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Experimental study for evaluating the response of the power take off of a point absorber wave energy generation system using a hydraulic wave simulator

Amin Al-Habaibeh [a,*], Lama Hamadeh [b], James McCague [c]

[a] Product Innovation Centre, Nottingham Trent University, Nottingham, UK
[b] University College London, London, UK
[c] DN22 Technical Ltd, Retford, Nottinghamshire, UK

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ABSTRACT

The increase in energy prices and the need to control the rate of climate change are two of the biggest challenges facing the planet. Despite the fact that the wave energy technology is still in its infancy, it is considered one of the most promising renewable energy sources that exhibits a large potential for sustainable growth towards Net Zero. In this paper, a novel design methodology for a new wave energy generation system is presented and the performance of its power take-off (PTO) or drivetrain is analysed. A complete description of the wave energy generation system is presented including the general concept of the power take-off, configuration, mechanical design, electrical system, simulation test-rig, expected power out and the force load on the system. The results from the power take-off system obtained from the simulation process of the test-rig using a hydraulic linear wave simulator, show that the change in the electric load produces different power and force values and consequently a wide range of efficiencies. It has been noticed that increasing the electric load leads to a better efficiency, i.e., high power and force values. However, there is a certain threshold where the system stops behaving in its high performance and its efficiency drops notably. This threshold depends not only on the electric load, but also on the values of the fixed parameters, i.e., wave cycle time, wave height and frequency. The finding will support the complete design of a point absorber system, including the buoy design, to interact with the expected level of wave patterns.

1. Introduction

Recent energy prices post Covid-19 pandemic is driving the need for low cost renewable energy. Energy usage worldwide is increasing and the requirement to increase the percentage of renewable energy is becoming vital. Reduction of carbon emissions, lowering pollution and preserving the world's fossil fuel resources are the main motivations. The recent global economic uncertainties, fluctuation in fuel prices, the Kyoto protocol agreement and the recent United Nations Climate Change Conference (COP27) drive many countries to research and consequently develop more efficient clean energy generation methods with an emphasis on green energy and energy efficiency. Energy security is also an important consideration for many countries and most are looking towards independence where possible in relation to their energy supplies. The average consumer, however environmentally concerned, is unlikely to want to pay a substantial amount more for energy derived from a developing renewable energy technology such as wave energy. Therefore, it is important to ensure that in developing the technology, the price per kw/h maintains affordable and comparable to other technologies via reliable systems and sub-systems that need minimum maintenance and have a long life expectancy of about 15–20 years.

Renewable energy, including solar, thermal and photovoltaic (Elavarasan et al., 2022), wind and wave (Weiss et al., 2018), tidal (Garcia Novo and Kyozuka, 2021; Mehri et al., 2017), geothermal (Raos et al., 2022), hydropower (Quaranta et al., 2021), biomass (Sher et al., 2020) and biofuels (Jung et al., 2021), are energy sources from natural replenishable and sustainable resources. Significant research has been conducted in recent years in relation to renewable energy, see for example (deLlano-Paz et al., 2015; Hussain et al., 2017). Reference (deLlano-Paz et al., 2015) indicates that to meet the emissions reduction

* Corresponding author.
E-mail address: amin.al-habaibeh@ntu.ac.uk (A. Al-Habaibeh).

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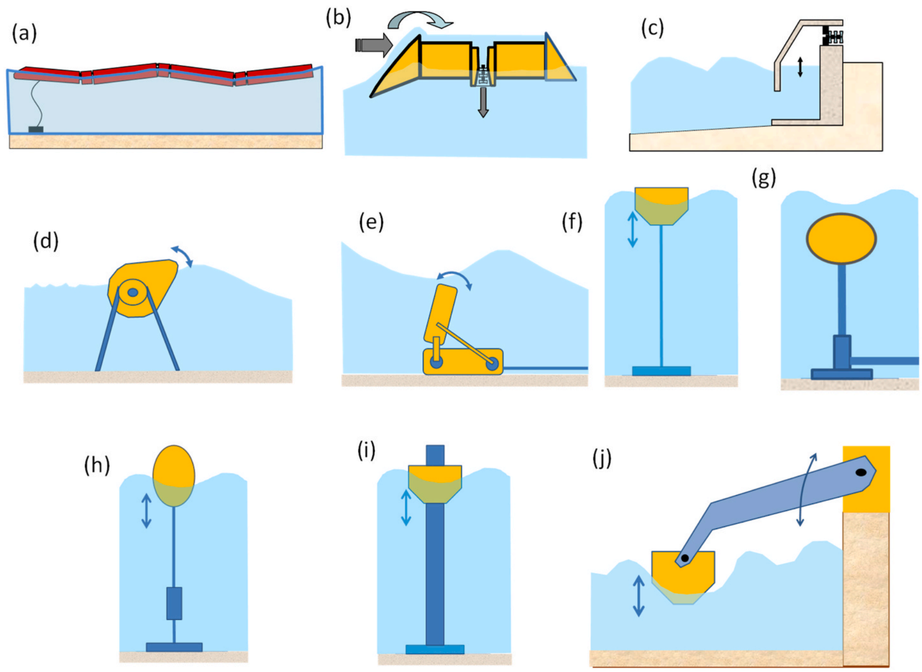

