# FINAL PUBLISHABLE SUMMARY

**Grant Agreement number:** 605987

**Project acronym:** TIDAL-EC

**Project title:** Tidal Energy Converter Cost Reduction via Power Take Off Optimisation

**Funding Scheme:** FP7 Research for the Benefit of Specific Groups; Research for the Benefit of SMEs

**Period covered:** from 1 September 2014 to 28 February 2017


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# 1 Executive Summary

The Tidal Energy Converter Cost Reduction via Power Take Off Optimisation (TIDAL-EC) project consists of research and development activities aimed at improving the overall economic competitiveness of in-stream tidal power generation. The largest and most critical component of a Tidal Energy Converter (TEC) is the Power Take-Off (PTO) system and includes the shaft, bearings, gearbox and any other equipment that connects the hydrodynamic absorber (blades) with the electrical grid (including the power converter and the electrical generator itself).

The TIDAL-EC project investigated designs and testing work previously undertaken by the SME partners involved in technology development across the tidal energy supply chain. Three are TEC OEM manufacturers (TOCARDO, OCEANFLOW & MINESTO) and one is a sensor supplier (FIBERSENSING - tier 2). The world leading European research institutions (ORE Catapult, SINTEF and UEDIN) provided access to their facilities and knowledge required to optimise the respective TEC PTOs for the improvement of reliability, increased efficiency and reduced LCOE. The RTD performing partners provided access to the 1MW drive train test rig (ORE CATAPULT), an advanced analysis model (SINTEF) and a state of the art Computational Fluid Dynamic (CFD) and PTO/generator loss/reliability model (UEDIN) of the system. A summary of the interaction between the partners and end customers can be seen in Figure 1 below.

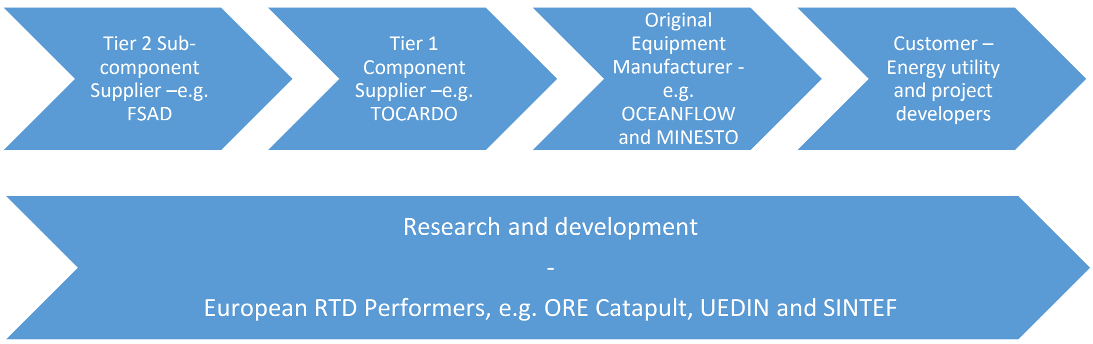


**Figure 1:** Position of TIDAL-EC consortium members within the Tidal Energy Supply Chain

As a result, the project consortium facilitated improved reliability, increased power conversion efficiency, a reduction in the Levelised Cost of Energy (LCOE), and a reduction in the total cost per kWh of power produced. Improvements factored in design, build and lifecycle costs such as the cost of maintenance, operations and decommissioning of tidal power. The results of this project will give SME tidal developers (and their SME suppliers) greater confidence to offer warranties and guarantees to end-users/customers (European Energy Utilities).

# 2 Summary Description of Project Context and Objectives

Information from the offshore wind industry shows that 39% of the overall capital and operating cost is attributed to operation and maintenance.

The Tidal Energy Converter Cost Reduction via Power Take Off Optimisation (TIDAL-EC) project consists of research and development activities aimed to improve the overall economic competitiveness of in stream tidal power generation. The largest and most critical component of a Tidal Energy Converter (TEC) is the Power Take Off (PTO) system and includes the shaft, bearings, gearbox and any other equipment that connects the hydrodynamic absorber (blades) with the generator and the electrical generator itself. The consortium of partners who are undertaking this work include leading Research and Technology Development (RTD) institutes National Renewable Energy Centre (ORE CATAPULT), University of Edinburgh (UEDIN) and SINTEF (SINTEF); the Small or Medium Enterprises are Oceanflow Energy (OCEANFLOW), Minesto AB (MINESTO) & FiberSensing-Sistemas Avancados Demonitorizacao SA (FIBERSENSING). The consortium is looking at current turbine designs to identify areas that can be optimised in the whole TEC power take off system.

These radically optimised tidal turbine systems will improve reliability, increase power conversion efficiency and facilitate reduction in the Levelised Cost of Energy (LCOE, the total cost per kWh of power produced, factoring in design, build and lifecycle costs such as the cost of maintenance, operations and decommissioning) of tidal power. The results of this project will give SME tidal developers (and their SME suppliers) greater confidence to offer warranties and guarantees to end customers (European Energy Utilities).

The TIDAL-EC project looks at designs and testing work previously undertaken by the SME partners; involved in technology development across the tidal energy supply chain. Three are TEC OEM manufacturers (TOCARDO, OCEANFLOW & MINESTO) and one is a sensor supplier (FIBERSENSING - tier 2). The world leading European research institutions (ORE Catapult, SINTEF and UEDIN) are providing access to their facilities and knowledge required to optimise the respective TEC PTO for the improvement of reliability, increased efficiency and reduced LCOE. The RTD performing partners provided access to the 1MW drive train test rig (ORE CATAPULT), an advanced analysis model (SINTEF) and a state of the art Computational Fluid Dynamic (CFD) and PTO/generator loss/reliability model (UEDIN) of the system. A summary of the interaction between the partners and end customers can be seen in Figure 2 below.

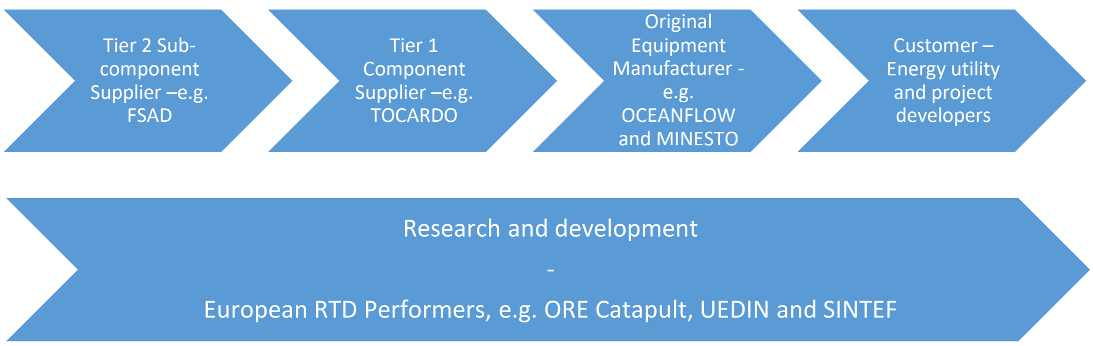


**Figure 2:** Position of TIDAL-EC consortium members within the Tidal Energy Supply Chain

## Key objectives of the TIDAL-EC project

The four key areas of improvement and innovation being explored during the optimisation process are:

- The removal of single point failures across the TEC PTO (e.g. electrical connections, cable harnesses) by improving the overall systems design;
- The introduction of improved additional redundant and or high reliability sub-components (e.g. sensors, brake, bearings, oil sensors);
- A revised design evaluation with the accessible location of critical systems (e.g. sensor transducers, local control systems);
- The introduction of a dielectric and electro-magnetic immune temperature sensor to the permanent magnet generator (PMG), providing greater reliability with the ability to monitor and operate within safe limits.

The impact of these improvements and innovations on the TEC PTO will be analysed via a three-fold empirical test programme:

- Accelerated life cycle testing of the TOCARDO T2 TEC PTO on ORE Catapult's 1MW Drive Train Test Rig in the Blade Test 1 Facility;
- Thermal profiling modelling of the TOCARDO PMG; and
- Efficiency/reliability modelling of the TOCARDO and MINESTO TEC PTOs.

The project will culminate in a set of design recommendations for the optimum method of PTO integration to improve reliability, increase efficiency and reduce the LCOE for mainstream tidal energy devices including the TOCARDO, OCEANFLOW and MINESTO devices.

## Work performed in RP2

Overall the consortium partners managed to achieve most of the project objectives identified under each work package. The second reporting period included the detailed scoping and completion of all work packages and agreement on testing requirements between ORE Catapult / Tocardo / FiberSensing.

During the early stages of RP2 (Month 10-15 it was agreed that it would not be possible to test the Tocardo T3 turbine due to the delay in its development). Following discussions with Tocardo and all consortium partners it was agreed eventually to test the 265kW T2 device through assembling a power train test rig in the Blade Test 1 facility in ORE Catapult, hence an amendment was required to the DOW specifically changing the WP3 scope and requesting an extension of six months to the project total duration.

The amendment was submitted to the European Commission and was approved on 13/07/2016 which allowed commencement of the 1MW test rig design, procurement and commissioning to allow eventually for testing the T2 turbine.

The tidal industry is a rapidly developing sector with new technologies appearing on the market and new challenges being discovered. A scoping exercise was carried out as part of WP 2 in which the original proposed project work was confirmed as still being valid. New current challenges that fit within the project proposal were also identified and where possible included in the scope to ensure the solutions found are current and up to date with the latest developments.

WP 3 included the development of a testing programme to ensure that the PTO system can be thoroughly tested through representative tidal environment conditions. The development and realisation of the physical mechanical and electrical interfaces to enable the commissioning of the Tocardo 265kW T2 turbine through assembly and commissioning of the 1MW power train test rig in the Blade Test Facility 1 in ORE Catapult in Blyth, Northumberland. Following the commissioning a test programme agreed previously between ORE Catapult & Tocardo through various submerged tests including efficiency, heat runs, and short circuit testing and results from testing measurements were processed and reported as part of this work package.  On May 10th 2016 a workshop was conducted for the definition of the requirements for the tidal turbine monitoring system which was implemented during the testing.

As part of WP3 a multibody dynamic model of the Oceanflow Evopod E35 was developed to represent the dynamics of a tidal turbine and optimise its control algorithm. The E35 turbine is a floating tethered device and as such its turbine operates in a region close to the free surface where wave action can be expected. The model was analysed with complex water flow field and output turbine speed for a given generator torque. WTperf was used to extract the turbine characteristics under various tip speed ratios (TSRs) and pitch angles. The controller of integrated Model was optimised by a Simulink model to derive an optimum cp-λ curve and turbine output.

In WP 4 a calculation model of heat flow in the turbine and generator has been developed. The current models and calculation tool developed are primarily designed for Tocardo generators. However, the base program and modelled mechanisms are generic, and can easily be extended to other generator models. The current version was built in details for Tocardo generators T1 and T2, and a separate Excel sheet (interface) for generator T3.

WP5 was aimed to produce new PMG designs and integrate them into the existing Tidal Energy Converters (TEC) technologies from the project partners. The final outcome in this report provides a design for each proposed device based on a specification provided by the tidal developers, Tocardo and Minesto.

New reliability numbers for the key components in the PTO were estimated as a result of investigating the efficiency, thermal characteristics, and reliability of the tidal energy converters. The research carried in this work package showed that the power converter and PMG are critical sub-assemblies that requires the attention for a further optimisation of the PTO and improvement of its reliability.

## Main results achieved

The following main results were achieved during RP2:

- Testing Realisation and Development of Testing Programme
- Testing and PTO Data Gathering, post processing
- Modelling the Evopod E35 turbine and optimising its control algorithm
- Thermal Analysis of Tocardo turbines
- Review of current PMG designs and their interfaces
- Reliability of Tidal energy converters review and improvement strategies
- Dissemination and Exploitation Plan

## Final results & and their impact and use (including the socio-economic impact and the wider societal implications of the project)

The objective of this project has been to reduce the LCOE from the tidal SME partners. The method employed in this project has been to look at reducing operation and maintenance cost and improving system performance.

An analytical numerical method of calculating the thermal cooling was generated as a tool to aid the SMEs in future generator development. The method was validated with CFD and then analysis results were evaluated with the results from the tests. As a result, this tool will help tidal turbine developers to reduce the development cost of generator and PTO design and to reduce the material usage in tidal turbines.

The turbine sensors have been identified as an area of common failures and errors. The project suggested a new sensor system using the Fiber Bragg Grating technology. By matching the sensor requirements with the local environmental conditions, which reduces sensor failure while increasing overall measurement accuracy.

It has not been possible to identify all failures/weaknesses by FMEA due to the small number of devices in service and the fact that they differ in design. However, key components have been identified as points of critical failure and these key components were tested as part of the life cycle analysis. The life cycle analysis used an accelerated loading cycle generated from a turbine situated in an open water environment. The result of accelerated life cycle testing shows the ability of the key component to withstand the harsh marine environment, which also provided a point of validation for the computer simulations and numerical analysis.

The results from the developed submerged PTO test were investigated further in order to evaluate the design and analysis. With this submerged test method, the Tidal industry can reduce the development cost and minimise the material usage by optimisation of design,

The work conducted by the RTDs for the SMEs directly aided their product development and generate new IP for them to exploit. The dissemination of the findings from the RTDs, who are independent bodies, will improve confidence in the SME technologies and the tidal sector as a whole. The project therefore has a greater impact beyond the SMEs involved directly.

## Project website

The project website was also delivered under WP6 and designed to be clean and simple to navigate. Care was taken to ensure logos and images are randomly displayed so as to ensure equal coverage for all SMEs. The website can be found at: http://tidalecfp7.eu/. The website was continuously updated through RP2 with most up to date project outcomes and releases.

### Disclaimer

# 3 A Description of the Main Scientific and Technical Results / Foregrounds

## 3.1 FiberSensing

The key interest of HBM FiberSensing within the TIDAL-EC project has been the identification of the main monitoring requirements on tidal generation systems and the design of a thermal monitoring system based on Fiber Bragg Grating (FBG) sensors, being this technology the company's core business.

Current thermal monitoring solutions used in tidal turbines are based on conventional sensing technologies (e.g.PT100), which need to be individually wired and interrogated, and may be unsuitable for installation in some specific areas (high EM fields, electrically hazardous environments). FBG based solutions offer the following advantages over conventional sensing techniques for application in tidal turbines:

- Completely electrical passive nature of the sensors, providing inherent electromagnetic immunity and electrical safety.
- Increased number of sensing points with reduced cabling due to sensor multiplexing capabilities
- High corrosion resistance of the silica optical fibers and cables
- Potential for remote location for the data acquisition equipment, up to several tenths of kilometres away from the turbines.
- High number of sensing points interrogated with a single equipment, with the capability to use a single equipment for several turbines.

The monitoring requirements have been gathered in the first part of the project from the turbine manufacturers and especially from Tocardo on their T2 turbine, which was used at the final part of the project as test bed. The thermal monitoring solutions already available at HBM FiberSensing have then been used as the starting point for the optimization towards tidal turbine monitoring.

