Integration of a Direct Drive Contra-Rotating Generator with Point Absorber Wave Energy Converters

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Abstract—**Wave energy converters (WECs) produce reciprocal motion which requires a complex power transfer and take-off system to generate the rotary motion necessary to drive an electrical generator. These systems are often expensive and unreliable, and can introduce considerable power losses reducing the efficiency of the device. This study investigates the application of a direct drive contra-rotating generator (DD-CRG), originally designed for the tidal energy industry, to a generic point absorber wave energy converter. The contra-rotation of the generator facilitates lower torque and higher speed inputs compared to a conventional direct drive generator, reducing the size, weight and cost of the power take-off system. It was found that the existing generator design was technically and physically compatible with the point absorber device. Furthermore the wave energy application enabled optimisation of the generator design to increase the generator speed and further reduce the applied torque. This led to a significant reduction in the levelised cost of energy of at least 20% compared to using a conventional hydraulic drivetrain in the same device. Adoption of the DD-CRG within the wave sector would bring additional benefits due to its tailored design for the marine environment, and further cost reductions could be realised through the increase in manufacturing volume.**

Keywords— **Direct drive; Contra-rotating generator; Power take-off; Point absorber; Technology transfer; Wave energy converter**

I. INTRODUCTION

Wave energy is a promising renewable energy technology currently under development that has the potential to contribute towards de-carbonising the economy in the drive to meet the targets set by the United Nations in the Paris Agreement [1]. However, existing wave energy converter designs require significant reductions in capital costs and improvements in reliability to become commercially viable. One aspect needing attention is the power take-off (PTO) solution. These systems can suffer from low efficiency and are susceptible to component wear due to the challenging marine conditions.

This paper investigates whether technology used in the tidal energy industry, which is at a more advanced stage of development, can be transferred to the wave energy sector in order to realise the benefits already established in this related field.

These benefits include the adoption of designs that are simpler and more robust because they have been built specifically for the marine environment. This coincides with lower maintenance requirements, and established installation and maintenance procedures. The use of the same technology across the tidal and wave sectors will also lead to cost reductions through greater volume of manufacture.

Similarly to the tidal sector, wave energy converters produce power in the low speed, high torque range, so transferring the technology between the two fields should only require minimal redesign, and the fundamental working principles should not need to be altered.

Fig. 1 The CoRMaT tidal turbine of Nautricity

The direct drive contra-rotating generator adopted by Nautricity Ltd. is an example of a system designed specifically for the tidal energy application with the marine environment in mind. The design encompasses simplicity through the direct drive configuration, made possible by rotating both the rotor and stator simultaneously with contra-rotating rotors aligned in the streamwise direction, see Fig. 1. This doubles the generator speed and halves the torque transmitted, thereby reducing the amount of electro-magnetic material needed in the generator. Therefore, significant cost and weight savings are made compared to a standard direct drive system, while maintaining the advantages of a simple, robust design.

This paper investigates whether this DD-CRG technology can be transferred to the wave energy sector to realise similar benefits in cost and weight reduction, and improve the reliability of the power take-off system through the introduction of a simple, robust and low maintenance PTO system.

While a number of WEC types were considered in this project to test the feasibility of transferring this technology, the focus of this paper is to show how the DD-CRG can be applied to a generic point absorber device. The objective is to establish how the generator would be integrated into a PTO system within the point absorber, and to assess the potential technical and economic benefits of adopting this system. The point absorber was chosen because it has been one of the more widely adopted designs in the industry, and is currently at a higher technology readiness level than some of the other device types. Discussion of integration of the DD-CRG with other WEC architectures, such as oscillating water columns is given in [2-4].

A. The contra-rotating generator

The DD-CRG was originally designed at the University of Strathclyde [5], and is currently operating at prototype scale within the CoRMaT tidal energy converter of Nautricity Ltd.

Unlike conventional generators which have a single unidirectional rotating section (rotor), the contra-rotating generator drive is applied to both the rotor and stator. The stator rotates in the opposite direction to the rotor, giving twice the speed of rotation, and halving the applied torque. Therefore, low speed, high torque inputs can be accommodated directly, mitigating the need for a gearbox. Compared to a conventional direct drive generator, the speed increase halves the size, weight and cost of the electro-magnetic components. Consequently a smaller, lighter generator can be connected directly to the rotors, see Fig. 1 and Fig. 2.

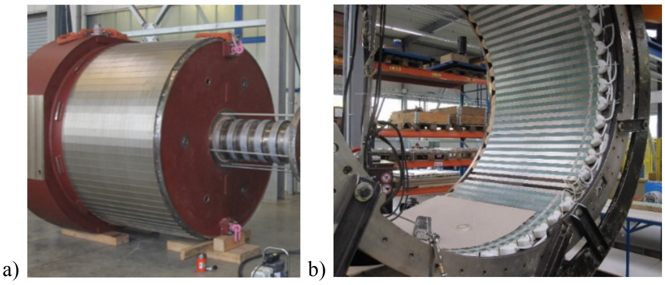

Fig. 2 The direct drive contra-rotating generator developed for Nautricity's 500 kW tidal turbine a) rotor b) stator

The work undertaken to date began with the build and testing of an axial flux, permanent magnet generator for the tidal energy application to a capacity of 10 kW, successfully demonstrating the technology in large-scale tow tanks and in-sea testing ([5]). This design was then scaled up to a 500 kW device which was tested at the European Marine Energy Centre (EMEC) in 2014 to show successful operation at prototype scale ([6]). The device is currently undergoing a second period of testing at EMEC including full grid connection, which if successful will demonstrate technology readiness at the highest level.

