidelity full-scale monitoring.

5.3 Cable and Reeler Compensation System Modelling

The mooring lines in the previously described model were replaced with the charging cable and compensation system. The passive arm and reeler drum hydraulic compensation system were crated in OrcaFlex using a combination of constraints, supports, links and 6D buoys. The system was designed to operate at the maximum level of compensation at a 2 Tonne load, which is 80% of the 2.5 Tonne cable breakaway load. Upon further design iterations, the compensation system could be tweaked to work optimally at a higher design load.

5.3.1 Reeler Rotational Compensation Modelling

The reeler compensates for vessel motion by rotating when under tension, which lets out the cable to add length to the catenary. Two horizontal cylinders react against the torque applied by the mooring line to the reeler drum. The hydraulic cylinders were designed so that the reeler would rotate 50° when subject to a 2 Tonne cable load. With a drum radius of 0.65m, this translates to 0.6m of cable length released into the catenary at 2 Tonnes.

To simplify the OrcaFlex modelling, the reeler rotational compensation was converted to a single degree of freedom spring-mass system. A non-linear spring stiffness was calculated based on the calculated force versus line payout response. The reeler rotational inertia was linearised to a linear mass. The single degree of freedom was imposed by using a constraint to allow only axial motion.

5.3.2 Arm Compensation Modelling

The cable is routed via a series of low friction rollers from the reeler through a pivoted arm. As tension on the cable increases to 2 Tonnes, the arm rotates upwards by 25° to act as a geometric spring (see Figure 19). The arm rotational stiffness is controlled by two hydraulic cylinders.

The arm spring was initially modelled in OrcaFlex using a series of supports to force the cable to follow the roller paths within the arm. The hydraulic cylinders were represented as non-linear springs. The pivot point of the arm was defined using a rotational constraint.

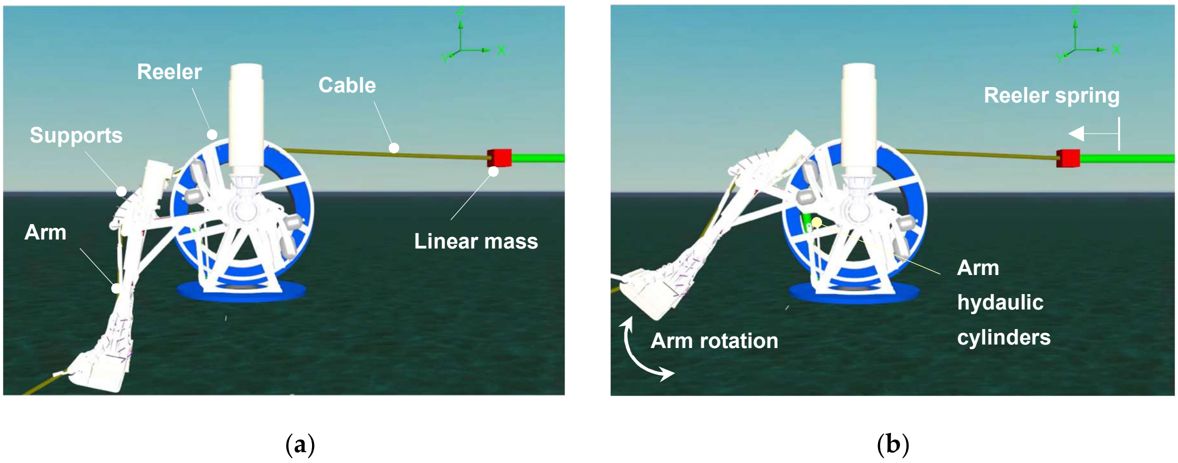


Figure 19: OrcaFlex model of reeler and arm compensation system **(a)** at 0.3 Tones; **(b)** at 2 Tonnes.

Modelling the arm in OrcaFlex requires a very small element size of 0.05m for the cable, which requires very long simulation times. The arm spring was replaced with an equivalent non-linear spring-mass system in the same manner as the reeler. The system response with the simplified linear model was calibrated to ensure the cable tension versus vessel surge displacement response was the same. The simplified model was found to give practically identical peak tensions in a full dynamic simulation with a much reduced simulation time. The linear spring model is shown in Figure 20.