Based on the gathered set of requirements, three different types of FBG temperature sensors have been developed to be used at different locations of the overall generation system (including the turbine itself and the control cabinet). For all three sensor designs the following development steps have been taken:

- Engineering models for the sensors
- Implementation of functional prototypes
- Prototype testing and calibration at FiberSensing
- Sensor installation in final testing setup (turbine, cabinet and testing tank)

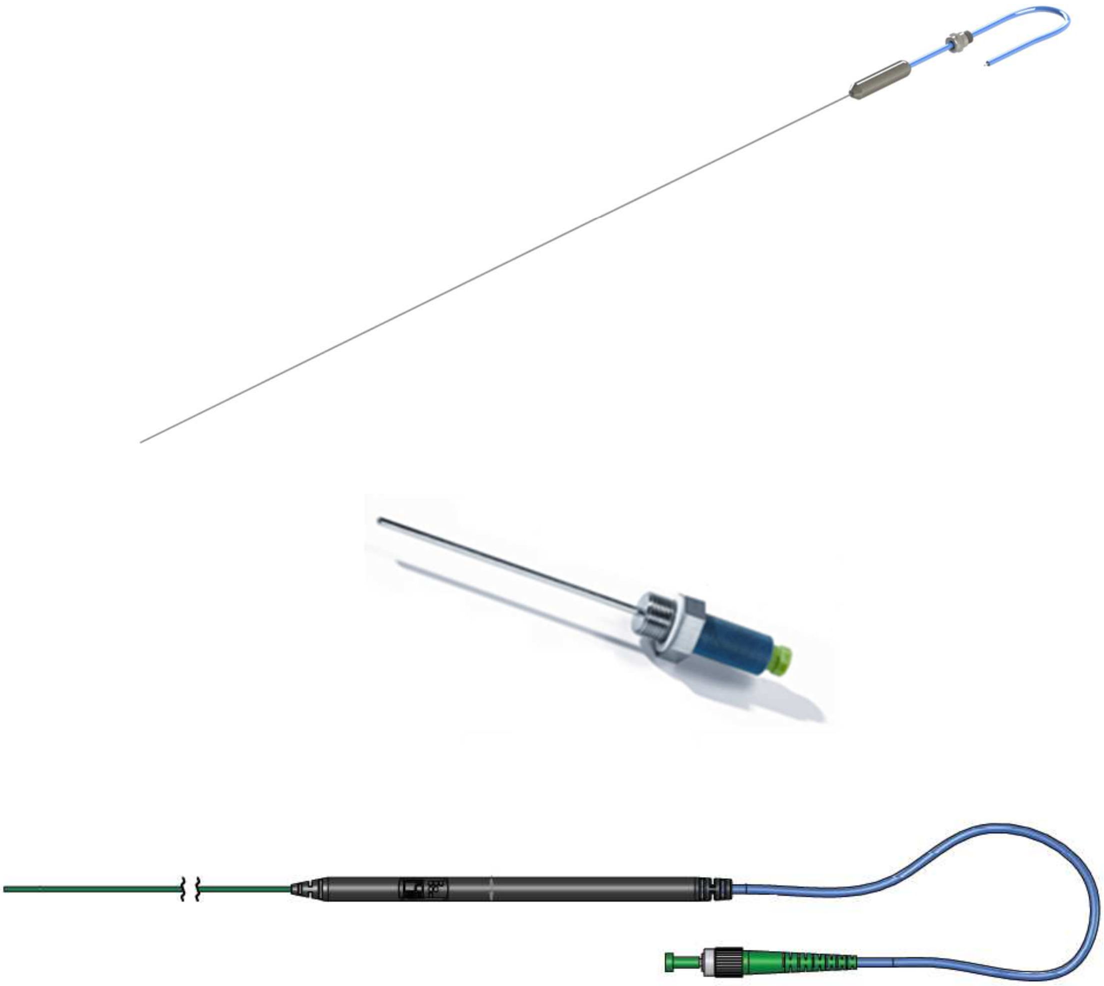

**Figure 3:** Schemes for the three types of sensors implemented and tested

A fourth sensor design has also been provided to be incorporated into the stator winding. Nevertheless, this last type of sensor could not be installed on the present project testing, since the turbine under test had already been manufactured before the project, and thus there was no access to the stator for the incorporation of additional sensors.

**Figure 4:** FBG sensor to be incorporated in the stator winding

The full FBG thermal monitoring subsystem has also been designed, including the FBG interrogation equipment and the fiber accessories (fiber cable, connectors and fiber multiplexers). The resultant FBG network is composed of 21 FBG temperature sensors, simultaneously interrogated at 1S/s over 6 optical channels.

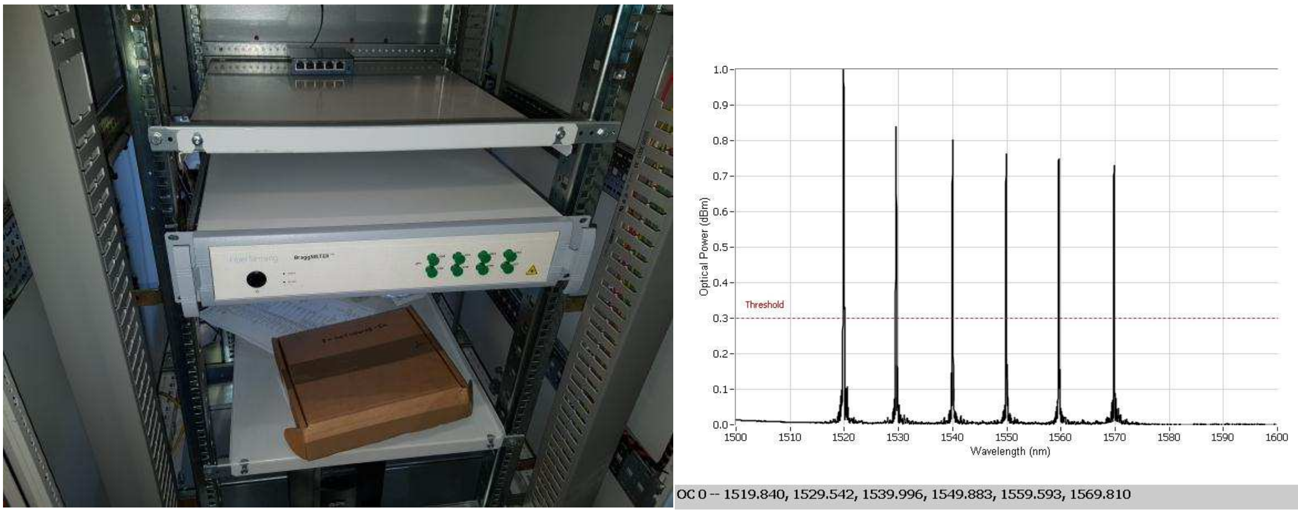


**Figure 5:** FBG data acquisition equipment and 8 FBG sensors being addressed on channel 0

As part of the project, a successful testing campaign has been performed, including the developed full FBG thermal sensing system.

The sensors have been designed to fulfil the requirements presented by the tidal turbine manufacturers, and are thus targeted to this market. Nevertheless, the designs could also be used in other energy generating systems (wind turbines, power generators, voltage transformers,…)

The outcomes from the Tidal-EC project will be used as the starting point for the development of a full monitoring solution for tidal turbines. This development is estimated to be finished in a 2-3 year period.

## 3.2 SINTEF

SINTEF contributed to Work Package 5.1 and was the lead partner in Work Package 4. The results from deliverable D4.1, produced simultaneously with D5.1, were used as an input to estimate the PMG losses.

As part of the TIDAL-EC (Tidal Energy Converter Cost Reduction via Power Take Off Optimisation, http://tidalecfp7.eu/) project, a calculation model of heat flow in the turbine and generator has been developed. For low-speed generators in this capacity range, heat generation and dissipation are important factors limiting performance and maximum power output.

A MS Excel interface to programmed models in C++ and Visual basic has been developed to calculate heat generation, heat transfer, and temperature distribution in submerged, permanent magnet generators.

The current models and calculation tool are primarily designed for Tocardo generators. However, the base program and modelled mechanisms are generic, and can easily be extended to other generator models. The current version has built in details for Tocardo generators T1 and T2, and a separate Excel sheet (interface) for generator T3. Figure 6 shows an example of that turbine showing the turbine in red.

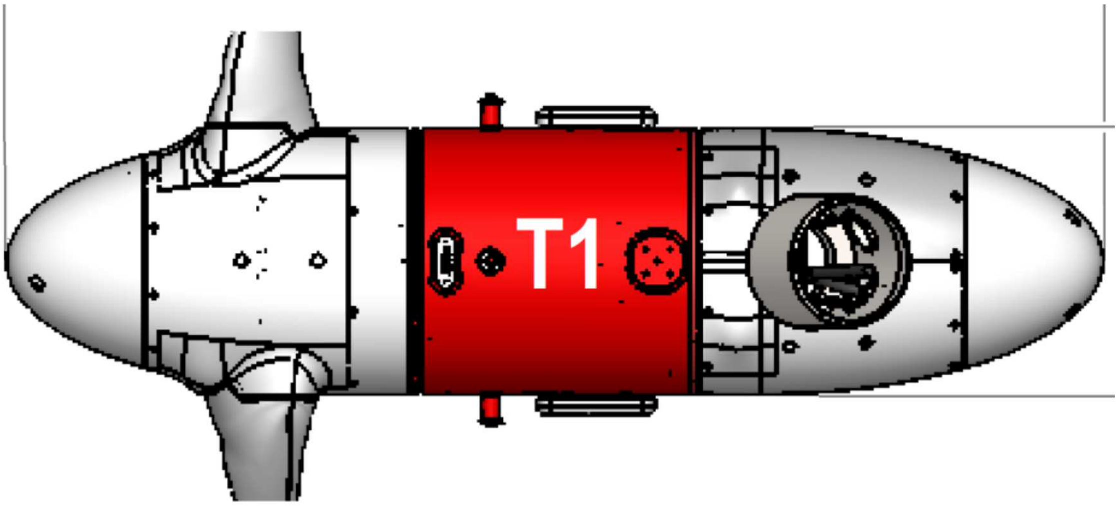


**Figure 6:** Tocardo turbine (Source: Tocardo)

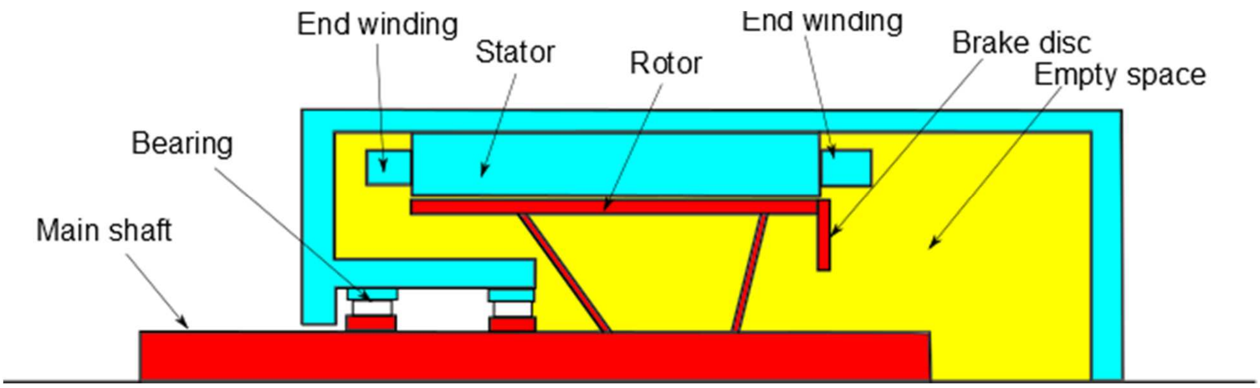


**Figure 7:** Cross section of turbine T2

### 3.2.1 Structure of the numerical model

The heat balance in the core and rotor is calculated using a three dimensional model. Figure 7 shows the cross section of turbine T1 and T2. The empty space is simulated using two fluid compartments, one in the back and one in the front end. Because of symmetry, only one section (or slice) is calculated. The model also includes heat transfer to the empty space, with corresponding heat transfer models.

The core section, stator and rotor in Figure 7 is discretised. The numbers of nodes in tangential and radial directions are locked in the model according to selected generator geometry, while axial node count/resolution can be set by the user, with a default of 10 nodes.

There are two types of nodes in the core; fluid and solid. In fluid nodes, both heat and mass balance must be fulfilled. The thermodynamic state of the fluid is set depending on inlet state and heat transfer, and output state calculated. The convective heat transfer coefficient on surfaces surrounding the fluid nodes is calculated.

In each solid node, the heat balance to be solved consists of conduction based heat transfer/exchange with up to 6 neighbouring nodes. If fluid surfaces are present on solid node (i.e. the solid node has a fluid node as neighbour), the convective and conductive heat resistances are added accordingly.

The model for end windings is slightly different, but follows the same principle.[1]

The system is solved with a linear system that gives a sparse matrix. That system is solved by CSPARSE produced by Timothy Davis

### 3.2.2 Modelling of heat transfer

The numerical model need heat transfer between the solid nodes and fluid nodes. For doing that mathematical models are needed for the heat transfer coefficient between the fluid nodes and the solid nodes. Here the most important is in the gap between the rotor and stator and for the end windings at the outside of the core.

For the end windings, the heat transfer depends on the velocity of the fluid and the detailed geometry of the end windings. Happily, the temperature in the end windings are measured and then used to get the heat transfer coefficient.

### 3.2.3 Heat transfer in the gap between the rotor and stator.

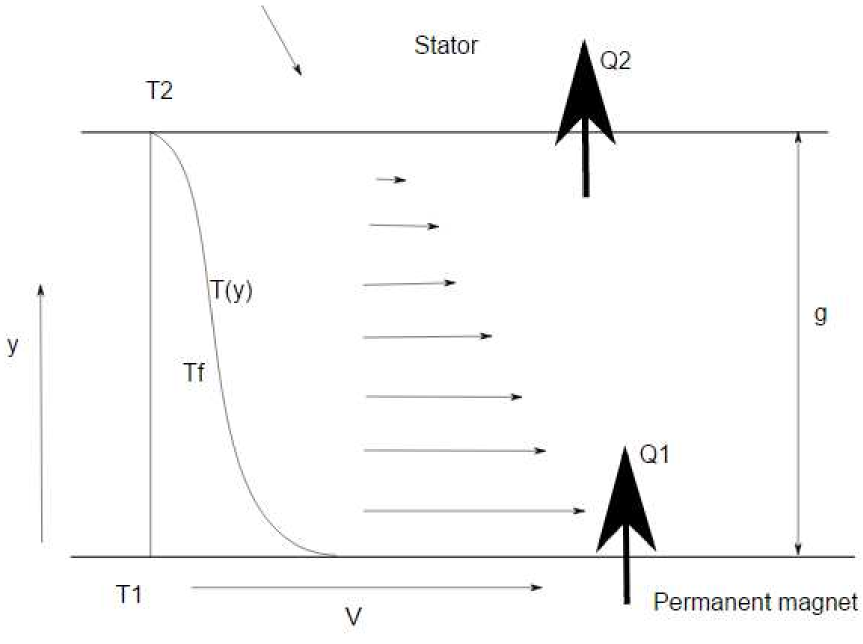


**Figure 8:** Heat Transfer between magnet and stator

Figure 8 shows the heat transfer from the magnet to the fluid and then to the stator. Stator is standing still and the rotor is moving. It is also a space between the magnets for the fluid to mix. This shows the tangential component; in addition can the flow have an axial component.