Through this sequence of testing the DD-CRG has demonstrated considerable cost and weight reductions of the PTO components. The device was built specifically to cope with the harsh marine environment in terms of its operability in seawater and managing the associated water proofing and corrosion aspects. This, in tandem with the simplicity of the design has resulted in a reduction in maintenance requirements leading to an increase in device availability ([5]).

Nautricity's 500 kW turbine design currently uses a radial flux permanent magnet generator. The 500 kW DD-CRG has its maximum efficiency point (96%) when working at rotational velocities of 15 rpm for each of the rotor and stator. At this point, the generator can work with torque values of about 158 kNm. The generator specifications as built for the tidal energy application are detailed in Table I.

TABLE I
DD-CRG GENERATOR CHARACTERISTICS FOR TIDAL ENERGY TECHNOLOGY

Parameter	Value
Rated power (kW)	500
Generator torque (kNm)	158
Rotor/stator rotational velocity (rpm)	15
Relative speed of stator and rotor (rpm)	30
Radius of rotor/stator (m)	1.1
Length of generator (m)	1.8
Weight of generator (tonnes)	17

The high torque, low speed parameters for the optimum point of operation of the generator provide a good starting point for testing the feasibility of application of this technology to the similar field of wave energy. However, if a suitable match with the WEC motions cannot be achieved with these parameters (Table I), the generator parameters can be adjusted to suit the specific characteristics of the wave energy converter. This will result in a change in the size and weight of the generator as the amount of electro-magnetic material is altered, but will not result in any fundamental design changes.

B. Point absorbers and their PTOs

To test the feasibility of adopting the DD-CRG within wave energy technology, the point absorber type WEC has been chosen. A point absorber consists of a floating body connected to a secondary submerged float or a seabed mounted structure. Wave motions cause the main float to oscillate in heave, creating relative motion compared to the secondary structure for power take-off. The main float oscillations are synchronised with the wave period (usually in the range of 5-10 s), so the resulting forces and velocities of the body can be converted into torque and rotational velocity values that are well suited to the DD-CRG requirements (low speed, high torque). The linear motion (heave only) of this type of WEC also enables a simple drivetrain configuration to be adopted at this first stage of analysis.

Point absorbers are the most prolific type of wave energy converter currently under development ([7]). Approximately 40% of the wave energy research effort can be attributed to this device type ([8]). Demonstrating the DD-CRG in this device, therefore, should ensure the findings of this study are highly relevant to a number of developers.

There are a wide range of configurations of point absorber WECs in terms of their size and scale, geometry, and interaction mechanisms between the two bodies. There are devices at all stages of TRLs including several that have been sea-tested. These include the PowerBuoy by Ocean Power Technologies, the Seabased WEC, and the WaveBob WEC.

The different point absorber designs have included a variety of PTO mechanisms. Seabased's device uses a direct drive linear generator. Although linear generators are a promising technology and have the benefits of a direct drive system, the technology is relatively new to this application and further development is required to successfully transfer the technology ([9]).

WaveBob, AquaBuOY and IPS Buoy among others have employed hydraulic PTO systems. These consist of a pumping module that uses the linear motion of the device to drive a piston to pressurise fluid. The pressurised fluid is stored in accumulator tanks to smooth fluctuations in the input power from the waves. The latter enables a standard, high speed generator to be spun by a hydraulic motor, which converts the pressure energy into kinetic energy. The use of a standard generator reduces the weight of the drivetrain. This system also has the advantage of consisting entirely of off-the-shelf components. However, the number of components increases the maintenance requirements ([10]). The number of energy conversions through the system reduces the efficiency, and there are some environmental concerns in terms of the type of hydraulic fluid used, should it leak into the surrounding environment.

Mechanical PTO systems have also been used in point absorbers. For example, the PowerBuoy employs a rack and pinion mechanism to convert the linear motion of the float to rotary motion to drive a generator. With the addition of a gearbox to increase the rotational speed, a lighter, cheaper generator can be used. However, the addition of a gearbox significantly increases both the maintenance effort and the risk of failure.

This is evidenced by considering the related field of offshore wind, where gearboxes have been associated with some of the highest repair times and repair costs, and the greatest number of major replacements compared to other turbine components ([11]). Furthermore, [11] showed that there is a correlation between turbine failure rates and wind speed. With the even higher forces experienced in the wave energy application, the failure rates can be expected to be more severe, and gearbox failures will constitute a significant proportion of the maintenance costs. Recognition of the shortcomings of employing existing off-the-shelf gearbox systems within WECs is demonstrated by an increase in custom design solutions which are currently in the early stages of development e.g. [12].

The DD-CRG has the potential to facilitate a much simpler drivetrain configuration compared to the existing hydraulic or mechanical systems by mitigating the need for a gearbox. This makes it likely that the DD-CRG could increase the efficiency of power transfer in these devices while significantly reducing device costs, maintenance effort and risk of failure.

C. *Linear to rotary motion conversion*

As the point absorber WEC produces reciprocating linear motion, and the DD-CRG requires rotational motion to drive it, thought needs to be given as to how to convert the WEC motions to suitable inputs for the DD-CRG, in terms of an appropriate drivetrain design.

In the tidal energy application turbines are employed to transfer power to the generator, but this method has been found to be inefficient as a power transfer system in point absorbers ([13]). Therefore, other methods for direct connection of the float to the generator need to be considered, as the design of the DD-CRG should mean that a gearbox is not required.

There are a number of mechanical systems designed to convert linear to rotary motion. These include chain and belt drives, rack and pinion systems and cranks. A review of these is given in [3].

Selection of the most suitable system will depend on matching the drive specifications to the wave energy application, considering the maximum forces, maintenance procedures, cost and weight. However, the rack and pinion system will be selected at this first stage of analysis to simplify the modelling procedures.