5.3.3 Reeler Active Rendering Modelling

In addition to the passive spring compensation system, an active line rendering system is present to pay out line on the reeler based on a tension feedback system. Line tension can be accurately measured from the torque on the reeler motor. For the render system design, there is a balance between paying out too much line and thus working the system too hard, versus having insufficient compensation when needed. Care needs to be taken to avoid any resonance between the render control system and the reeler system. The rendering system is implemented in OrcaFlex as a winch controlled by a Python script with the following properties:

- Line can be let out (rendered) at a maximum rate of 1.5 m/s

- It is assumed to take 0.2 seconds for the render system to kick-in, and render rate is ramped up over 0.8 seconds i.e. it takes a full second to reach maximum payout. The system is likely to be much more reactive, subject to system load testing.
- The rendering system starts above 1.8 Tonnes and stops when tension drops below 1.5 Tonnes.
- The rendering system reverses to recover cable back into the reeler when tension drops below 0.8 Tonnes.

A summary of the complete modelled compensation system properties is provided in Figure 20. A total horizontal vessel surge sinusoidal displacement is imposed, which produces the compensation response summarized in the Table 7. Note that whilst the cable is much more axially stiff than the polypropylene mooring rope, the weighted catenary gives an equivalent level of spring stiffness.

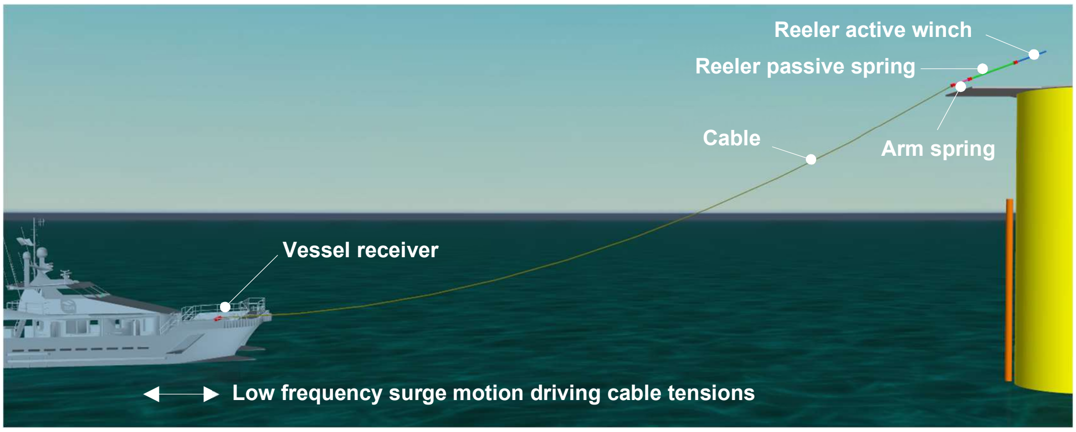


Figure 20: Simplified single degree of freedom spring model of cable compensation system

Table 7: Modelled compensation system properties with imposed sinusoidal surge displacement

Parameter	Polypropylene Mooring [1]	Cable with no compensation	Without Render System	With Render System
Peak tension	2 Tonnes	2 Tonnes	2 Tonnes	2 Tonnes
Applied surge offset	0.8 m	1.0 m	2.0 m	2.5 m
Surge period	20 seconds	20 seconds	20 seconds	20 seconds
Arm spring travel	-	-	0.45 m	0.45 m
Reeler spring travel	-	-	0.55 m	0.55 m
Reeler render payout	-	-	-	0.70 m
[1] Load on a single mooring rope.				

6 Results and Discussion of the Stationkeeping Analysis

6.1 Comparative Performance of Cable Charging System in Trial Weather

A comparison of the charging cable and reeler compensation system response is provided in the Figure 21. The loads on the cable are significantly lower than the loads measured and simulated on the mooring load link. The cable system performs well without the rendering system in moderate sea conditions, but requires the assistance of the rendering system to reduce loads below 2.5 Tonnes for more extreme sea conditions.