For calculating the gap between the stator and rotor, the flow was modelling with a CFD simulation by UEDIN when the gap is oil-filled. That simulation gives temperature profile and velocities in the gap between the stator and rotor and the heat flow (*Q1, Q2*) can be found from the temperature gradient on the surface. The results are then used to improve the formula for heat transfer in the 3-dimensional model.

[1] T. A. Davis, Direct methods for sparse linear systems (Siam, 2006)

### 3.2.4 Adjusting the model to measured results

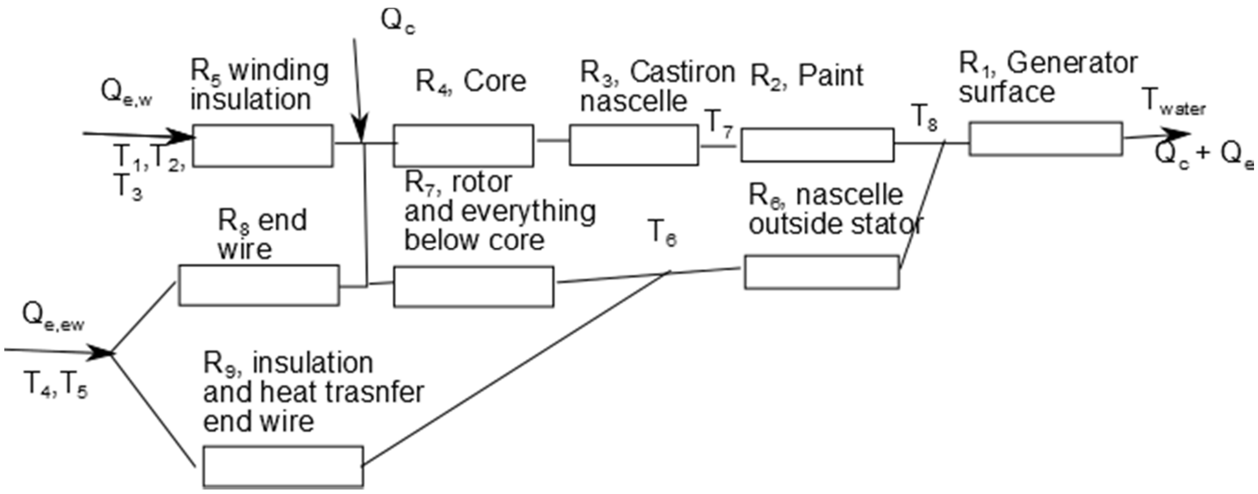


**Figure 9:** The rotor modelled as a resistance network

The heat transfer can be illustrated as a net of resistances shown in Figure 9, and is useful for understanding the calibration of the model based on measured results, but too coarse for modelling the system. Here the heat generated are shown as Q that is modelled and the measured temperatures is shown as $T_1$ to $T_8$. $Q_{e,ew}$ is heat generated through the end winding. Part of that heat is gone to the air outside of the end winding ($R_9$) and part of it is conducted along the wire ($R_8$) to the core. $Q_{e,w}$ is the rest of the heat generated in the wire, that is gone through the wire insulation ($R_5$) to the core. Most of that heat plus the heat generated in the core ($Q_c$) is going through the rest of the core ($R_4$), casting of the nacelle ($R_3$), paint ($R_2$) and from the surface ($R_1$). Some of the generated heat is going to the air inside of the generator ($T_6$) trough heat transfer ($R_7$) and then through the nacelle ($R_6$).

The heat through the windings are resistance heat generated in the windings. Eddy current generate heat but here that heat is very small and can be neglected. The heat generated in the core is calculated by UEDIN.

The following resistances are adjusted after the temperatures are measured:

$R_5$, Resistance in winding insulation: The resistance at the winding insulation is unknown because of insecurity in the geometry and heat conductivity of the insulation. This in opposite to the core that is well known. Then $\Delta T = Q/R$ can be used to model resistance of winding insulation. The conductivity of the insulation was reduced from 0.2 W/mK to 0.14 W/mK to fit the simulation to measured temperatures.

$R_9$: The heat transfer coefficient of the end winding. Where the heat transfer from end wire to the core is known because area and conductivity of wire is known is this difficult to model and taken from measurement of temperatures.

$R_2$, paint: This i the product of thickness and heat conductivity. The thickness was reported from Tocardo to be 0.72 mm, and no0 adjustment of conductivity was necessary.

### 3.2.5 Thermal Modelling

The thermal modelling provided the heat transfer coefficients as an input for the calculation of the losses in the PMSG. The work developed by SINTEF and UEDIN in the task 4.1 provided a numerical tool for calculating these inputs. The thermal resistance Rth from eq. (3), is affected by the rotor and water speed, among other variables

## 3.3 Tocardo

### 3.3.1 Existing PTO review

The currently existing PTO system was reviewed via a workshop with the participation of all the partners at which:

- Opportunities for improvement were highlighted
- Modifications that would result in an improvement of the overall system functionality were identified

Main room from improvement was identified to exist in the generator design:

- Use of concentrated windings instead of distributed
- Adopt advanced thermal management to minimize temperature rise and hot spots (oil filled generator instead of air filled)
- Introduce special thermal paths to enhance heat transfer

### 3.3.2 PTO description

A variable speed system, designed to inject energy into the grid, requires a power converter to adapt variable-frequency input power to fixed-frequency output power. The configuration involves a Permanent Magnet Synchronous Generator (PMSG), with the first converter stage to rectify the variable frequency AC to DC. After this first rectification stage, there is a second inverter stage that turns DC into AC at a fixed grid frequency (Figure 10).

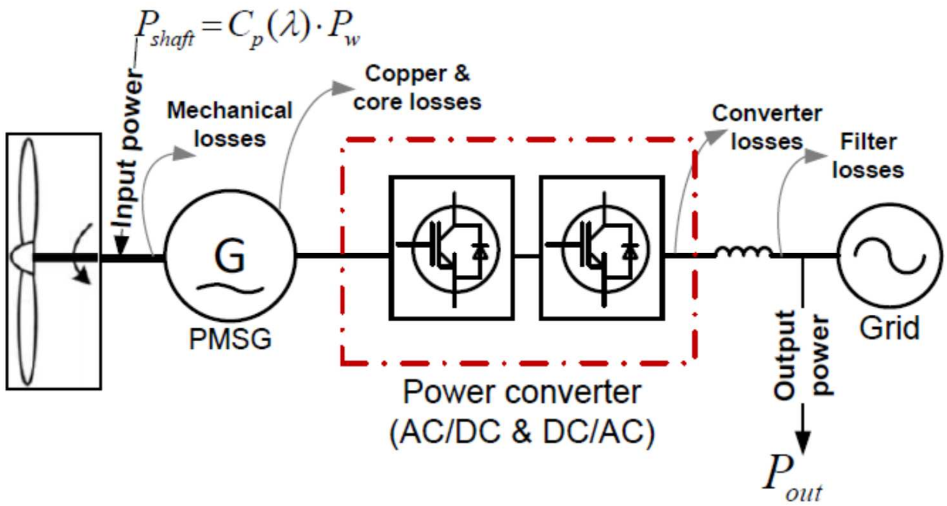


**Figure 10:** Simplified block diagram of a typical tidal energy power conversion stage based on a PMSG direct-drive configuration

The direct-drive PMG maintains a high efficiency and reliability at a wide range of loads and speeds, compared to the induction generator. The lower cost of the induction generators (Doubly Fed Induction Generator, DFIG) and associated power converter made them popular in the wind industry, but some of their weaknesses are undesirable for tidal energy applications. One of their advantages is that they do not require fully rated power converters as PMGs. An important drawback however, is that DFIGs need slip-rings increasing their maintenance requirement, making them less suitable for offshore energy applications, including tidal energy.

### 3.3.3 Loss modelling

Losses in the generator are in mechanical and electrical forms. In low speed machines, the main loss occurs in the windings. Due to the low rotating speed, the mechanical losses (bearing and windage losses) have a negligible contribution in the overall system. Hence, the electrical losses can be considered as the main losses.

In the stator, all losses are in the copper coils and in the steel laminations. Both no-load and load losses need to be considered. No-load losses are caused by the action of the rotating field of the magnets inducing hysteretic & eddy losses primarily in the steel and coils. Fortunately the diameter of each conductor in the current machine is very small, therefore eddy currents in the coils can be neglected. The remaining loss in the steel is modelled using FEM, termed as iron loss

Finally, the phase currents produce $I^2R$ loss in the windings, designated as copper loss in this report.

#### 3.3.3.1 Iron loss

The loss in the laminations can be modelled using the traditional formulation:

$$P_{steel} = k_h f B^n + k_e f^2 B^2 \qquad (1)$$

where,

$P_{steel}$: loss in the lamination (W/kg).

$k^h$: hysteresis coefficient.

f: fundamental electric frequency (in Hz)

B: flux density (in T)

$k_e$: eddy current loss coefficient

n: Steinmetz constant (dependent on the material type, as well as the flux density).

More complex formulations than eq.(1) for determining iron losses can be found in the pertaining literature, but for the reduced range of operation at low frequencies, this formula is accurate enough. The first and second terms in eq.(1) represent the hysteresis and the eddy current loss, respectively. In this low speed application, the dominant loss is the hysteresis component.

The direct application of eq.(1) in the stator laminations (without dividing the parts into finite elements), allows to derive a simple approximation of the iron losses for several speeds or frequencies.

#### 3.3.3.2 Copper Loss

The copper loss estimation is based on the estimation of the Joule loss:

$$P_{Cu} = 3R_{Cu}I_{rms}^2 \quad (2)$$

where,

$R_{Cu}$: is the electric resistance per phase, that depends on the operating temperature of the windings.

$I_{rms}$: is the phase current (rms), derived from the equivalent circuit of the generator.

The steady-state value of the copper resistance is deduced from:

$$R_{Cu}^{final} = R_{Cu}^{ambient}(1 + R_{th}P_{Cu}\alpha_{Cu}) \quad (3)$$

where,

$R_{th}$ : is the equivalent thermal resistance from the windings to the outside water (in °C/W),

$\alpha_{Cu} = (T_{ambient}+K_{Cu})$-1: is the temperature coefficient of resistance, KCu inferred absolute temperature of copper (234.5°C).

Solving (2) and (3) is not simple because the final temperature depends on the copper loss term $P_{Cu}$. The electric resistance $R_{Cu}$ also depends on the final temperature, and $R_{th}$ depends on the water and rotor speed. Therefore, there is no explicit solution for these two equations.

Nevertheless, equations (2) and (3) can be solved using a numerical algorithm that takes as inputs the electro-thermal equivalent circuit representation of the generator (i.e. phase resistance, inductance, emf source voltage, etc.), the power converter efficiency, and the hydrodynamic characteristics of the rotor blade. From this numerical algorithm, the phase current and final copper resistance are calculated to find the copper loss term.

#### 3.3.3.3 Additional Losses (Rotor losses)

The flux reaction from the current flowing in the windings can induce additional losses in the rotor (i.e. magnets & iron). Since the windings in the analysed machine are distributed, the rotor losses can be neglected. This simplification does not apply in a PMSG with concentrated windings, as the armature flux reaction induced by the windings has a significant amount of space harmonics, which in turn can induce eddy current losses in the rotor.

### 3.3.4 Thermal modelling

An advanced PMG thermal modelling tool calibrated on measured data was developed in order to provide the heat transfer coefficients as an input for the calculation of the losses in the PMSG. The inputs to the model are the geometrical and material properties of the tidal turbine (Figure 11).

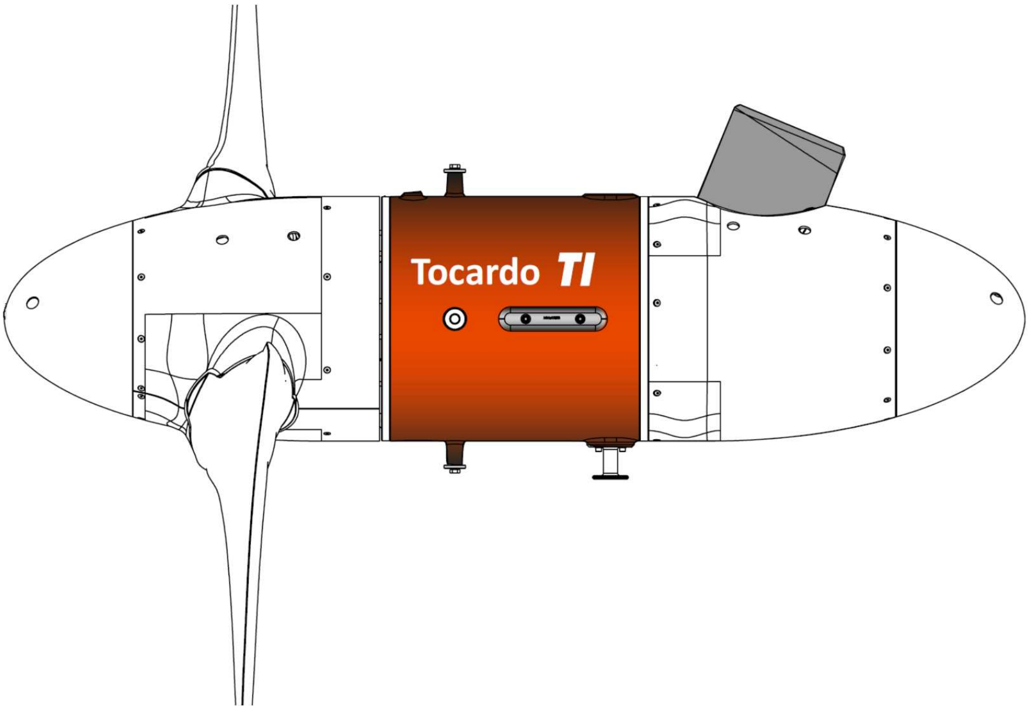


**Figure 11:** Tocardo Turbine (Source: Tocardo)

The calculation models the heat flow in the turbine and generator assuming that steady state thermal equilibrium has been achieved. The heat balance in the different generator components is solved using a 3 dimensional model. The model considers a number of fluid compartments when applicable. CFD simulations were run to estimate heat transfer coefficients, which are difficult to estimate analytically. The CFD was key in providing the Heat Transfer Coefficient (HTC) at the interface boundaries where the fluid flow interacts with the rotor and stator surface in the gap. A heat transfer coefficient boundary condition allowed the model in WP4 to compute the temperature distribution throughout the solid rotor and stator. Last but not least, a number of significant model parameters which are characterized by high uncertainty were calibrated based on measured data in WP3.