II. METHODOLOGY

One generic point absorber design was chosen to demonstrate the feasibility of transferring the DD-CRG technology to point absorber WECs in this preliminary study. This does not mean that the DD-CRG wouldn't be compatible with other designs. In fact, as the motions of other point absorber devices will be in a similar range to the example device used in this paper, if follows that the results should be equally applicable to a range of devices. Although, some tailoring of the PTO design may be necessary to ensure optimum performance.

The point absorber studied in this project is based on the design of [14], and was chosen due to the availability of the necessary technical and economic data. The hydrualic PTO system analysis published in [15, 16] for this device also provides a benchmark for comparison with the proposed DD-CRG PTO system.

The device is shown in Fig. 3. It consists of a float that moves against a spar connected to a heave plate. The spar and heave plate are designed to stay relatively stationary, while the wave motions move the float up and down at the water surface. The WEC is designed for the PTO system to be housed in the spar section. The design and dimensions of the device, shown in Fig. 3, represent a simplified design suitable for this prelimnary feasibilty study. Consequently this device should not be considered as a fully optimised system.

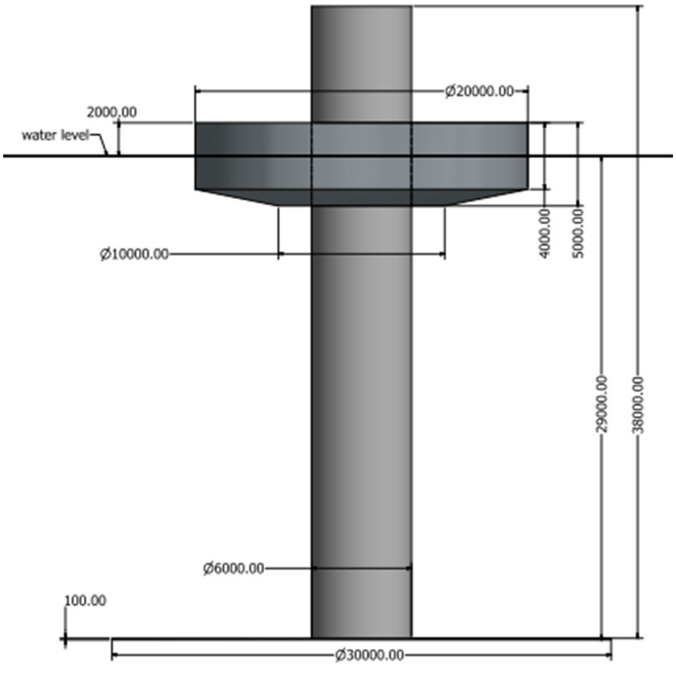

Fig. 3 Generic point absorber design of [14] consisting of a float, spar and heave plate. The position at which the device sits in the water column is also marked

To assess the feasibility of integrating the DD-CRG with this point absorber device, the motions of the WEC need to be modelled to quantify the WEC velocity and the forces that will be transferred to the generator. Consideration then needs to be given to the drivetrain design to determine how to transfer the captured power to the DD-CRG. The existing prototype specifications for the DD-CRG shown in Table I will be used to determine if its power, torque and speed requirements can be matched directly. Optimisation of the DD-CRG for the wave energy application will then be considered to ensure the full benefits are realised. Finally, a preliminary assessment of the cost of the PTO system will be made and compared with the cost and energy capture of an existing hydraulic PTO system to assess the economic benefits that the DD-CRG can bring to the wave energy sector.

A. Modelling the WEC motions and forces

The open source simulation tool WEC-Sim developed by the National Renewable Energy Laboratory (NREL) and Sandia Corporation, [17], was utilised in this project to model the WEC motions and forces. The code operates in MATLAB using Simulink routines to solve the multi-body dynamics of WECs in the time domain.

The hydrodynamic coefficients required as inputs to the WEC-Sim model were obtained using the open source boundary element method code Nemoh developed by [18] which also runs in MATLAB.

At this preliminary analysis stage a number of simplifications were made to the modelling to enable a wider range of parameters to be considered within the time frame. Mooring forces were omitted and only regular waves were run. Power take-off was modelled simply by inclusion of a linear damping force.

B. Wave conditions

To ensure that the WEC motions were representative of typical and extreme operating conditions a number of wave cases were selected to include in the analysis. These were based on data presented in [19] and [20] from EMEC and the North Sea. These sea states were simplified to regular waves for an initial characterisation of the WEC. Table II depicts the wave parameters used to study the point absorber.

TABLE II
WAVE PARAMETERS USED FOR THE PREDICTION OF POINT ABSORBER MOTIONS, BASED ON DATA FROM EMEC AND THE NORTH SEA

Case	Location	T (s)	H (m)
C1	EMEC	6.5	1
C2	EMEC	12	4
C3	North Sea	7	2
C4	North Sea	11.2	5

C. Integrating the DD-CRG with the point absorber

Once the forces and velocity associated with the point absorber have been calculated, these need to be converted via the mechanical linkages of the drivetrain (in this case rack and pinions) to torque and rotational velocity inputs to the rotor and stator of the DD-CRG.

Simplified calculations that assume no losses in the mechanical linkages were used to obtain initial estimates of the torque and rotational velocity transferred. Rack and pinions are employed in this study, although as discussed in Section IC other systems may also be suitable. Rack and pinions are typically 98% efficient so the assumption of no losses is not unreasonable.

In this ideal case, the torque and angular velocity of the pinion can be related to the radius of the pinion and the input linear force and velocity (transmitted from the float to the rack) as follows:

$$\tau_p = r_p F_{rh} \quad (1)$$

$$\omega_p = v_r / r_p \quad (2)$$

where τ_p is the torque transferred to the pinion, r_p is the (effective) radius of the pinion, F_{rh} is the relative heave force between the point absorber float and spar generated by the waves, ω_p is the angular velocity of the pinion, and v_r is the relative linear velocity between the float and spar of the point absorber.