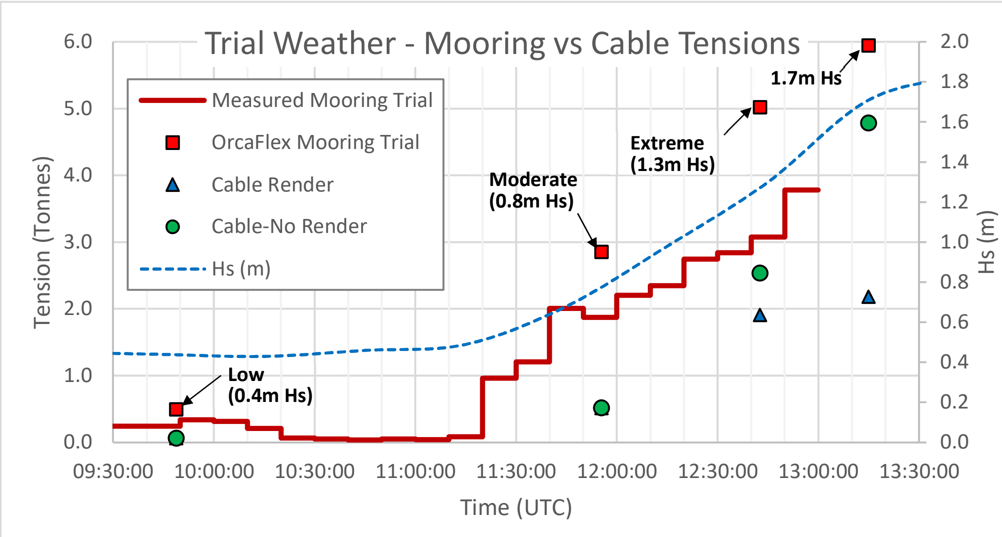


Figure 21: Reeler system peak tensions compared to the mooring response for the trial weather

6.2 Analysis of 1-Year of Hourly Weather Data

Predicting the performance of the compensation system depends on the specific combination of wave height, wave period, and the relative direction and magnitude of current and wind. There is also an element of random uncertainty in extreme response from hour to hour in the same conditions. It is difficult to generalize the response with only a few metocean cases. Hourly directional wave, wind and current measured data for the Inner Dowsing over 2021 was used to explore operational performance in real conditions.

Figure 22 features a point for each of the 8600 hourly simulations. Tensions are well within acceptable limits for the green points (<1.5 Tonnes), blue points are marginal but broadly workable (<2.5 Tonnes), and the red circles would initiate the charger disconnection (>2.5 Tonnes). The results show performance can be predicted based on wave height (Hs) and mean period (Tz). There is a noticeable scatter, due to the randomness of the wave response, and the different combinations of current and wind directions.

The dotted black line shows one interpretation of an operating limit based on both Hs and Tz. If weather is forecast to be above the limit, then the connection would not take place. The operability results are presented in Table 8 for a charging system use case scenario of 1000 connections per year (roughly 3 connections per day).

Table 8: Charging system operability results summary

Connection Case	Without render System	With active render system
Assumed total connection attempts per year	1000 cases (100%)	
Above the operating limits defined in Figure 22 and cannot connect	150 cases (15%)	
Successful connection with peak load below 1.5 Tonnes	792 cases (79%)	
Successful connection with peak load between 1.5 and 2.5 Tonnes	51 cases (5%)	57 cases (6%)
Connector emergency release activated at load above 2.5 Tonnes	7 cases (0.7%)	1 case (0.1%)

The reeler rendering system reduces the occurrence of peak loads above 2.5 Tonnes. It should be feasible to further refine the relatively coarse render control system used in the model to further reduce the peak loads.

The trial has indicated the OrcaFlex model is conservative; the operability results are indicative only and shall be adjusted based on further system design iterations and testing. The actual decision as to whether it is safe to connect and remain connected should also be based on the weather forecast reliability, whether the conditions are rising or falling, and the judgement of the vessel master. Limits based on weather conditions could be replaced or supplemented with measured vessel motions and cable loads. The 1-year of data gives a representative picture of typical operability; however the year-on-year and seasonal operability will vary. For example, from a metocean study from 1991 to 2011, an Hs of 1.5m was exceeded between 5% and 15% of the time between years.