For low-speed direct drive applications, heat generation and dissipation are important factors that can limit performance and maximum power output. Therefore, precise thermal modelling will allow the safe and reliable operation of the tidal energy converter by ensuring that the thermal stresses in the generator remain at acceptable levels.

### 3.3.5 Testing campaign

In January 2017, Tocardo commenced testing its T2 turbine at the ORE Catapult's 1 MW drive train facility in Blyth, UK, as part of the EU funded TIDAL-EC project. The test setup was composed of a Tocardo T2 turbine and its corresponding electro cabinet connected to the grid via a transformer. Additionally, an electric motor is connected via a mechanical shaft at the location of the turbine rotor hub. This motor serves as a mean for the application of torque to the turbine for excitation purposes. The turbine was placed inside a tank filled of water (Figure 12). In this way, the nacelle was in direct contact with water which is also the case in actual employment, ensuring the presence of adequate cooling capacity.

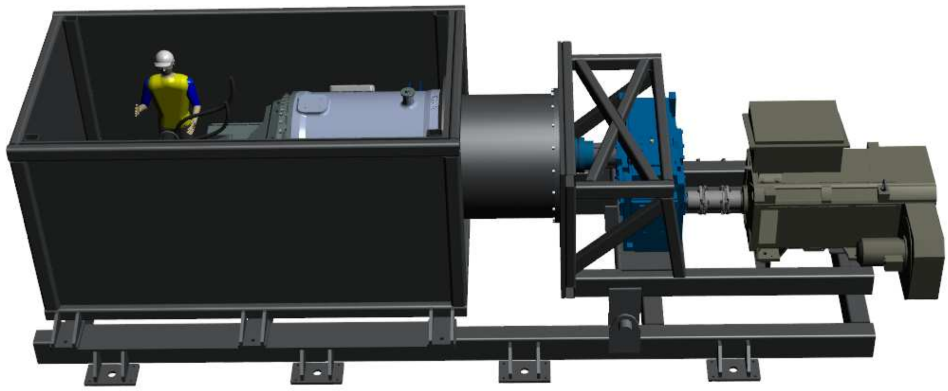

**Figure 12**: Tidal EC – conceptual testing setup

The tests aimed to evaluate the efficiency of the turbine system at various stages of the power conversion process, and ultimately establish the magnitude of the losses between the turbine shaft and the distribution network, or grid. During the testing period, the turbine was put to different speed and torque operational points to verify the electrical steady state performance in both cold and hot conditions. Therefore, the measure of the turbine system performance was evaluated as a function of a number of generator variables, namely speed, temperature and torque, as well as the switching frequency of the DC-AC power converter

Testing results were utilized for the achievement of the following objectives:

- Validation of the electrical models developed in Work Package 5. More specifically the efficiency of the power - take - off system was measured as a function of rpm and torque experimentally validating the:
    - o Generator copper and core losses
    - o Power converter losses
- Validation of the thermal models developed in Work Package 4

Additionally, the acquired measurements will increase to a high extent the validity of the predictions of energy yield and will contribute in decreasing the technological risks, which are important factors when evaluating the different projects' feasibility

#### 3.3.5.1 Summary of key findings

The overall losses across the turbine system were found to be dominated by copper losses that arise from the generator currents (torque), with the energy lost as heat. The magnitude of these losses clearly increased with generator torque, while the relative losses, or efficiency, decreased.

Losses in the turbine system were also found to increase with generator speed, although the magnitudes are insignificant in comparison with those found from increasing generator torque. This resulted in the efficiency increasing with speed, unlike torque. Thus there are clear benefits from operating the turbine at high speed and moderate torque.

Power conversion efficiency was observed to decrease at constant speed and torque with respect to temperature, as a consequence of increased resistive losses that occur when the generator heats up over operational time. Similarly, the expected decrease in efficiency with increasing power converter switching frequency was observed, due to increased switching losses. However, the difference was negligible for the switching frequencies considered and the losses across the DC-AC converter were consistently found to be low in comparison to those incurred elsewhere in the turbine system.

The results suggest that the entire Tocardo T2 turbine system (input to output) achieves a net power conversion efficiency up to 91% for the operational conditions and regions considered. These results are expected to support the experimental validation of numerical models of the thermal and electrical aspects of the turbine system, developed in D4.1 and D5.1 respectively in the TIDAL-EC project.

In terms of areas for improvement to the test setup, some instrumentation problems were encountered during the test campaign, specifically the LSS torque transducer and the generator current sensors. The ORE Catapult and Tocardo are currently investigating these issues, with the intention of updating the test results once instrument calibration information is obtained. Addressing these instrumentation issues is of key importance before further testing takes place.

## 3.4 Minesto

The scientific and technical results having most direct bearing on Minesto's technology were created in work package 5 "High reliability PTO design and numerical modelling". Task 5.2 resulted in block diagrams of the power take off system, and these were used as a basis for the analysis work following. The principle behind the reliability analysis originating from the block diagrams is illustrated below.

Reliability Block Diagrams (RBDs) were built by the SMEs partners following the generic model proposed by Delorm[2] (Figure 13) as a way of standardising the reliability analysis. Each sub-system RBD may be expanded to show individual sub-assembly block diagrams (Figure 14). The figure shows each of the sub-components of the subsystem RBD drive train or PTO, the focus of the reliability analysis. The coding for each component was taken from VGB PowerTech Guideline[3], to give a generic categorisation on each different functionality.

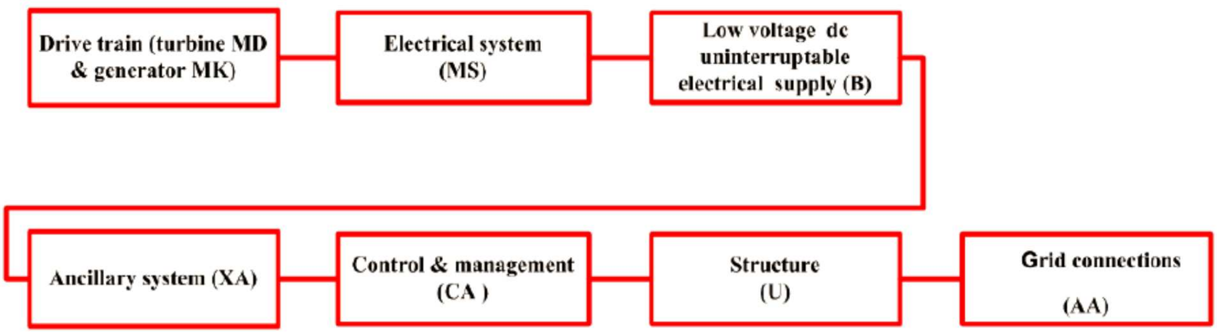


**Figure 13:** Generic device reliability block diagram (RBD) describing each of the main sub-systems present in tidal energy converter

[2] Delorm, T. M. (2014). Tidal Stream Devices: Reliability Prediction Models During Their Conceptual & Development Phases. Durham University. Retrieved from http://etheses.dur.ac.uk/9482.

[3] VGB PowerTech. Guideline, reference designation system for power plants (RDS-PP): application explanation for wind power plants (VGB-B 116 D2). Essen: VGB Power- Tech, 2007.

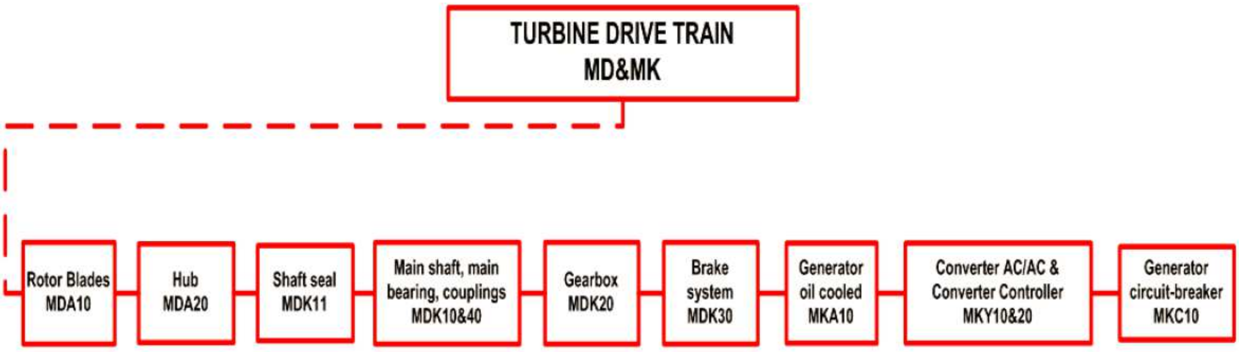


**Figure 14:** Generic turbine drive train & generator for a tidal energy converter proposed by Delorm[1]

Task 5.3 analysed the reliability of Minesto's current power-take-off topology (in both redundant and non-redundant configurations) and compared it to the reliability of an alternative and improved design.

The methodology used for calculating the failures rates of the sub-assemblies and sub-system can be summarised in the following flow diagram (Figure 15):

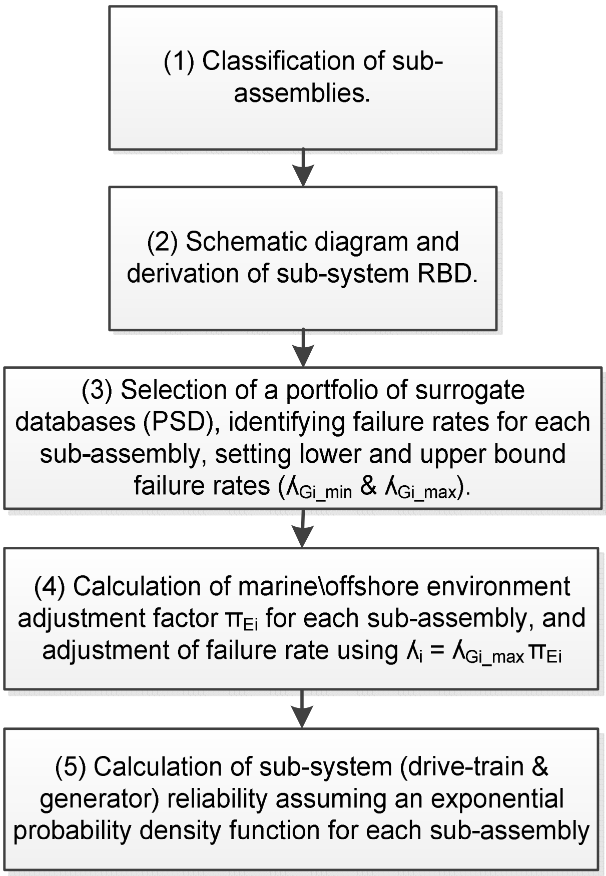


**Figure 15:** Sequence for obtaining reliability numbers for sub-assemblies and sub-system (drive-train and generator). Adapted from Delorm et al[4].

[4] Delorm, T. M., Lu, Y., Christou, A., & McCluskey, P. (2016). Comparisons of offshore wind turbine reliability. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 230(3), 251–264. http://doi.org/10.1177/1748006X15624592

Task 5.4 produced an analysis on the lifetime of the power converter. As bonus and by-product of the TIDAL-EC project Minesto obtained from UEDIN some thermal modelling of the tether that provided valuable insights (Figure 16).

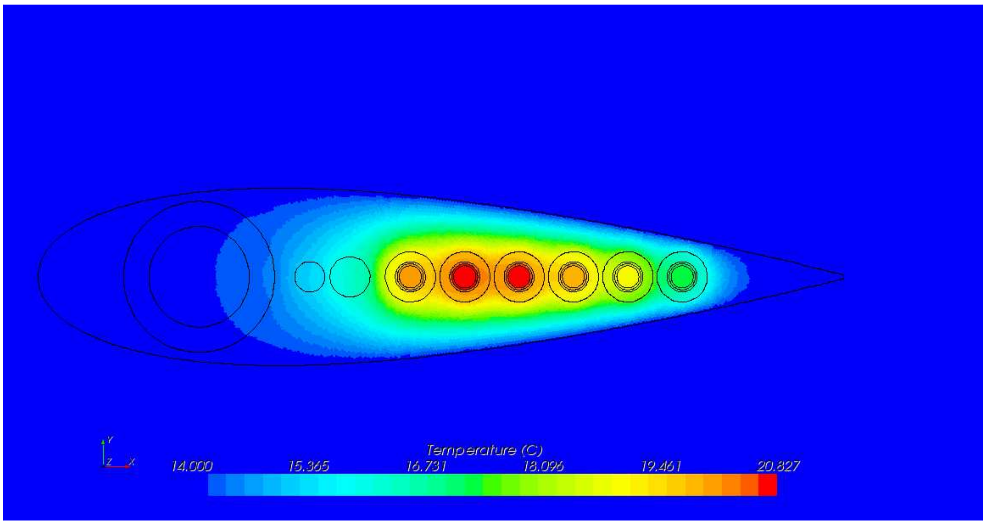


**Figure 16:** An early and tentative tether thermal modelling result

## 3.5 UEDIN

### 3.5.1 New PMG Design & Control

#### 3.5.1.1 Introduction

A conventional PMSG was proposed in Section 3, but WP5.1 & WP4.1 supported the case for finding new optimised PMG designs. In particular, it was found the key aspects for reduction of LCOE (by increasing AEO and reliability):

a) Reduction of copper losses.
b) Improving cooling capabilities.
c) Integrated design approach (e.g. cavitation speed limit matching maximum PMG speed) (outside the scope).
d) Incorporating a global loss minimisation approach.

UEDIN developed new conceptual designs for the power take off (PTO) system, focussing on Tocardo's T1 turbine.

The previous research activity in tasks 4.1 & 5.1 showed that the PMG losses were dominated by the copper losses. In order to increase the efficiency and cooling capability, UEDIN investigated the performance of a novel generator concept, based on an air-cored machine with multi-stage topology. This novel concept was initially proposed for direct-drive wind turbines [1, 2], with the main advantage of eliminating the attraction between stator and rotor, adding modularity, hence easing the manufacturing process. Also, the axial flux topology was investigated due to its desirable cooling advantages compared to other types of generators. In this sense, it is possible to use a passive cooling system, as opposed to a submerged PMG or a forced\active cooling system. Preliminary results confirmed the hypothesis that the Annual Energy Output (AEO) and reliability can increase by the air-cored multi-stage concept. Two concepts were proposed. One of them does not involve any modification in the T1 nacelle structure, whereas the second one will require a modification to attach the stator into the nacelle, as a way to increase the machine radius, and allowing a thermal connection between the windings and nacelle.

#### 3.5.1.2 C-GEN – a modular air-cored PMG

UEDIN proposed to use of the air-cored topology – also known as C-GEN (Figure 17) - as a way to study the potential improvement on power performance and reliability of the T1 turbine through the use of concentrated windings. These type of windings can easing the rotor & stator assembling, improving the copper fill factor in the windings, and reducing the end winding, without increasing torque ripple & eddy current losses as it would happen in a traditional iron-cored machine. Also, as in direct-drive PMGs the copper losses are one of the main losses, there is a need for improving the thermal capability of the windings.