In order to improve the match between the force and velocity of the WEC and the generator torque, rotational velocity and power requirements, the diameter of the pinion attached to the drive shaft of the generator can be varied. In this way it can be determined if the existing generator design (Table I) is suitable for direct integration with the point absorber. Secondly, optimisation of the generator parameters is considered in order to improve the compatibility with the point absorber.

For each wave condition modelled, the maximum force, maximum velocity and maximum power within one wave cycle will be used to determine the maximum torque, rpm, and power transferred to the generator. The maximum values are focused on to understand the compatibility of the generator at its limits of operation. It is not the aim at this stage to conduct a full optimisation study taking into account operation throughout the wave cycle.

Neither is a full model of the generator included. Instead the damping force is varied in the analysis to get an idea of the influence that the DD-CRG would have on the WEC motions. In reality the PTO damping would be controllable via a power conditioning system and so it is reasonable to model the generator in this way during this initial analysis.

D. Costing methodology

The final stage of this feasibility study is to assess the cost of the proposed drivetrain in order to make a preliminary assessment of the potential for cost reduction by using this technology compared to existing systems. The benefits can be made clear by benchmarking against a conventional drivetrain design applied to the same point absorber device. The analysis of [15, 16] will be used which focuses on a hydraulic drivetrain. To make this a fair comparison the mass and cost of the systems are first compared with respect to their rated capacity to account for differences in the device ratings.

To extend this comparison to take into account the actual power produced by each PTO system, the annual energy capture is calculated. The energy capture of the point absorber with the DD-CRG was estimated by simplifying sea state data from the North Sea given in [20], to sets of regular waves with height equal to the significant wave height and period equal to the peak wave period, and factoring in the occurrence level in each case (Table III). Device availability of 85% and efficiency of 85% were then applied. Note that as the device design was not optimised for these wave conditions, the energy capture can be taken as a conservative estimate, assuming the availability and efficiency parameters are appropriate.

The energy capture per cost of the PTO systems are compared in terms of the levelised cost of energy (LCOE) so as to be in a standardised format. The Carbon Trust's methodology [21] for calculating LCOE for marine energy devices was adopted for this analysis. This methodology was devised for comparing the costs of wave and tidal devices at various stages of development during The Carbon Trust's Marine Energy Challenge (MEC) and is now considered a standard framework for assessing and comparing the costs of marine energy converters. An 8% discount rate was used in the analysis (this compares with 7% for the hydraulic drivetrain analysis of [16]).

The resulting LCOE should not be considered a final value. It is presented purely for comparison of the two drivetrain options at prototype scale, with similar costs set for the other aspects not related to the PTO system. It does not take into account the potential reductions in LCOE due to optimisation of the point absorber structure itself or refinements applied to other aspects such as the moorings, installation procedures etc.

TABLE III
WAVE PARAMETERS USED FOR THE PREDICTION OF ANNUAL ENERGY CAPTURE FOR THE POINT ABSORBER

Wave height (m)	Wave period (s)	Annual occurrence level (%)
1	5.6	46.8
2	7.0	22.6
3	8.4	10.8
4	9.8	5.1
5	11.2	2.4

III. DESIGN ANALYSIS RESULTS AND DISCUSSION

The results from the WEC-Sim analysis of the point absorber device are discussed in Section IIIA to understand the operating range of the device. These results are then used to assess the feasibility of integrating the DD-CRG with the device in terms of providing an appropriate match with the generator inputs at rated power in Section IIIB. The options for re-designing the DD-CRG for the wave energy application to improve its compatibility are also considered. A preliminary design of the drivetrain is then presented (Section IV), to determine the dimensions and weight of the system and availability of off-the-shelf components. Finally the benefits of the proposed system are discussed and the drivetrain is costed and compared with a hydraulic system in Section V to fully quantify the potential benefits of transferring this technology to the wave energy sector.

A. Establishing the WEC motions

In Fig. 4 the WEC-Sim computations of the maximum instantaneous velocity, heave force and power per wave cycle, obtained from the relative motion between the float and spar of the point absorber are presented. The maximum values of these parameters do not necessarily occur at the same time during a wave cycle, as the phasing depends on the level of damping, but it is important to understand what the maximums of each of these parameters are separately in order to check for compatibility with the maximum torque, speed and power specifications of the generator (Table I), and for suitable sizing of the drivetrain components (Section IV). The results in Fig. 4 cover a range of wave periods, for two wave heights at different damping levels, and also encompass two of the cases shown in Table II (case 3 and case 4) to ensure applicability to field conditions.

Firstly considering the non-damped cases in Fig. 4, the curves for the two wave heights follow a similar shape with a peak at a wave period of about 5 s, with a significant reduction in power, force and velocity at longer wave periods. This results in the power for the 2 m wave case 3 actually exceeding that for the 5 m wave case 4, because for case 3 the wave period is much closer to the peak in the curve than that in case 4.