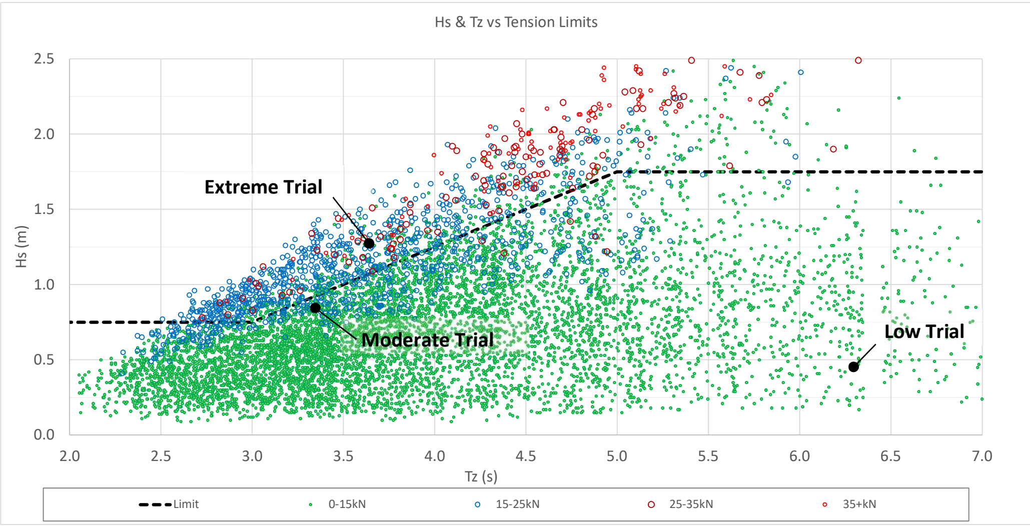


Figure 22: Reeler system tension response against 1-year (2021) of weather data at Inner Dowsing (with render system)

6.3 Analysis and Testing Lessons Learned

Predicting wave drift response is challenging, and sensitive to modelling assumptions. This is particularly the case for weather vaning systems, where there is a complex coupling between motions in all degrees of freedom. The analysis highlights the importance of test data to resolve modelling uncertainties – both in terms of vessel response and mooring stiffness characteristics.

7 Plans for Further Development and Scale-up

The charging system was built within the 7 month timeframe set by the funding window. This imposed a number of constraints on the design of the system, namely that it must be built before the performance can be properly analyzed and optimized. Whilst the system is functional as a demonstration system, further refinements are planned in all aspects of the system for wider deployment. These additional features will increase the flexibility and capability of the system. A non-exhaustive summary of some key features to be incorporated are outlined below.

7.1 Component and system testing

A suite of factory testing of the cable, reeler and electrical systems is planned. A focus will be on long term mechanical and electrical resilience, aiming towards high reliability and maximum safe capacity utilization of the system. Testing of combined vessel and reeler system response through commissioning tests and in-situ trials is also planned.

Model basin tests will be considered to improve the understanding of the fundamental vessel behaviour, as well as developing a simulator model of the system for crew training and fault finding.

7.2 Integrated vessel performance data

Vessel performance data can be delivered via the control system and portal without having to install separate motion and performance monitoring systems.

7.3 Low cost vessel dynamic positioning

A simple integrated vessel dynamic positioning system could be developed to automate vessel positioning under the charger, and moving to and from the standoff position. This would enable a more efficient connection operation by allowing the vessel positioning system to be synchronized with the reeler control system.

Vessel dynamic positioning and drift motion damping would enable the vessel to stay at the defined standoff position when charging, maintain weather vaning heading within defined limits, and reduce peak mooring loads. This would make for a simpler, more cost effective and potentially more capable charging system.

7.4 Charging system enhancements

Further design engineering will be performed towards system enhancements in terms of the reeler compensation system and control system, slewing system and the bellmouth receiver positioning on the vessel. Particular attention needs to be paid to enhancing the ability of the system to accommodate vessel yaw and bearing relative to the platform.

7.5 System scale-up

Scale-up on a number of levels is being considered once the demonstration phase is complete. Assessment of a range of different wind farm sites and CTVs will be necessary to roll out the system at scale. Increasing the charge power capacity from 250kW for the demonstration system to approximately 2MW for a commercial scale system will be required.