**Figure 17:** General structure of the air-cored PMG technology (C-GEN)

The next figures are meant to provide a better understanding of the flux paths in the air-cored machine:

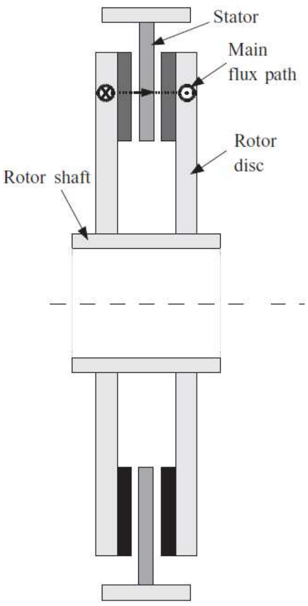


**Figure 18**: Cross section of double sided axial-flux machine

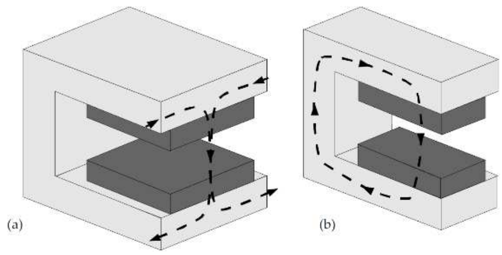


**Figure 19**: Steel core module with magnets: (a) longitudinal flux path, and (b) transverse flux path. Images from [1].

Figure 20 shows the flux density distribution in the core and direction of flux through the outer core, for a multi-stage machine. The purpose of assembling many c-cores modules in the axial direction is to increase the axial length of the generator and its torque rating, without increasing the outer diameter of the PMG.

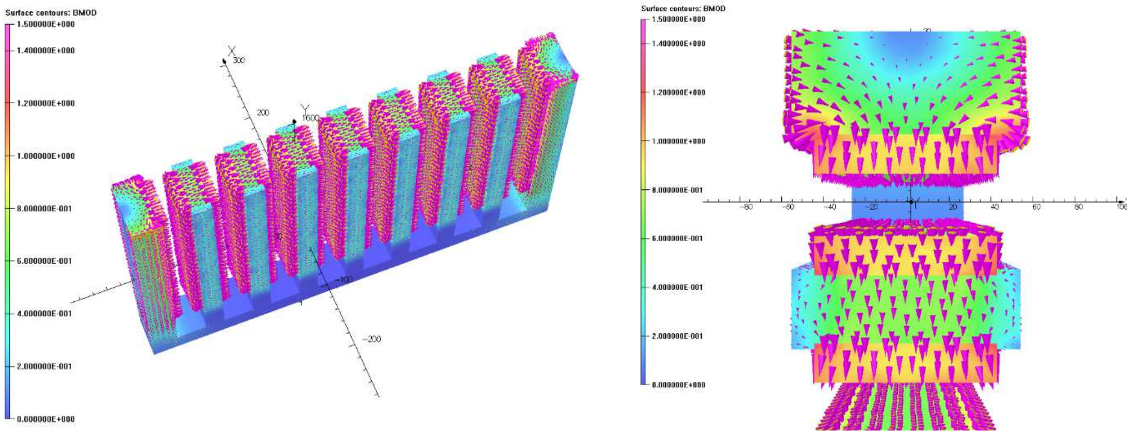


**Figure 20**: Flux density distribution in the C-core modules (3D FEA). Images taken from a different design, not used in this report.

The advantages of the C-GEN air-cored PMG can be summarised as [3]:

- Circular coils offering the shortest turns and lowest resistance.
  - Simple manufacture and low production costs.
  - Easy assembling as no magnetic forces between rotor and stator.
  - No cogging torque, hence negligible mechanical resistance to turbine starting.
  - Potential for passive cooling over the machine periphery increases the reliability of the drive train (desirable in marine applications).

#### 3.5.1.3 C-GEN concepts applied to Tocardo T1.

Two integration concepts were considered for the T1 with the C-GEN as the proposed generator. The concept of integration focussed on improving the thermal performance. There are two major options for the cooling system. Both were analysed in terms of power performance and the steady-state average coil temperature: Natural cooling & External Water Cooling.

##### 3.5.1.3.1 Concept 1: Multi-stage air-cored PMG completely fitted inside the T1 nacelle, with natural cooling

Concept No 1 is a 6-stage machine with an external diameter of 920 mm (including the stator support band). Therefore, the nacelle does not need any structural modification. The generator is housed entirely within the nacelle as shown in Figure 21.

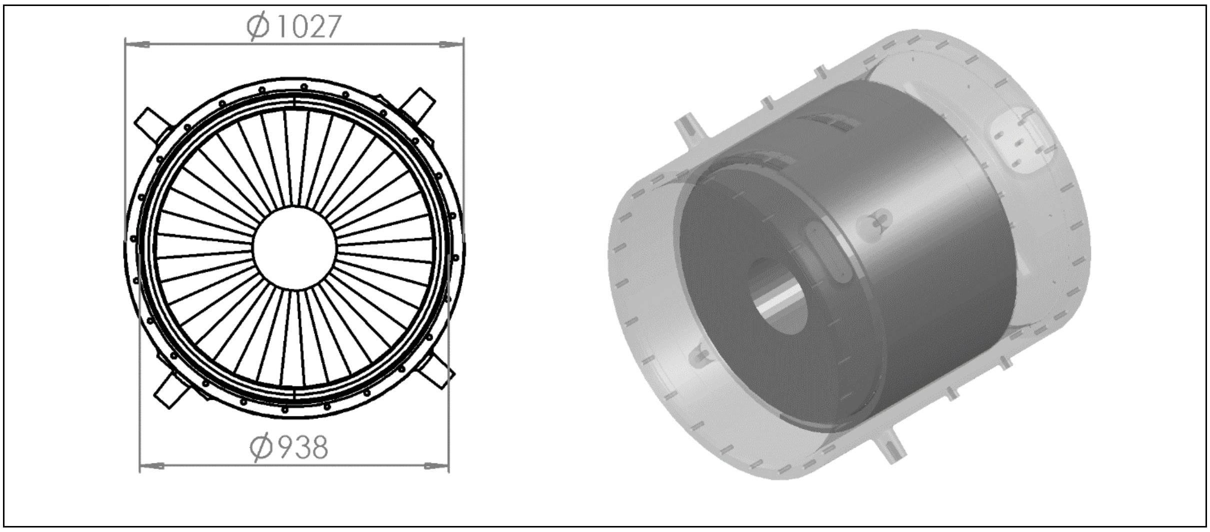


**Figure 21:** Air-cored generator fully fitted inside the T1 Nacelle. Nacelle file and drawing provided by TOCARDO.

In terms of annual mean power, the AEO for Concept 1 is greater than the baseline case. The cooling system is passive, similarly to the baseline case. This preliminary design may have some mechanical advantages (i.e. no need to modify current T1's nacelle). However, it is a redundant design as the stator band can be embedded into the stator (increasing the mean gap radius). Concept 2 provides an alternative design making use of this advantage

#### 3.5.1.3.2 Concept 2: Multi-stage Air-cored PMG with stator support band embedded into the nacelle

Concept 2 achieves an increased mean winding radius (better efficiency and less weight compared to Concept 1). The coils can be attached to the nacelle steel, eliminating the stator structure previously shown in Concept 1. The benefits are mass reduction & better cooling as there is a potential for incorporating a direct thermal connection between the stator and nacelle frame.

The cooling system can use the tidal currents as the cooling liquid without filling the nacelle with water/oil (potentially bringing a higher reliability compared to a generator submerged in oil). The use of fins can improve the heat transfer coefficient of the external nacelle, but TOCARDO believes this will induce algae growing. Alternatively the use of a flat band can still help to provide better dissipation of heat from the windings. Figure 22 shows how the stator support structure is integrated into the nacelle frame providing a very good thermal contact to optimise heat flow from the coils to the nacelle.

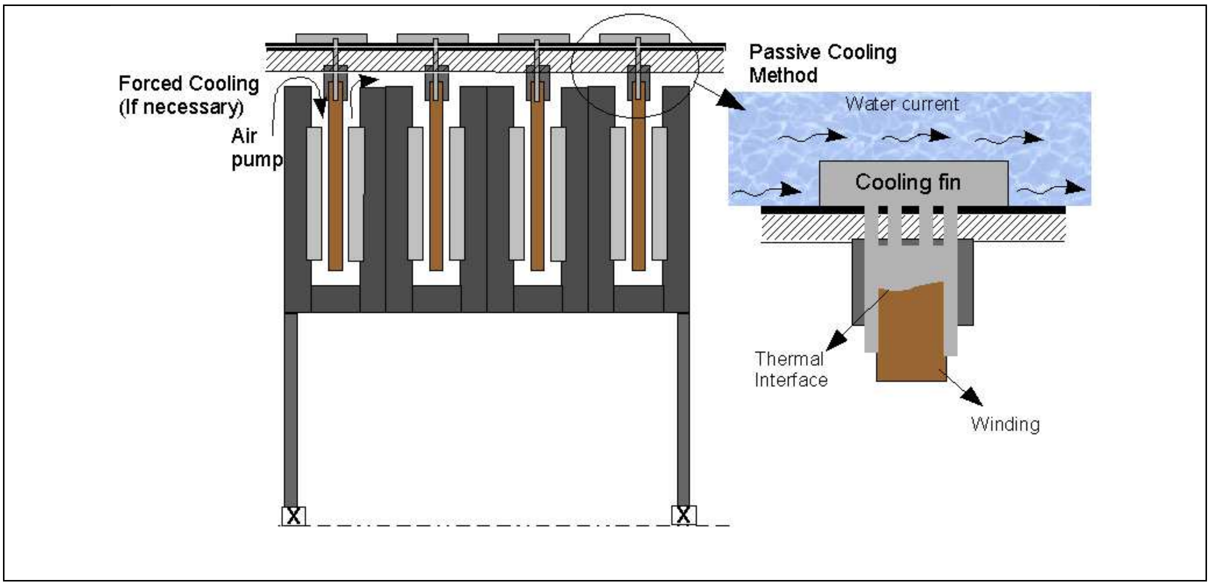


**Figure 22:** Cooling method for the axial flux machine (patent pending). The excess heat of the coils will be transferred through radial direction with a special thermal interface to the outer cage of the nacelle. Alternatively, the cooling fin can be removed but still keeping a thermal interface between the winding and steel of the nacelle.

Results from the design of Concept 2 showed an increase of the AEO compared to the baseline case. The material costs are expected to increase significantly, as the air-cored generator requires more magnet than the iron-cored machine. However, in a much larger power rating (i.e. 1MW), the air-cored machine may be able to compete in cost with the iron-cored machine, because the last one will eventually require more structural material to withstand the attraction between rotor and stator.

Further optimisation may be achieved by:

- Increasing the nacelle diameter: The axial-flux machine has the ability to reduce the axial length, requiring however a larger diameter.
- Integrating the generator, rotor blade profile and power converter in the optimisation routine.

Another further exercise may be to compare the iron-cored machine with concentrated windings (instead of the traditional distributed winding). However, this modification may increase the eddy current losses in magnets and rotor.

#### 3.5.1.4 Control Improvements

In this section we analyse potential improvements that can be made to the current system (T1) by:

- adopting a system loss minimisation approach,
- increasing the tip-speed limit of the blades

##### 3.5.1.4.1 On-line Minimisation of Losses

The efficiency and power performance can be improved by optimising the power injected into the grid below the rated speed, taking into account the losses within the PTO, PMG and power converter. Energy gains can be achieved by finding the global optimum of the system, rather than trying to maximise the hydrodynamic efficiency in the rotor blades (7. By keeping to the actual limit of tip speed in the blades the power gains are modest. Within the site analysed, the AEO can be increased across the speed range and into stall.

#### 3.5.1.4.2 Increasing Tip Speed Limit

One important limitation of the actual system is imposed by the risk of cavitation in the blades, triggered when the rotational speed of the blades exceeds the speed limit. It was shown that if this limit can be exceeded there are benefits regarding power performance and AEO, even at low tidal velocity. An increase in tip-speed limit will also lead to reduced losses in the system. Further analysis using CFD is required to investigate tip speed and cavitation further.

### 3.5.2 Summary

Two conceptual designs for TOCARDO's T1 turbine have been developed with the aim of maximising the Annual Energy Output, and increasing the reliability of the generator by decreasing the average temperature of the windings through an axial flux PMG with good thermal capabilities. These optimised designs were developed using a proprietary software tool owned by UEDIN for air-cored machines. For both designs the CAD drawings were produced and are available for the manufacturer. These designs as preliminary, and more detailed modelling is required to confirm the electromagnetic and thermal characteristics of the generators. Further optimisation may be achieved by increasing the nacelle diameter and integrating the generator, rotor blade profile and power converter in the design optimisation routine.

### 3.5.3 References


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## 3.6 Oceanflow

As part of the TIDAL-EC (Tidal Energy Converter Cost Reduction via Power Take Off Optimisation) project a time domain simulation model was built to simulate the energy extraction and control of the Evopod E35 turbine operating in a combined steady flow with wave environment. E35 is a semi-submerged floating tethered turbine that operates in the near surface zone where the orbital wave induced particle velocities can be significant. The simulation model reflected the "as-built" characteristics of the turbine, mechanical and electrical system to allow an inertia model of the Evopod E35 to be generated. The two mass model considered inertial effects only while balancing the torque generated by the rotor and the torque generated by the generator. A speed controller was introduced in this work to control the speed of the rotor by manipulating the generator torque. The model was tested in realistic environmental conditions as representative of the Sanda Sound test site where E35 is deployed. This allowed investigation of combined steady tidal stream plus wave induced particle velocity components. A high level schematic of the control system is shown in Figure 23.

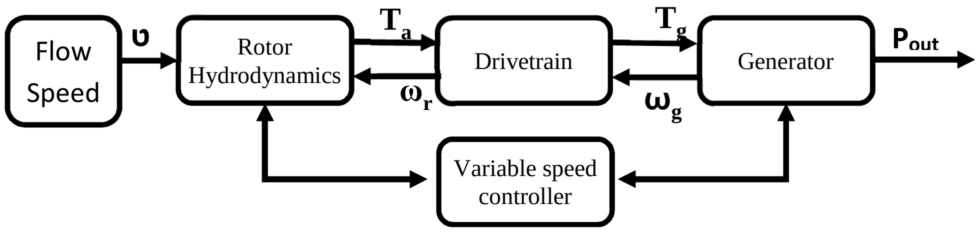


**Figure 23:** Schematic of simulation modelling process

The Simulink block diagram is shown in Figure 24.