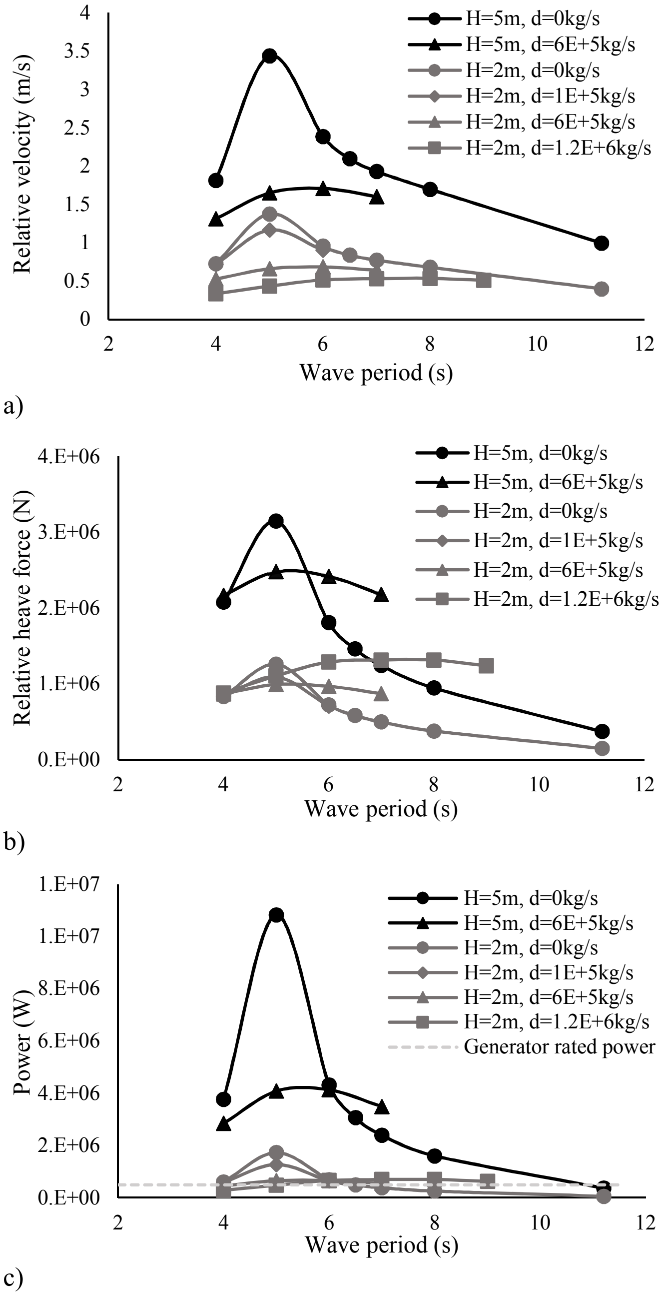

Fig. 4 WEC motions for a range of wave conditions and damping levels a) maximum relative velocity per wave cycle b) maximum relative heave force per wave cycle c) maximum power per wave cycle

In Fig. 4 the wave conditions close to the peaks in the curves for the non-damped cases result in the power exceeding the generator rated power. However, larger wave heights tend to correlate with longer wave periods so it would be unlikely that the cases around the peak of the 5 m wave, at much shorter wave periods would occur very regularly. Cases near the peak period for the 2 m wave would be more likely to occur, although for the case studies 1-4 (Table II), the wave periods are longer than the peak period in the curve, and hence power is reduced below the generator rated value.

It should also be noted that for waves with a very short period compared to wave height wave breaking will occur, dissipating the available energy. The wave breaking limit will affect the 5 m wave for periods from about 4.8 s and lower so the values on the left hand side of the graph for this wave height are not realistic. They are plotted only to give an idea of the theoretical trends and the placement of the peak wave period.

The second aspect to consider in Fig. 4 is the effect of damping on the relationship between wave period and maximum power, velocity and force. Four different damping values are plotted for the 2 m wave, and two values of damping are plotted for the 5 m wave. It is clear in Fig. 4 that damping changes the peak wave period. The peak period increases with the damping level, but the height of the peak reduces, so that the curve is much flatter over the range of wave periods for the higher damping values. This also means that for some sections of the graph the power is increased when damping is applied. The effect of damping is clearly complex, depending on wave period. For example, at the peak period for the 2 m wave increasing the damping results in a decrease in power but at longer periods increasing the damping actually increases the power. This gives an indication of the potential for optimisation of the PTO system through control of the damping force.

B. *Transferring the WEC motions to the DD-CRG generator*

As with the tidal energy application, the idea with the DD-CRG is to make use of the contra-rotation to reduce the torque input to the generator thereby reducing its size and cost compared to a conventional direct drive generator. Therefore, the aim when transferring the WEC motions quantified in Section IIIA to the generator is to utilise both the rotor and stator in tandem, thereby halving the torque and doubling the rotational speed compared to having only one side of the generator connected to the WEC as in a standard model.

As discussed in Section IC rack and pinion systems were chosen to transfer the WEC motions to the generator in this initial study. Following this methodology, the results of transferring the WEC motions for each of the wave conditions from Table II to the generator are shown in Table IV. The maximum instantaneous torque, velocity and power per wave cycle are given. The torque and rotational velocity that generate the maximum power are also shown.

Firstly considering the four cases C1-C4 from Table II, at this stage with no damping applied, it is clear in Table IV that by adjusting the pinion diameter, appropriate torque and speed parameters are obtained for compatibility with the existing generator specifications from the tidal energy application. However, this requires a large pinion diameter, although this is still smaller than the dimensions of the generator (Table I).

In each of the cases C1-C4 the power delivered by the WEC to the PTO is considerably lower than the generator rated value. This is a consequence of using a generic point absorber design with generic wave parameters i.e. the point absorber design has not been optimised for the chosen wave characteristics.

To check the compatibility of the generator with the WEC motions closer to rated power of the generator, and more realistically by including damping, cases 5 and 6 in Table IV show the design for a case close to rated power selected from the results in Fig. 4, with and without damping applied (C5 and C6). It can be seen that the same pinion diameter as the other cases works for this un-damped case at the optimum power, but when considering the maximum velocity and maximum torque per wave cycle these are both higher than the optimum points for part of the wave cycle. This may be acceptable as the generator will be able to operate with temporary loading above design conditions but consideration needs to be given as to the likely effects of this on the generator performance.