7.6 Adaptation of the system towards SOV charging

The adaptation of the system for offshore charging of larger Service Operations Vessels (SOVs) is being considered. SOVs are capable of operating further offshore and in harsher sea conditions; an offshore charging solution for these vessels is needed to allow a fully electric fleet to service all wind farms. The principal technical challenge in provision of such a solution relate to the size and energy requirements of SOVs, which are an order of magnitude more than for CTVs. For a practical SOV charging system, power must be transmitted to the vessel using medium voltage AC via a safe and practical interconnection system.

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Appendix A Vessel RAOs

Displacement RAOs for the CTV are shown below. The * key indicates the damping effects of the Morison Elements was included. Displacement RAOs are presented, because these give a more intuitive understanding of vessel motion behavior. It should be noted that load RAOs were used in the full OrcaFlex analysis.

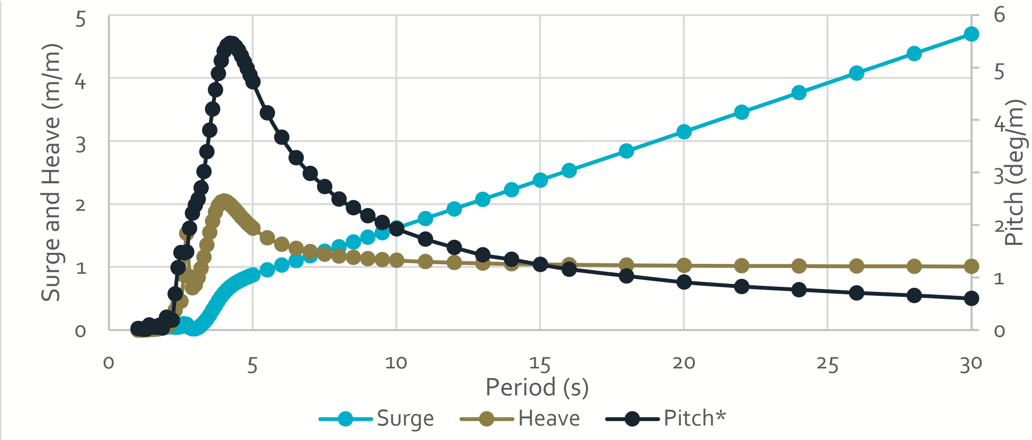

Figure A1. 0° heading (head-on to waves) RAOs

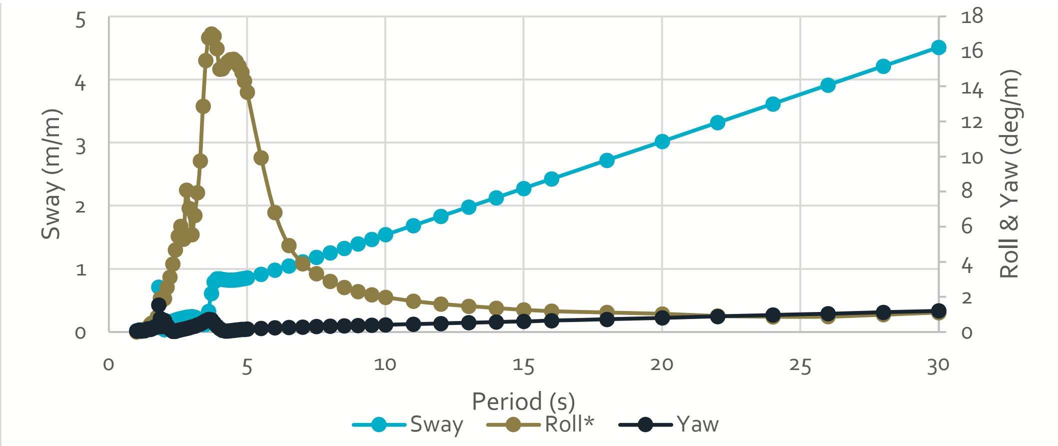

Figure A2. 90° heading (beam-on to waves) RAOs

Appendix B Control and Booking System User Interface

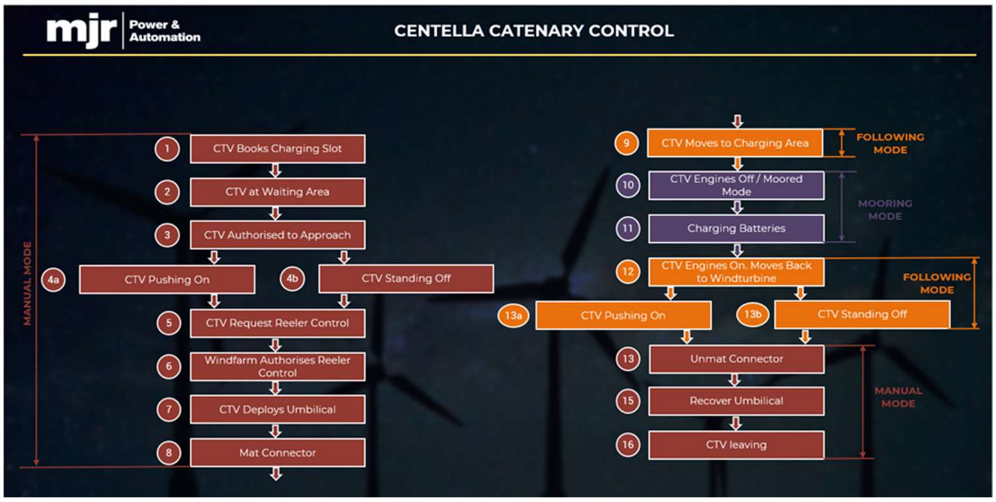

Figure B1: Catenary control sequence

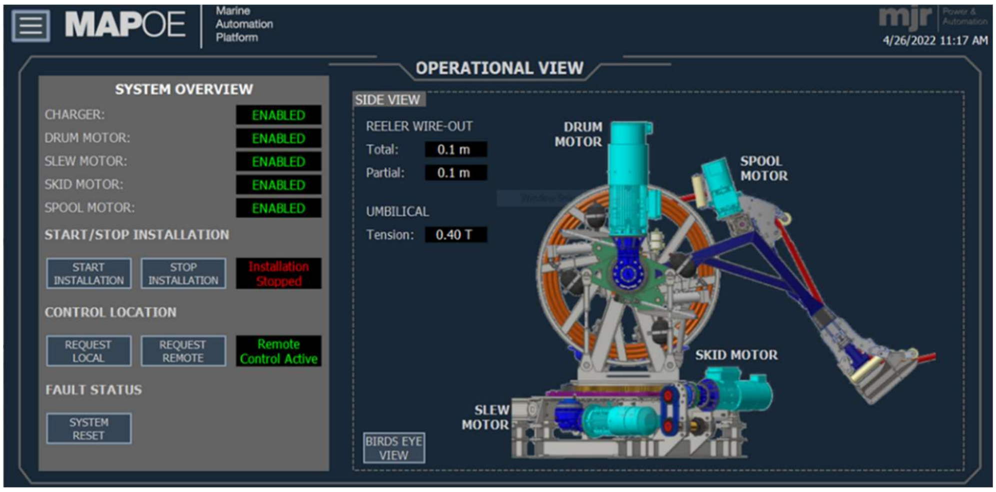

Figure B2: Operational view of vessel HMI prior to charging

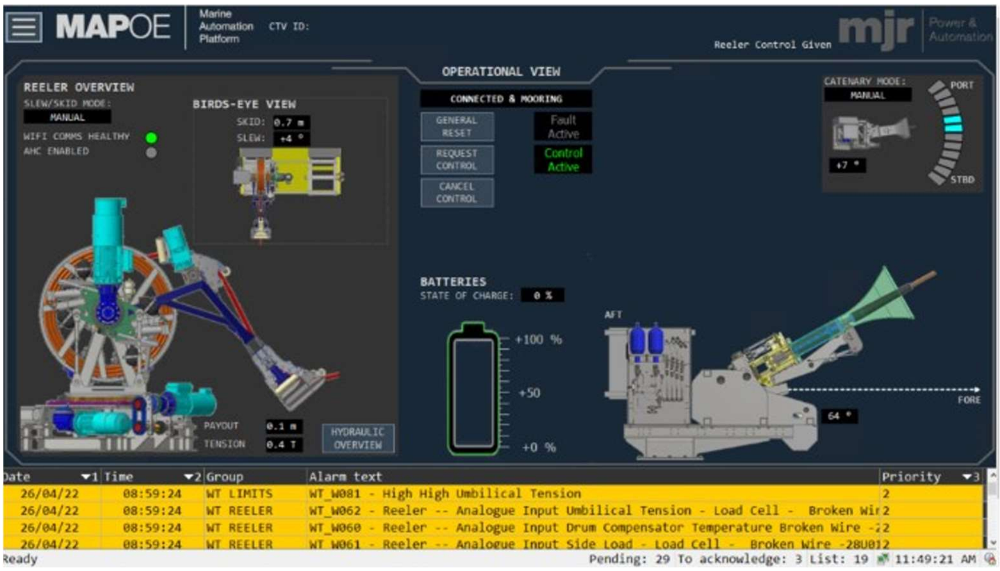

Figure B3: Operational view during charging