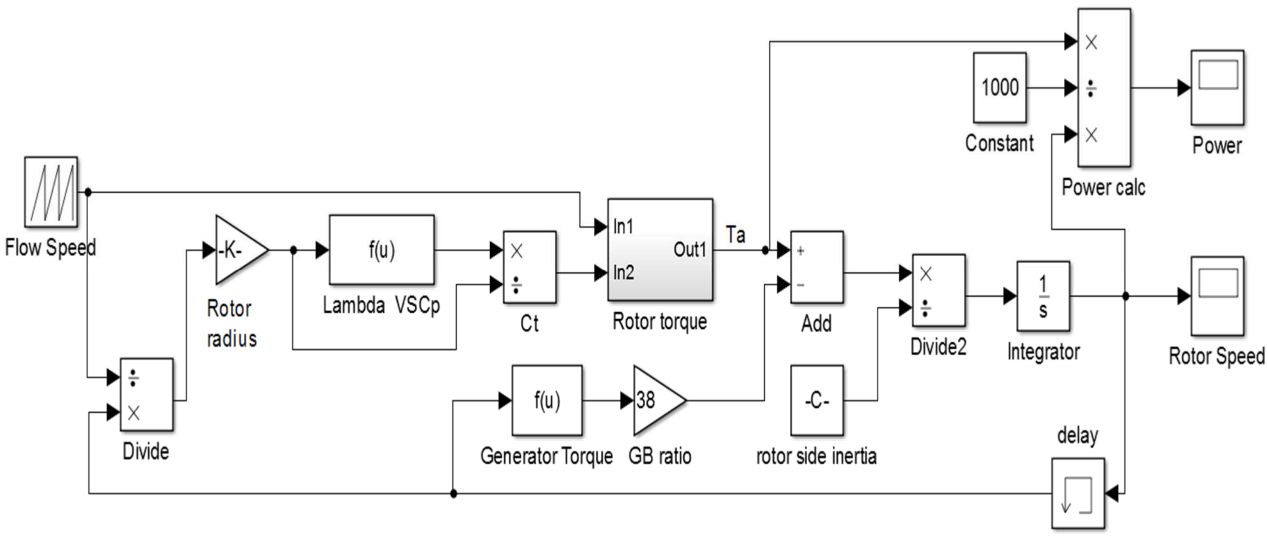


**Figure 24:** Simulink block diagram

The model was run in both steady flow (T1) and steady flow with regular waves (Wave + T1) and steady flow with irregular waves (Sea State + T1). A sample trace of the flow conditions to which E35 was subjected is shown in Figure 25 below.

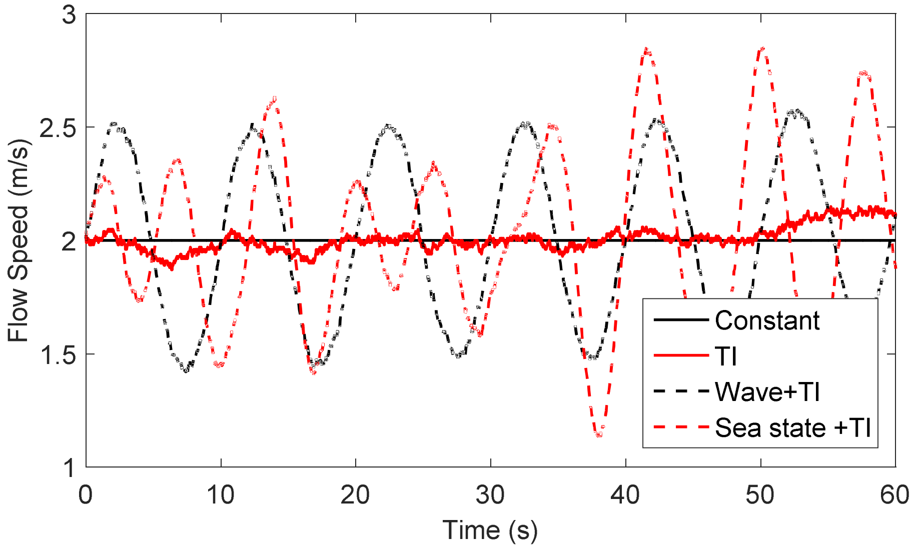


**Figure 25:** Flow speeds for the considered load cases

An enhancement to the time domain simulation was developed with the aim of maintaining the torque speed and power within a required envelope and also optimising the generator torque to maximise the power output in energetic wave conditions. The role of this advanced controller was to follow a predefined flow –speed-/ rotor-speed relationship in an attempt to maximise the power coefficient of the turbine at a variety of flow speeds. In very high energy flows the controller was used to curb energy extraction after the rated speed was reached to avoid overloading to generator thus offering more optimal system control capabilities than the simple controller described above.

As before the model was tested in realistic environmental conditions as representative of the test site where E35 is deployed. This allowed investigation of combined steady tidal stream plus wave induced particle velocity components.

The Simulink block diagram with the enhanced PID controller is shown in Figure 26.

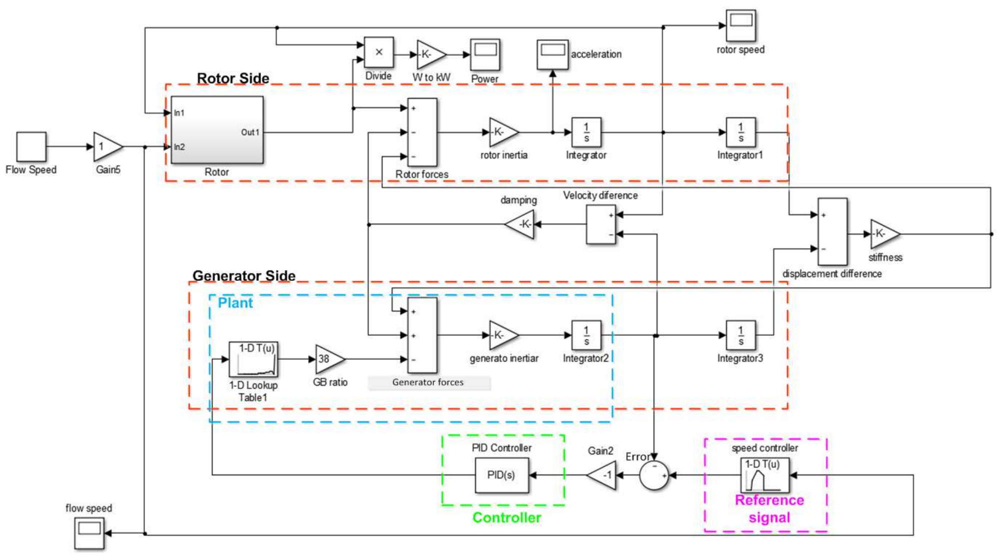


**Figure 26:** Simulink block diagram of two mass turbine system with PID controlled generator torque

The Proportional- Integral-Derivative (PID) controller is among the most common control techniques in industry. The controller achieve defined control goal by the application of proportional gain, and integral gain and a derivative gain. The typical process for control of a plant (system in diagram) is shown in Figure 27. The controller takes a reference value, compares it to the output of the system to identify what the error is, then tries to minimise the error.

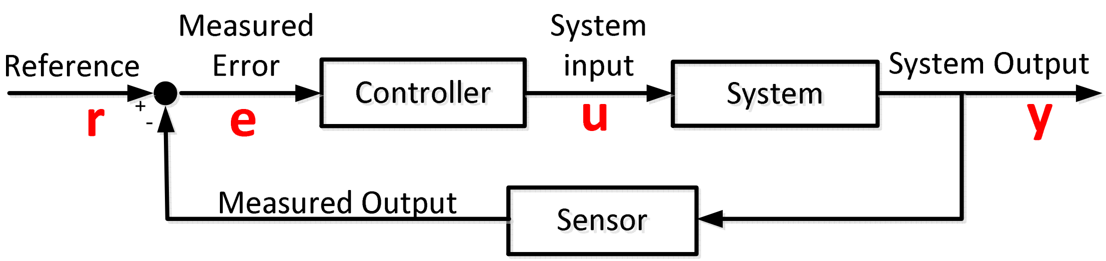


**Figure 27:** System control schematic

A comparison of the power coefficient of the tuned (PID controller) and un-tuned system is shown in Figure 28 below. The tuned system is able to maintain a reasonably stable rotor power efficiency under combined wave and tidal stream conditions which will enhance the economics of the device.

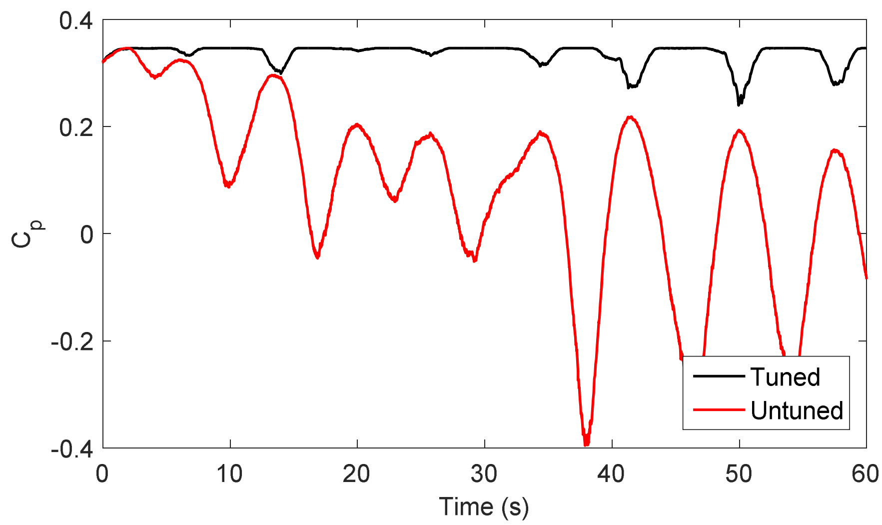


**Figure 28:** Rotor Cp values obtained for tuned and un-tuned controllers

The simulation work described above clearly demonstrated the benefit of developing a tuned controller for turbines operation closer to the sea surface that are exposed to steady currents plus wave induced and turbulence generated non-steady state flow conditions. Because tuned controller enables turbine to operate at high Power Coefficient (Cp) region with low rotating speed, power output is maximised while the turbine operated with an un-tuned controller clearly cannot extract the maximum energy from flow due to the low Cp operating values.

As a result of this work Oceanflow will be able to apply the advanced control strategy to its next deployment of E35 turbine with the expectation of enhanced power generation and therefore improved economics.

## 3.7 ORE Catapult

As a project partner, ORE Catapult contributed to the following tasks:

- Identification of improvement point on existing PTO design
- Testing realisation and development of testing programme
- Testing and PTO Data Gathering, post processing
- Multibody dynamic model development and Turbine Operation Optimisation

### 3.7.1 Identification of improvement point on existing PTO design

ORE Catapult reviewed the existing power take off (PTO) systems used by three tidal energy converter (TEC) developers, to ensure that accelerated life cycle testing could be executed on a TEC PTO, so that additional information could be obtained on the permanent magnet generator (PMG) and PTO operation.

ORE Catapult led a workshop held with key personnel from TOCARDO to identify the potential risks and improvement points with the TOCARDO PTO systems and highlighted areas of potential work for this project. Focus was on removing known trouble spots and improving overall system reliability. The workshop was also used to provide a detailed scope upon which to complete the first ever accelerated life cycle testing of its kind of a tidal turbine on the test rig.

The main ways to improve the generator were defined as the following:

- Single layer concentrated winding with the highest fundamental winding factor
- Neodymium iron boron rare earth magnets which depict high remanent flux density
- Halbach magnet arrangement which increases the airgap flux density
- Soft magnetic material with high saturation flux density
- Rectangular copper bars and open slot design which can lead to increased slot fill factor
- Advanced thermal management to minimize temperature rise and hot spots
- Introduction of special thermal paths to enhance heat transfer to the surrounding water

### 3.7.2 Testing Realisation and Development of Testing Programme

With consortium partners, ORE Catapult developed a testing programme to ensure that the PTO system could be thoroughly tested through representative tidal environment conditions. This involved the development and realisation of the physical mechanical and electrical interfaces to enable the commissioning of the Tocardo 265kW T2 turbine through assembly and commissioning of the 1MW power train test rig in the Blade Test Facility 1 at ORE Catapult in Blyth, Northumberland. Following the commissioning, a test programme agreed previously between ORE Catapult & Tocardo through various submerged tests including efficiency, heat runs, and short circuit testing and results from testing measurements were carried out. On May 10th 2016 a workshop was conducted for the definition of the requirements for the tidal turbine monitoring system which was implemented during the testing.

Based on the FMEA, analysis and design data for the PTO optimization, a submerged test programme was developed to evaluate the electrical, and thermal performance of prototype. During this test, data was gathered to identify hidden weak points and evaluate analysis model. As a result, the efficiency of the total tidal energy converter including the generator, cables, inverter and/or possible losses in the AC filter were evaluated under more realistic and controlled testing conditions.

**Figure 29** Test rig for the submerged test

A detailed baseline programme was agreed between ORE Catapult and Tocardo including all testing interfaces, breaking down the activities on a daily basis to allow monitoring and efficient progress tracking, which included:

- Procurement and delivery of equipment/components
- Design of test rig and Interface with the T2 turbine
- Mechanical and electrical assembly works
- Commissioning works for the test rig
- Detailed testing programme

A testing programme to ensure that the PTO system could be thoroughly tested through representative tidal environment conditions was developed. The testing philosophy included a number of control and monitoring tests as well as various electrical tests. The main objectives were to:

- experimentally verify the electrical and thermal models
- experimentally verify the efficiency of the total tidal energy converter including the generator, cables, inverter and/or possible losses in the AC filter
- experimentally verify control strategies as well as control algorithms
- evaluate the control system dynamic behaviour under different normal and extreme operational and limiting conditions
- evaluate built-in electrical and mechanical safety mechanisms associated with control and extreme operational behaviour
- verify the overloading capability of the PTO electrical components

Figure 30 shows the final setup and layout of the developed test rig.