These results are promising, as they show that in general a wide range of regular wave conditions can be accommodated with a single pinion diameter, without needing additional damping control.

The damped case C6 also shows full compatibility with the generator requirements, with a smaller pinion diameter. Note that in this case the damping has resulted in a phase shift so that the maximum velocity and maximum force per cycle occur approximately at the same time, and hence produce the maximum instantaneous power input per wave cycle.

TABLE IV
TRANSFER OF WEC PARAMETERS TO SUITABLE GENERATOR INPUTS AT POINT OF MAXIMUM POWER PER WAVE CYCLE FOR THE WAVE CONDITIONS DESCRIBED IN TABLE II AND UNDAMPED AND DAMPED CASES CLOSE TO RATED GENERATOR POWER. MAXIMUM VELOCITY AND HEAVE FORCE PER CYCLE ARE ALSO SHOWN

Parameter		**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Relative heave force (kN)	At max power	207	353	264	168	580	1109
	Max per cycle	292	497	370	236	818	1109
Relative heave force per DD-CRG side (kN)	At max power	104	177	132	84	290	554
	Max per cycle	146	249	185	118	409	554
Pinion radius(m)		0.54	0.54	0.54	0.54	0.54	0.28
Torque input to DD-CRG (kNm)	At max power	56	95	71	45	157	158
	Max per cycle	79	134	100	64	221	158
Relative (vertical) velocity of WEC (m/s)	At max power	0.30	0.55	0.71	0.49	0.83	0.45
	Max per cycle	0.42	0.77	0.99	0.69	1.17	0.45
Angular velocity of each pinion (rad/s)	At max power	0.56	1.02	1.31	0.91	1.54	1.57
	Max per cycle	0.78	1.43	1.83	1.28	2.17	1.57
rpm of each pinion	At max power	5.3	9.7	12.6	8.7	14.7	15.0
	Max per cycle	7.4	13.6	17.5	12.2	20.8	15.0
Max. inst. power input to DD-CRG/ cycle (kW)		62	194	187	83	483	493

C. *Optimising the DD-CRG generator for the wave energy application*

The results in Section IIIB were constrained to matching the WEC inputs with the parameters of the existing DD-CRG prototype design for the tidal energy application.

Since the drivetrain includes a mechanism for linear to rotary motion conversion this provides control of how the force and velocity are converted to torque and rotational velocity through the sizing of the pinion, as discussed in Section IIC. Therefore, the design does not have to be constrained to the velocity and torque described in Table I for the existing DD-CRG design.

In fact it is desirable to reduce the torque and increase the rotational velocity in order to reduce the amount of magnetic material in the generator, the removal of which will facilitate weight, size and cost reductions in the generator design.

This will also allow a reduction in size of other components of the drivetrain due to the reduction in torque, further decreasing the cost and weight of the system. The exact reduction in torque depends on the design of the rack and pinion or other drive system, which is discussed in Section IV.

The disadvantage of redesigning the generator is that it potentially reduces the possibility of bulk production across the wave and tidal sectors. However, by assuming a modular approach to the design and construction of the generator, it should be possible to accommodate either a range of set designs, or fully adjustable designs depending on the torque and speed requirements for a given device, as these parameters do not affect the fundamental operating principles of the generator.

IV. PRELIMINARY DRIVETRAIN DESIGN AND COSTING

In this section the linkages between the float and the generator are defined in a more practical sense to present a preliminary design for the PTO system, and demonstrate that a compatible system can be constructed, that it fits within the given dimensions, and that its weight is not a constraint i.e. it is not so heavy that it would affect the WEC motions substantially.

It is also the aim to find off-the-shelf components that are suitable, to demonstrate that a supply chain would be available, to obtain realistic component costs, and to realise the benefits of using tried and tested components for which the performance characteristics and limitations are understood.

This analysis will be undertaken for the original generator design from the tidal energy application, and also for an optimised design for the wave application to compare the associated costs and weights of the systems.

As described in Section IIIB the drivetrain needs to consist of rack and pinion connections to both sides of the generator which operate simultaneously to halve the torque and double the speed inputs to the generator, thereby making use of the contra-rotating feature.

To maximise energy capture throughout a wave cycle a second pair of rack and pinion drives can also be inserted, with one on each side of the generator, to operate together during the opposite stroke of the float. Clutches need to be included between the pinions and the drive shaft to disengage each set of drives during the opposite stroke direction.

Fig. 5 shows a schematic of the preliminary design. Two drive shafts, each holding two pinions, are connected to each of the rotor and stator of the generator. A rack runs on each of the pinions. The float of the point absorber is connected to the top of each rack. The racks on either side of the generator operating within the same stroke of the float are connected on opposite sides of the pinions so that the motion of each drive shaft is in the appropriate direction (contra-rotation).

During the opposite stroke of the float, a clutch or freewheeling mechanism employed within the pinions prevents backwards rotation of the drive shaft. The addition of the second rack and pinion on each side of the generator, placed on the opposite side of the pinion compared to the first drive, enables the generator to continue to run in the required direction, as shown in Fig. 5.

This is the basic design that will be costed, as it enables off-the-shelf components to be selected. However, it is important to note the potential for custom drive solutions to be developed to remove the need for a double set of drives. For example, possibilities to run two racks on opposite sides of one pinion could be considered in conjunction with a clutch mechanism. Also other options such as belt and chain drives should be considered during the next stage of development as they may present the potential for further cost and weight reductions.

To size and cost the drivetrain design shown in Fig. 5, a set of requirements was determined using the analysis in Section III to enable appropriate selection of components to withstand the maximum forces and be compatible in terms of the dimensions of the system. These are summarised in Table V.