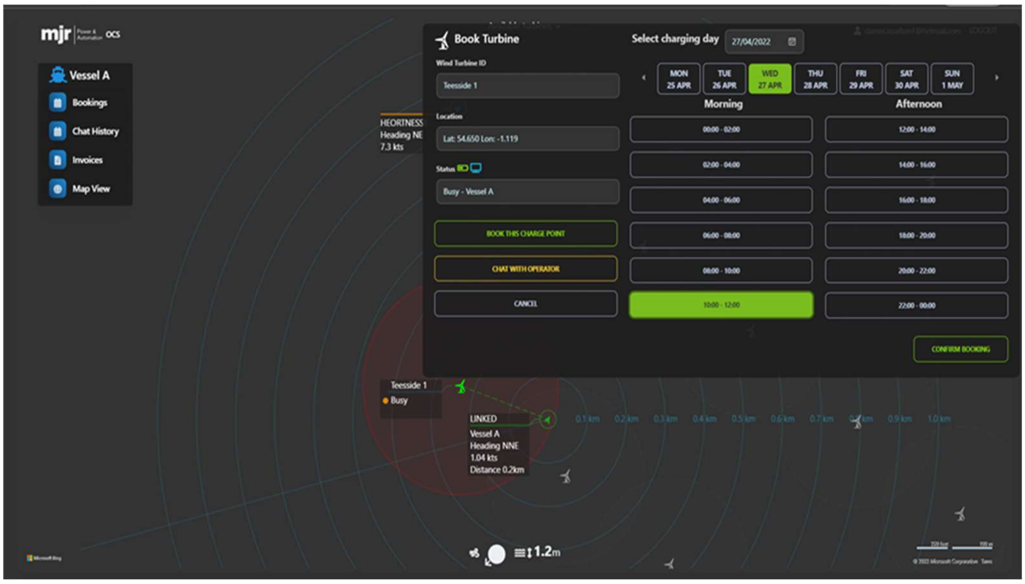

Figure B4: Booking screen available via web portal access

Contact

GLASGOW

Inovo
121 George Street
Glasgow
G1 1RD

T +44 (0)333 004 1400

BLYTH

National Renewable Energy Centre
Offshore House
Albert Street
Blyth, Northumberland
NE24 1LZ

T +44 (0)1670 359 555

LEVENMOUTH

Fife Renewables Innovation Centre (FRIC)
Ajax Way
Leven
KY8 3RS

HULL

O&M Centre of Excellence
Ergo Centre
Bridgehead Business Park
Meadow Road, Hessle
HU13 0GD

ABERDEEN

Subsea UK
30 Abercrombie Court
Prospect Road,
Westhill
Aberdeenshire
AB32 6FE

CORNWALL

Hayle Marine Renewables Business Park
North Quay
Hayle, Cornwall
TR27 4DD

PEMBROKESHIRE

Pembroke Dock
Pembrokeshire
South West Wales

CHINA

11th Floor, Lan Se Zhi Gu No.5
Ke Ji Avenue, Hit-Tech Zone
Yantai City
Shandong Province
China