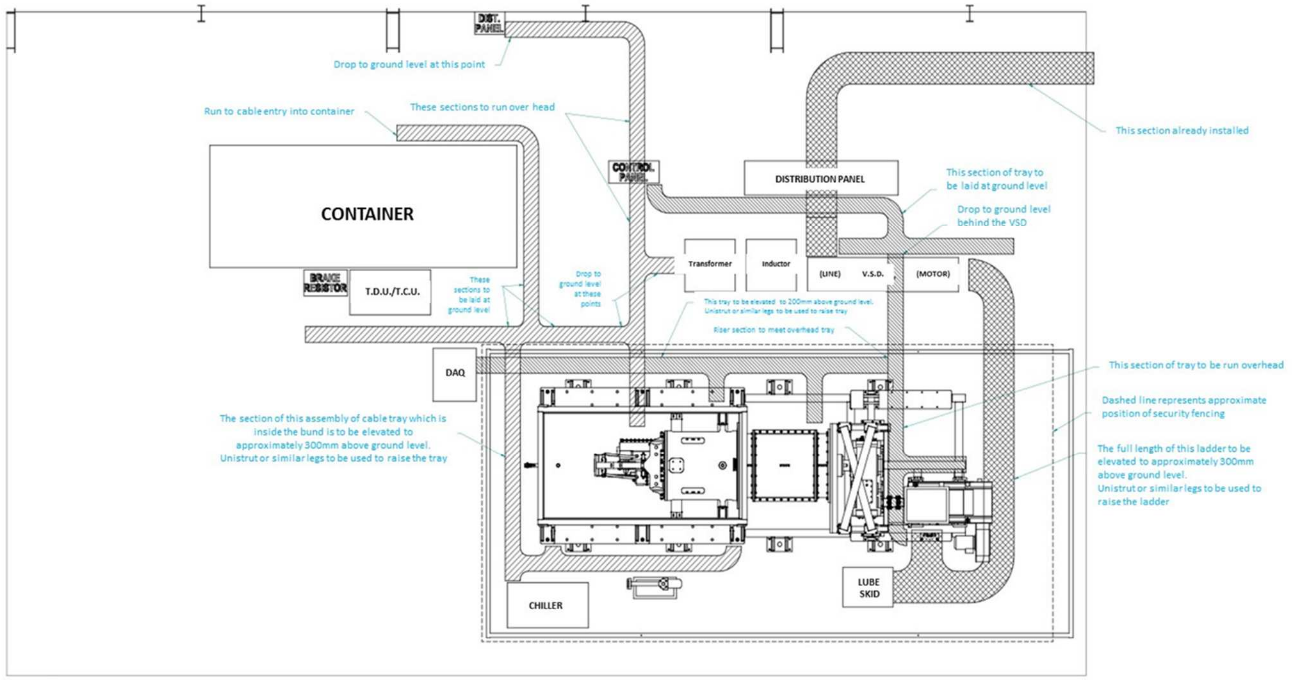


**Figure 30**: Containment Layout

### 3.7.3 Testing and PTO Data Gathering, post processing

ORE Catapult and Tocardo completed the T2 turbine submerged PTO testing at the ORE Catapult's 1 MW drive train facility in Blyth, UK. The tests aimed to evaluate the efficiency of the turbine system at various stages of the power conversion process and, ultimately establish the magnitude of the losses between the turbine shaft and the distribution network, or grid. This measure of the turbine system performance was evaluated as a function of a number of generator variables, namely speed, temperature and torque, as well as the switching frequency of the DC-AC power converter.

The results suggested that the entire Tocardo T2 turbine system (input to output) achieves a net power conversion efficiency up to 91% for the operational conditions and regions considered. These results are expected to support the experimental validation of numerical models of the thermal and electrical aspects of the turbine system, developed in D4.1 and D5.1 respectively in the TIDAL-EC project.

### 3.7.4 Multibody dynamic model development and turbine operation optimisation

A multibody dynamic model of the Oceanflow Evopod E35 was developed by ORE Catapult and Oceanflow to represent the dynamics of a tidal turbine and optimise its control algorithm. The E35 turbine is a floating tethered device and as such, its turbine operates in a region close to the free surface where wave action can be expected. The model was analysed with complex water flow field and output turbine speed for a given generator torque. WTperf was used to extract the turbine characteristics under various tip speed ratios (TSRs) and pitch angles. The controller of integrated Model was optimised by a Simulink model to derive an optimum cp-λ curve and turbine output.

The production of turbine performance data in combined tidal flow and waves was carried out using an enhanced time domain simulation model. The work made use of E35 turbine "as-built" turbine and mechanical and electrical system characteristics used to create the inertia model of Evopod E35. The role of this advanced controller was to follow a predefined flow –speed-/ rotor-speed relationship in an attempt to maximise the power coefficient of the turbine at a variety of flow speeds. In very high energy flows the controller was used to curb energy extraction after the rated speed was reached to avoid overloading to generator thus offering more optimal system control capabilities than the simple controller developed. As before the model was tested in realistic environmental conditions as representative of the test site where E35 is deployed. This allowed investigation of combined steady tidal stream plus wave-induced particle velocity components.

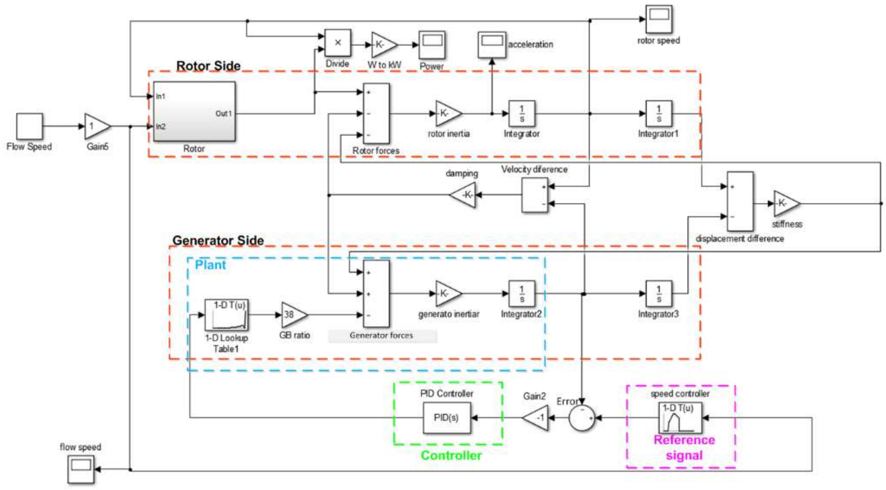


**Figure 31:** Simulink block diagram of two mass turbine system with PID controlled generator torque

Figure 32 shows also the effect of tuned controller under sea state + turbulence condition which simulates most realistic flow field. Because tuned controller enables turbine to operate at high Cp region with low rotating speed, power output is maximised while turbine with untuned controller cannot extract the maximum energy from flow due to the low Cp operation.

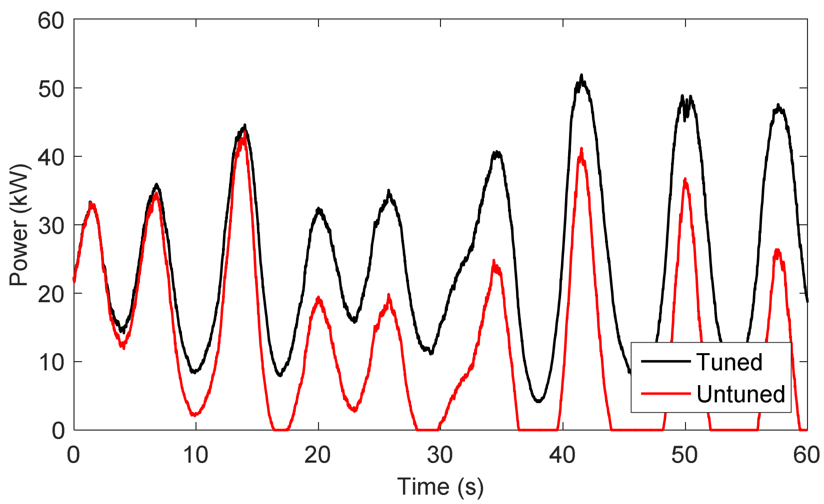


**Figure 32:** Power derived from a tuned and untuned controller systems

The simulation clearly demonstrated the benefit of developing a tuned controller for turbine operation closer to the sea surface that are exposed to steady currents plus wave induced and turbulence generated non-steady state flow conditions. Because tuned controller enables turbine to operate at a high Power Coefficient (Cp) region with low rotating speed, power output is maximised while the turbine operated with an untuned controller clearly cannot extract the maximum energy from flow due to the low Cp operating values.

# 4 Potential Impact

## 4.1 Background

Even spokesmen for major oil producers, such as Sheikh Zaki Yamani, of Saudi Arabia, who was his country's oil minister and representative at OPEC for many years, recognise that our future energy demands cannot be met by fossil fuels[5] alone, and that advances in technology are beginning to offer a way for economies to diversify their supplies of energy and reduce their demand for fossil fuels. Energy suppliers such as E.ON have identified that parts of European Union ("EU") will face an energy supply shortage by 2015[6] and that, with the long lead times and high capital costs, nuclear power cannot fix this gap. Renewable energy sources offer a solution, but by their very nature are intermittent and variable in consistency of supply; many are seasonally variable; sun, wind, tides, etc., or can impact on carbon emissions (e.g. biofuels). Therefore to meet future energy demands, a diversified portfolio of renewable energy sources commercially needs to be established within the EU. All indicators show strong growth in demand for renewable energy generation; which is also being driven by legislation on global[7], EU[8] and national[9] levels. Currently, the EU renewable energy sector generates over €10 billion in annual sales, with legislative targets driving further growth across the EU of 22% energy generation via renewable sources by 2020. Our proposed Power Take Off R&D project is designed to improve the economic competitiveness of a key sector of the renewables market; that of marine tidal energy capture.

Estimates of the total renewable energy available from the marine environment can be made by summing together the individual components available from the six principal subdivisions of this energy source (Wave, Bio-mass, Ocean Thermal, Tidal, Subsea Current and Salinity Gradient). Estimated availability varies widely with researchers such as Isaacs and Seymour posting estimates of between 1,000 and 10,000 GW[10]. More recent commentators suggest approximations in the order of 2,000 GW may be extractable around the world[11]. All estimates identify a highly significant energy source, even if only a limited percentage of the available energy can be recovered, either due to the remoteness of the source, transformation inefficiencies, or impact on marine ecosystems.

Tidal energy is a true renewable energy source that has great potential for a significant contribution to the reduction of European greenhouse gas emissions. Ultimately it can represent up to 15% of the European electricity mix, offering a local and decentralised energy source, create world-class high-tech industries, and can generate significant economic development.[12] This project will involve three of the current leading Tidal Energy Converter (TEC) technologies: turbines being developed by TOCARDO (Figure 33), MINESTO (Figure 34) and OCEANFLOW (Figure 35). The TOCARD TEC is designed to be used as a self-contained unit that can be deployed on their own structures or third party platforms. They are therefore considered both an OEM and tier 1 supplier.

[5] The Economist 23 October 2003, The end of the oil age

[6] The Economist 5 April 2008 – Green and black – a looming supply crunch

[7] Kyoto protocol to the United Nations framework convention on climate change, 11 Dec 1997. Kyoto

[8] Directive on Electricity Production from Renewable Energy Sources, 2001/77/EC, October 2001

[9] For example: "Energy White Paper Our Energy Future – Creating a low carbon economy", HMSO, 2003.

[10] Isaacs & Seymour, The Ocean as a Power Resource, Int. J. of Environmental Studies vol 4(3), p201-205

[11] World Energy Council 2000

[12] Oceans of Energy 2010-2050 Road Map, EU-OEA, 2010

- The turbine, installed in Den Oever, has been operational for 5 years.
- A range of unit sizes to meet developers requirements.
- Permanent magnet direct drive generator
- Turbines can be bottom mounted, installed underneath floating platforms or retrofitted to existing structures like bridges and barrages.

**Figure 33:** Tocardo TEC

- The Deep Green technology has been tested at scale in tank testing and real sea environment conditions (Strangford Loch)
- The innovative aspects of the project originate in the technical principle of Deep Green, the power plant is illustrated in Figure 2. Deep Green consists of a wing (1 in Figure 2), which carries a nacelle (2) and a turbine (3) which is directly coupled to a generator inside the nacelle. The wing is attached to the seabed by struts and a tether (4). The tether accommodates power cables as well as cables for communication. By means of a rudder (5), a servo system in the rear cone (6) of the nacelle and a control system the kite is steered in a predestined trajectory.


**Figure 34:** Minesto TEC

- The Patented low motion hull form provides an ideal stable platform to mount a tidal turbine on.
- Multi turbine configurations are also planned.
- 1KW system deployed for over 1yr in Strangford Loch N. Ireland
- 35KW grid connected mono turbine to be deployed in Sanda sound, South Kintyre.
- Environment carefully selected as a scale representation of the Pentland Firth.


**Figure 35:** Oceanflow E35 Evopod TEC

Whilst the environmental and sustainability case for renewable energy development is compelling, the current high cost of energy from renewable sources, in comparison to that of fossil fuels, is delaying investment into many renewable energy projects. Levelised Cost of Energy (LCOE) is used to calculate the price at which electricity must be generated from a specific source to break even or make a defined return on investment over the lifetime of the project. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital, and is very useful in calculating the costs of generation from different sources. LCOE is often used to compare the cost of generation from varying sources. LCOE can be defined in a single formula as:

$$\mathrm{LEC} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

$\mathrm{LEC}$ = Average lifetime levelised electricity generation cost

$I_t$ = Investment expenditures in the year t

$M_t$ = Operations and maintenance expenditures in the year t

$F_t$ = Fuel expenditures in the year t

$F_t$

$E_t$ = Electricity generation in the year t

$r$ = Discount rate

$n$ = Life of the system

Reliability has proven to be a critical parameter in determining the LCOE associated with offshore wind energy project[13], particularly when compared with onshore installations. This is because turbine down time creates both an increase annual operations and maintenance cost and a reduction in annual electricity generation; resulting in lower returns on investment. Intervention for maintenance of tidal energy converters is arguably more difficult and costly than offshore wind turbines, due to the difficulty of navigating and operating in high tidal flow offshore environments. Therefore reliability will hold further significance in the LCOE for tidal energy arrays; as the amount of time that elapses between turbine failure and fault rectification will be longer, resulting in a greater impact on annual electricity generation. This has been highlighted by those seeking to make investments into the first tidal array projects – utilities, project developers and financial institutions.

## 4.2 Specific TIDAL-EC Impact

The Tidal Energy Converter Cost Reduction via Power Take Off Optimisation (TIDAL-EC) project proposes a set of research and development activities to substantially improve the economic competitiveness of a key developing sector of the renewable energy market: that of tidal stream power generation. Two of the largest and most critical components of any mainstream tidal energy converter (TEC) are the power take off (PTO) system (the shaft, bearings, gearbox and other equipment which connects the turbine blades or hydrodynamic absorber with the electrical grid) including the electrical generator itself. Experts in the field of turbine and generator testing (the UK's Offshore Renewable Energy Catapult (ORE CATAPULT)) together with Small or Medium sized Enterprise (SME) partners (Tocardo Tidal Turbines (TOCARDO), Oceanflow Energy (OCEANFLOW), Minesto AB (MINESTO) & FiberSensing-Sistemas Avancados Demonitorizacao SA (FIBERSENSING)) and Research and Technology Development (RTD) performing partners (the University of Edinburgh (UEDIN) and SINTEF (SINTEF)), conducted vital research and concept design activities to determine the optimum design of a TEC power take off system and permanent magnet generator (PMG).

These radically optimised tidal turbine systems have the potential to improve reliability, increase power conversion efficiency and facilitate reduction in the Levelised Cost of Energy (LCOE being the total cost per kWh of power produced, factoring in design, build and lifecycle costs such as the cost of maintenance, operations and decommissioning) of tidal power. In turn, the results of this project

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[13] Offshore Wind Cost Reduction Task Force Report, June 2012

will also help SME tidal developers (and their SME suppliers) to be able to offer warranties and guarantees to end-users/customers (European Energy Utilities) and enable large scale roll out of tidal energy in the European Union (EU); supporting diversification of the European energy mix and helping to achieve European 2020 renewable energy and carbon emission reduction targets.