Table VI presents the components and number of units required for the conceptual design detailed in Fig. 5. The total mass and cost per item is listed. The mass and cost of the racks, clutches and bearings are based on the specifications and quotes obtained from manufacturers. Further details are given in [4]. The generator and control system costs were provided by Nautricity based on their prototype device. The costs for the drive shaft and structural connections to the float and spar were based on their estimated dimensions and the cost of steel, as off-the-shelf designs were not available. The pinion cost for the original (non-optimised) design was based on a quote for bespoke manufacture due to its large diameter compared to the off-the-shelf options.

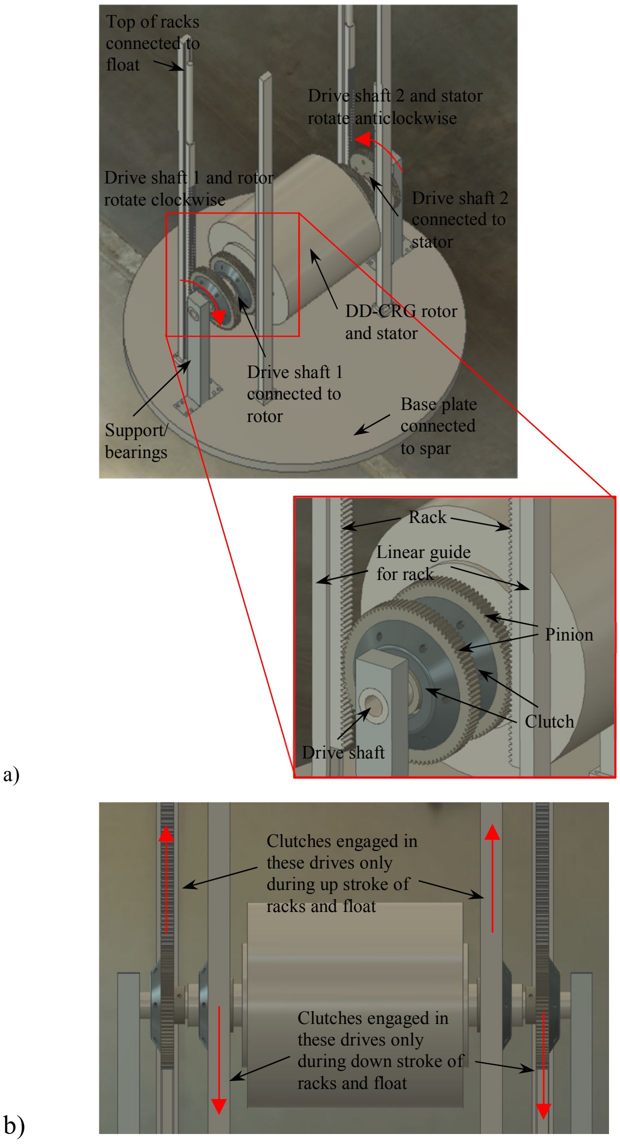

Fig. 5 Preliminary PTO system design for integration of the DD-CRG with the generic point absorber device a) overview of system components and rotation directions b) operating principle with arrows showing the stroke direction when each drive is engaged via the clutch connected to each pinion

For the optimised design the pinion diameter recommended by the manufacturer for the chosen rack was used. The optimised design is shown alongside the initial design based on the tidal energy prototype in Table VII. The optimisation has resulted in a torque reduction of over 70%, and an estimated cost reduction of about 60%. This is very significant and demonstrates the importance of optimisation of the PTO design for the wave energy application, and probably for specific devices should it be utilised in different WEC designs.

TABLE V
DRIVETRAIN SPECIFICATIONS AND DESIGN PARAMETERS

Parameter	Value
Pinion diameter (m)	1.1
Maximum torque for pinion (kNm)	200
Maximum force for rack (kN)	400
Maximum power transmitted by a rack (kW)	250-260
Maximum rpm for pinions	15-20
Total width of drivetrain (m)	< 6
Height of drivetrain (maximum stroke length) (m)	3.5-4

TABLE VI
DRIVETRAIN COMPONENTS SELECTION AND COST FOR ORIGINAL DD-CRG DESIGN (UNCHANGED FROM TIDAL ENERGY APPLICATION)

Component	No. of units	Mass orig. (kg)	Cost orig. (£)
Rack (1 m each)	16	1776	18208
Pinion	4	497	2288
Rotary clutch	4	3260	206600
Connection drivetrain - float	4	3000	18800
Drive shaft	2	734	3374
Bearings/ supports	2	200	60000
DD-CRG generator	1	10000	600000
Control system	1	2000	15000
Total:		21467	924270

TABLE VII
DRIVETRAIN ORIGINAL AND OPTIMISED DESIGN PARAMETERS

Parameter	Original design	Optimised design
Pinion radius (m)	0.55	0.116
Generator rpm each side	15	80
Generator torque (kNm)	168	45
Estimated mass (kg)	21467	9000
Estimated PTO cost (£)	924270	367670

In terms of the mass of the PTO system the original design represents about 2% of the mass of the spar and heave plate. Therefore, this is not expected to influence the WEC motions to a significant extent. Furthermore once the optimised design has been applied, this mass would be reduced by approximately 60%, further ensuring compatibility with the point absorber structure.

Considering the dimensions of the drivetrain design, the length of the spar means that there are no constraints in the vertical direction, so the racks can be sized to suit the stroke length of the float, see Table V. The width of the PTO system is constrained by the width of the spar. The original generator design is 2.2 m x 1.8 m, comfortably fitting within the 6 m diameter spar. This leaves ample room for the four rack and pinions to be attached. Again, these constraints are further reduced when considering the optimum design, where the generator dimensions are significantly smaller. This also makes it likely that the optimised design will be physically compatible with a wide range of point absorber designs.