The TIDAL-EC project was based on designs and testing work previously undertaken by the above mentioned SME partners who are involved in technology development across the tidal energy supply chain: three TEC manufacturers (TOCARDO, OCEANFLOW & MINESTO), one of whom produces their own generator in a versatile pod (TOCARDO - tier 1) and a sensor supplier (FIBERSENSING - tier 2). The SME partners in turn subcontracted to the above noted world leading European research institutions to provide access to their facilities and knowledge required to optimise their respective TEC PTO and PMG technology for improved reliability, increased efficiency and reduced LCOE. The RTD performing partners provided access to the temporary powertrain test rig in the Blade Test 1 Facility (ORE CATAPULT), an advanced Computational Fluid Dynamic (CFD) analysis model (SINTEF) and a state of the art PTO/generator loss/reliability model (UEDIN) of the system.

The four key areas of improvement and innovation were explored during the optimisation process:

1. The removal of single point failures across the TEC PTO (e.g. electrical connections, cable harnesses) by improving the electrical systems design;

2. The introduction of improved additional redundant and or high reliability sub-components (e.g. brake, circuit breaker, medium voltage circuit breaker pod);

3. A revised design evaluation with the on-shore relocation of critical systems currently subsea (e.g. programmable logic controller – the TEC computing system) [14]; and

4. The introduction of a dielectric and electro-magnetic immune temperature sensor (FIBERSENSING) to the PMG, providing greater ability to monitor and operate within safe limits.

The impact of these improvements and innovations on TEC PTO and PMG were analysed via a three-fold empirical test programme:

1. Accelerated life-cycle testing of the TOCARDO TEC PTO at the Blade Test 1 Facility (ORE CATAPULT);

2. CFD thermal profiling modelling of the TOCARDO PMG (SINTEF); and

3. Efficiency/reliability modelling of the TOCARDO and MINESTO TEC PTOs (UEDIN).

The project culminated in a set of design recommendations for the optimum method of PTO integration to improve reliability, increase efficiency and reduce the LCOE for mainstream tidal energy devices including the TOCARDO, OCEANFLOW and MINESTO devices.

Collectively, the industrial base of the TIDAL-EC consortium represents each of the key stages of a viable SME centric supply chain for TEC systems, capable of taking the project concept forward to market. The RTD performers have provided the SMEs with the enabling systems, technologies and

[14] Optimisation strategy C (a revised design leading to the on-shore relocation of critical systems currently subsea) has been highlighted as the preferred route for improving the reliability of the programmable logic controller. No power modulation equipment will be moved from underwater to the shore. This work is accounted for in WP2 (scoping the requirements capture). It is a design activity only. There will be no physical relocating of equipment.

know-how to further facilitate this process.  The TIDAL-EC consortium brings together the necessary critical mass of technological expertise, industrial experience and scientific know-how in a complementary and non-competitive framework. The formation of the consortium has been carefully considered, in parallel with the resource commitments required to support the proposed programme of work. All consortium members had clearly defined roles and responsibilities within the work programme, and determined that their return on investment is significant, appropriate and is in alignment with their strategic vision.

The socio-economic impact of this project is more potential than actual at present.  There is significant potential to improve the reliability and availability of tidal turbines by applying the outputs of this project.  This will provide employment benefits in the supply chain, e.g. the increased supply of tidal turbines and sensor systems to owner/operators.  Furthermore, the already identified reduction in the levelised cost of energy (LCOE) will help to securing a place for the tidal turbine technology in the future energy mix.

Regarding wider societal implications, the general public of the European continent will benefit from a clean, secure, efficient and carbon-free energy system.  A system that is not dependent on other member states outside of the continent.  Tidal turbine technology can provide clean and carbon-free energy.  It can also be independent of non-EU member states.  However, it needs to be more efficient in terms of reliability and availability performance to make it more cost-competitive and therefore financially secure in the energy mix.  As discussed previously, this can be achieved, in part, by increased market confidence, by utilising the outcomes developed in this project.

Concerning other societal implications, the project consortium were able to directly recruit a number of researchers to work on the Tidal-EC project.  Some of these researchers have been retained following the conclusion of the project.  During the course of the project, at least one of the SMEs (Minesto) has seen the injection of significant funds into their business.  Another of the SMEs (FiberSensing) has been acquired by a larger organisation.  This economic growth and acquisition activity creates additional jobs which can be linked to the work undertaken on this project.

It was identified at the start of the project that there were no ethical implications related to the Tidal-EC project; this was monitored during the project and no changes were identified.

Finally, the project has engaged with a wide mix of organisations and groups, including public bodies, policy makers and government, particularly during the various dissemination activities.  All of these groups will benefit from the improved reliability of tidal turbines, i.e. it enables a clean, secure, efficient and carbon-free energy system.  This in turn will safeguard jobs and create many new employment opportunities for the sector as confidence grows to construct future tidal turbine arrays in addition to current projects such as MeyGen.  The project has also involved dissemination by beginning teaching of this subject matter through the academic institution participating in the project.  This is an important part of the project’s corporate social responsibility (CSR) to educate and benefit present and future generations of the European Community.

## 4.3 Main Dissemination Activities

### 4.3.1 Plan for the Use and Dissemination / Exploitation of the Foreground

To ensure that all created knowledge generated by the project is managed, disseminated and exploited in a coherent and coordinated manner, a plan for the foreground dissemination and exploitation has been developed over the lifetime of the project.  This plan has been published in the form of a deliverable report (D1.4). The creation of this plan ensures that all technical activities, legal aspects and other issues are managed in an effective way.

### 4.3.2 Publication / Dissemination of Project Findings

The TIDAL-EC consortium has used a range of media to disseminate the project activities. These media routes have been outlined and discussed during the regular project consortium meetings, as well as being included in the plan for foreground dissemination and exploitation. Deliverable D6.4 summarises the work carried out during the project regarding the publications and dissemination of the project findings. A summary of the main activities are detailed in Table 1.

**Table 1: Summary of dissemination activities covered by the TIDAL-EC consortium to date**

| Type of dissemination | International Outreach Yes/No | Number of Outputs | Consortium Members involved (number of outputs) |
|---|---|---|---|
| Invited speeches / presentations (including keynote presentations at conferences) | Yes | 8 | UEDIN (3), ORE Catapult (5) |
| Website | Yes | 1 | All (1) |
| Press releases | Yes | 5 | Tocardo (2), Minesto (2), Oceanflow (1) |
| Video | Yes | 1 | Tocardo (1) |
| Brochure | Yes | 1 | ORE Catapult (1) |

Table 1 provides a breakdown of the type of dissemination activities carried out by the consortium members. It should be noted that as the testing of the Tocardo device was only completed in Month 29 of the project, the final data has only just been analysed and so, the main project results are yet to be disseminated. Future dissemination post-project is also expected.

#### 4.3.2.1 Internal and External Communication

Internal communication for the TIDAL-EC project was set-up using a secure web portal called SharePoint. This tool has been used by all of the project partners to share/store data, work package information, project deliverables and to disseminate project findings internally.

External information relating to the project was disseminated first via the creation of a public website for the project. The site can be found by following this link www.tidalecfp7.eu. This informative website is targeted at the general public and other interested parties. It has been updated regularly to publicise the progress made on the project.

All of the public deliverables have been published on the website, with the agreement of the consortium. This publishable summary document will also be uploaded to the website, once approved.

#### 4.3.2.2 Technical Papers and Published Articles

As mentioned in Table 1, a variety of presentations have been given during the project, some of which were for technical industrial / academic conferences. These include:

- Mejoramiento de la eficiencia en aero-generadores y turbinas de corrientes marinas", Echenique, JP., Mueller, Markus, Wave and Tidal Energy – Research Collaboration Workshop, Santiago, Chile, 11th May 2015.

- "TIDAL EC and Accelerated Life Cycle Testing", Dr Mark Knos, UK Magnetic Society's Electromagnetics in Renewable Energy Generation, Edinburgh, 8th July 2015.

- "Tidal EC Cutting Edge R&D", Dr Mark Knos, Tidal Today's International Tidal Energy Summit (ITES) 2015, London, 24th – 25th November 2015.

- "TIDAL-EC Cutting Edge R&D", Dr Mark Knos, RenewableUK's International Conference on Ocean Energy 2016, Edinburgh, 23rd – 25th February 2016.

- "The interaction between waves and offshore renewable energy", Dr Mark Knos, International Centre for Mathematical Sciences (ICMS) Trapped waves and wave radiation in fluid mechanics, Edinburgh, 18th – 22nd July 2016.

- "Optimising Tidal Technology", Dr Mark Knos, Scottish Renewables' Marine Conference & Exhibition, Inverness, 12th - 13th September 2016.

- "Increasing Annual Energy Yield by Minimisation of Electrical Losses", Estanislao Juan Pablo Echenique, Energy Networking – Edinburgh University & CDC Scotland Ltd, Edinburgh, UK, 8th February 2017.

- "Optimisation of power take-off (PTO) in tidal turbines", Juan Pablo Echenique, Professor, Markus Mueller, Dimitrios Papaoikonomou, All-Energy, Glasgow, UK, 10th May 2017.

#### 4.3.2.3 Events

A number of high-profile events have been attended during the course of the project. These include:

- International Tidal Energy Summit (ITES) 2015, November 2015, London, UK

- International Conference on Ocean Energy 2016, February 2016, Edinburgh, UK

- Scottish Renewables Marine Conference & Exhibition, September 2016, Inverness, UK

#### 4.3.2.4 Academic Collaborations

There has been interaction with academia through the following events:

- Wave and Tidal Energy – Research Collaboration Workshop, May 2015, Santiago, Chile - organised by la Escuela de Ingeniería de la Pontificia Universidad Católica de Chile

- Trapped waves and wave radiation in fluid mechanics, July 2016, Edinburgh, UK – organised by International Centre for Mathematical Sciences (ICMS)

- Energy Networking – Edinburgh University & CDC Scotland, February 2017, Edinburgh, UK – organised by Energy Thrive Networking

## 4.4 Exploitation of Results

In order to be able to identify and track the main innovative results generated by the project, a template was distributed to all partners. The partners have completed the template for each identifiable project result and the completed forms have been compiled to form the TIDAL-EC Knowledge Portfolio. In turn, the Knowledge Portfolio has been used to identify the project's foreground. Once the foreground was identified, the discussion of the consortium focused on the protection of the foreground intellectual property (IP) and Intellectual Property Rights (IPR).

The consortium has referred to the Convention Establishing the World Intellectual Property Organization (1967) and acknowledges that intellectual property relates to items of information or knowledge, which can be incorporated in tangible objects at the same time in an unlimited number of copies at different locations anywhere in the world. The property is not in those copies but in the information or knowledge reflected in them. Intellectual property rights are also characterised by certain limitations, such as limited duration in the case of copyright and patents.

According to the TIDAL-EC Consortium Agreement, which all of the project partners signed up to, the consortium agreed that "the RTD Performers agree to transfer ownership of the Project Results to the SME Participants". In other words, the Beneficiaries and the Project Coordinator agree that the Project Results shall belong solely to the SME Participants who, as part of this transfer of ownership will honour the obligations under the EC Grant Agreement, in particular regarding the granting of Access Rights, Protection, Use and Dissemination of the Foreground.

Based on the information above and the identified project results, of which there are currently six, the foreground intellectual property has been classified as one of the following items: patent, copyright, trade secret or utility model. Due to the confidential nature of the identified project results, they cannot be explained in more detail in this report, however, the following section gives a high-level summary of various partners' activities.

### 4.4.1 Minesto

Minesto expects to feed the results of the TIDAL-EC project into the ongoing H2020 project PowerKite, of which Minesto is a part (http://powerkite-project.eu/). The overall objective of the PowerKite project is to gather experience in open sea conditions to enhance the structural and power performance of the PTO for a next generation tidal energy converter to ensure high survivability, reliability and performance, low environmental impact and competitive cost of energy in the (future) commercial phases. The project has a budget of 5.1M Euros and gathers nine partners from three countries.

The understanding of the reliability of the PTO system gained in the TIDAL-EC project is helpful in Minesto's development of its Deep Green technology. In particular, the knowledge gained can inform design choices leading to a lower levelised cost of energy (LCOE). An accurately forecasted LCOE is key in Minesto's work of attracting funding from current owners, new private investors as well as from national and regional authorities.

In the H2020 project PowerKite the results from TIDAL-EC could be useable as inputs particularly in the following tasks: T1.2 (generator and converter modelling), T4.2 (power conversion optimisation), and T5.2 (maintenance schedule).

### 4.4.2 FiberSensing

The outcomes from the TIDAL-EC project will be used as the starting point for the development of a monitoring solution for tidal turbines. In order to achieve that solution, financing will be sought by seeking direct contracts with the tidal manufacturers.

### 4.4.3 Tocardo

TIDAL-EC project results can be considered to have an important role in Tocardo's technology de-risking policy as well as in strengthening of Tocardo's business model and plan. PTO Testing results can be exploited to not only to optimize the technology but also to facilitate the aim to achieve Type Certification for the upgraded T2s turbine in early 2017. The latter will in turn promote and build confidence amongst investors and insurers, enabling thus a decrease in a project cost of capital.

The majority of the project results are theoretical electrical and thermal models. However there is a number of innovative technical concepts developed directly via research activities such as the two PMG concepts designed in D5.2. Moreover, a portion of the work performed by the RTDs proved the hypothesis of the T3's superior thermal performance compared to T1 and T2. T3 holds a significant role in the Tocardo's Technology development planned up to 2020.

Four main sets of financing routes have been identified:

- Loans from Banks
- Equity investors
- Feed-in tariff system
- Subsidies and grants
- Company's own investment out of profits form a commercial projects

Due to the fact that development of either the T3 and/or the air cored PMGs in D5.2 constitute essentially research and development projects using debt (loan) or finding an investor do not seem viable options. Moreover, a feed-in system is considered rather inappropriate for supporting projects in an R&D or pilot phase. Therefore, the preferable route to fund these developments can either be via own profits and/or by grants and subsidies.

Grants can be made available via the following ways:

- Via the European Union participating in a project of the Horizon 2020 program at which various SMEs and RTDs will cooperate
- Via indirect public funding from intermediary organisations such as:
    - The NL Agency
    - The Netherlands Organisation for Scientific Research (NWO)
    - The Foundation for Fundamental Research on Matter (FOM)
    - Various government ministries

### 4.4.4 Oceanflow

Oceanflow has been able to build and deploy technology demonstrator projects with the aid of EU Regional Development Funds supporting community energy generation projects. Such funding is now drying up in the UK and the company's recent focus has been to develop regional research projects with European academic bodies that can continue to source funding to advance the development of tidal stream turbine technology. Currently Oceanflow is providing its small 1:10th scale Evopod turbine into the SCORE research project being run by the University of the Algarve and Oceanflow is a party to other Atlantic Area research applications of a similar nature.

# 5 Project Website and Contact Details

## 5.1 Website

A project website has been set-up which contains basic information about the TIDAL-EC project (www.tidalecfp7.eu). In addition to this public website, all consortium members have access to a private SharePoint web portal, where confidential information about the project is shared.

## 5.2 Contact Details


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