V. COMPARISON OF DD-CRG AND HYDRAULIC DRIVETRAINS

To quantify the potential benefits of using the DD-CRG system within a point absorber WEC the costs detailed in Section IV are compared with those for a hydraulic drivetrain operating within the same point absorber, published in [15, 16]. To account for differences in the device ratings in the present analysis and that of [15, 16], the mass and cost are normalized by the device ratings to enable comparison, see Table VIII. The original, non-optimised PTO design is slightly heavier and more expensive per kW than the conventional hydraulic drivetrain. However, once the DD-CRG has been optimised for the point absorber both of these metrics are significantly reduced, with a saving of approximately 50% on the cost per kW compared to the hydraulic system. While this is a very promising result, at this stage it does not take into account the actual energy capture of the device, which is key to assessing the performance. This is covered in the following section.

TABLE VIII
COMPARISON OF DD-CRG AND HYDRAULIC DRIVETRAINS

PTO system	Rating (kW)	Mass/kW	Estimated Cost/kW for 1 unit
Hydraulic	286	40	1488
Orig. DD-CRG	500	43	1849
Opt. DD-CRG	500	18	735

A. LCOE (prototype scale) comparison

Using the methodology detailed in Section II, the total energy output per year for one point absorber device working with the DD-CRG system was estimated to be 754022 kWh/year.

To compare this with the hydraulic drivetrain, the LCOE was computed, and the results are given in Table IX. For one 500 kW prototype unit the DD-CRG system improves the LCOE compared to the hydraulic system by over 20%, and if considering the more un-conservative estimate, by over 50%. The difference in these estimates reflects the difficulty in accurately determining the various capital and operational costs associated with the device. Full details of these issues and rationale for the LCOE figures are given in [4].

This demonstrates that the DD-CRG has the potential to reduce the LCOE considerably compared to a conventional PTO system. The DD-CRG can also bring the benefits of a marine tested system, established supply chain, simplicity of design, and low maintenance requirements to the wave energy industry.

TABLE IX
COMPARISON OF PROTOTYPE SCALE LCOE FOR DD-CRG AND HYDRAULIC DRIVETRAINS

Drivetrain	LCOE p/kWh
Hydraulic	288
DD-CRG	226
DD-CRG un-conservative	142

Note that the LCOE values are rather high compared to what is required for the wave energy industry to reach commercial viability. For context, the offshore wind energy industry is aiming to reach 10p/kWh by 2020 ([22]). The figures presented in Table IX are based on a prototype device so do not include cost reductions due to upscaling of the device, mass production of components, more efficient use of installation vessels etc. Furthermore, it cannot be expected that the level of cost reduction required could be obtained purely through improvements in the drivetrain design. Other aspects of the technology would need to be refined in tandem to realise this target. Nevertheless, the results in Table IX show that the transfer of this technology can make a significant contribution towards achieving this goal.

VI. CONCLUSIONS AND FURTHER WORK

This paper has presented a preliminary feasibility study to determine the potential for transfer of a direct drive contra-rotating generator (DD-CRG) technology from the tidal energy industry to the wave energy sector.

By transferring the linear motion of the point absorber to rotary motion required by the generator through simple rack and pinion drives attached to the rotor and stator, it was found that technically the existing 500 kW generator design was compatible with a generic point absorber WEC. The WEC force and velocity could be transferred at appropriate torque and rotational velocities to the generator for a wide range of regular wave conditions, and the generator and drivetrain weight and dimensions were appropriate for housing the PTO system in the spar of the point absorber.

The use of this technology in WECs has the following advantages:

- Simple drivetrain with few components and critically no gearbox, reducing maintenance requirements and simplifying installation and assembly
- Drivetrain uses predominantly off-the-shelf components benefiting from an established supply chain, well understood operating behaviour, and readily available design and maintenance support
- Generator has already undergone extensive in-sea testing and was built with the marine environment in mind

Preliminary costing of the initial drivetrain and generator design (i.e. no changes made from the tidal energy version) compared to its weight and power rating suggested this would not produce significant economic benefits compared to a conventional hydraulic drivetrain. However, the wave energy application enabled optimisation of the generator and drivetrain design to transmit power at lower torque and higher speed. This significantly reduced the cost, weight and size of the generator and other components of the drivetrain.

With this optimisation applied, a reduction in the PTO system cost compared to the original design of over 60% can be achieved. This was estimated to translate into a reduction in LCOE of at least 20% compared to a hydraulic drivetrain, signifying a substantial economic benefit as well as the wider benefits listed above that the transfer of this technology would bring to the sector.

Therefore, this study has found that this is a promising concept, and one which is worth continuing to develop further in the drive to reduce the LCOE of wave energy devices to achieve commercial viability in the sector.

As this was a preliminary feasibility study, a number of simplifications were made to the modelling work. For the next stage of development, a more comprehensive model would need to be developed that incorporated the drivetrain, clutches, generator and control system along with the WEC motions. This would enable a more detailed understanding of the losses in the drive, the efficiency of the generator over a wave cycle, and control strategies in terms of generator damping in tandem with operation of the clutches to maximise power capture. More complex wave conditions would need to be simulated (irregular waves) and a wider range of point absorber designs would be modelled to show the broader applicability of the technology. This would enable a better optimisation of the PTO system to be completed, producing a prototype design to fully demonstrate the technology.

Following this a scaled model of the prototype would be tested in the laboratory to validate the model results and understand the practicalities of building, installing and operating the device, and this would also enable a more detailed cost estimation to be made, extending the results of this study.

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