Fig. 1. A Schematic diagram of some of the main existing wave energy generation configurations. (a) Pelamis, (b) Wave Dragon, (c) LIMPET, (d) Edinburgh Duck, (e) Oyster, (f) FlanSea, (g) Carnegie, (h) Wallace Energy System, (i) Wavestar, (j) Ocean Power Technology (For more details, see Table (1)).

targets of 2020 in the EU, it would be necessary to increase the maximum share of zero-emissions technologies by 1 − 2%, except in the case of solar PV; and that efficient, safe and environmentally friendly energy future in the EU is closely related to the renewable energy sector.

Between 2018 and 2020, the global % growth in renewable energy generation was not expanding as expected, with solar energy growth of only 16% in 2020, wind power 12%, bioenergy 3%, hydropower 1%, and others including wave and tidal energy 3%. Overall the renewable energy sector growth dropped from 7% in 2018 to 5% in 2020 (The International energy Agency, 2020). Therefore, further development is needed to maintain the growth of renewable energy use.

Each type of renewable energy has pros and cons. Solar energy, for instance, is a mature technology and is being subsidised and as a result is becoming common and accepted, but without suitable storage methods and equipment it is only a daytime contributor to the grid. Wind energy is also expanding rapidly, but with many objecting to their visual impact on land they are being driven offshore which is more expensive. Many local communities are against the installation of wind turbines because of their visual impact especially in areas of outstanding natural beauty, which also tend to be in areas of significant wind resource, wild life and shadow flickering (Saidur et al., 2011). In addition, wind speed can change significantly which makes predicting wind pattern and availability of wind energy extremely difficult. Tidal energy is very predictable and sustainable and can be categorised as tidal flow, tidal barrage and tidal lagoon. Tidal flow has operational problems due to the location of the resource and is generally considered a dangerous and risky exercise; tidal barrage requires effectively blocking river estuaries and will require a huge capital investment regarding the civil structure and the impact on the environment would change the appearance for ever; with potentially devastating effect on the natural environment. Tidal lagoon is of a similar nature to the barrage and would require huge initial investment and acceptance that the payback period would be over several decades, though the might still prove to be an acceptable solution it is still under lengthy and costly debate and consultancy. On the other hand, with 2% of the world's 800 000 km (km) of coastline exceeding a wave power density of 30 kilowatts per meter $(\mathrm{kW/m})$, the estimated global technical potential from wave power is about 500 gigawatts electrical energy (GW) based on a conversion efficiency of 40%. Large wave energy resources can be found across the globe (Wave Energy). The wave energy, with the advantage of abundant reserves, wide distribution, predictability, high energy density, easy access and low environmental impact, is one of the most important renewable energy sources with a significant potential (Liang et al., 2017). If it were positioned more than 3 miles off shore, then from none elevated level it would not be visible. It is generally predictable and satellite imaging can also be used to see approaching wave fronts. However, this technology has shown that it is too costly. Wave power devices that are being tested are 10 times more expensive than other sources of low carbon power (https://www.theguardian.com/environment/2017/jan/16/uk-wave-power-far-too-costly-warns-energy-research-body, 2017). Additionally, salt water is corrosive, and powerful storms can damage machinery, so it is challenging to design buoys the can stand withstand the elements (http://www.dailymail.co.uk/wires/ap/article-3797174/Developers-face-challenges-capturing-wave-energy.html) which makes the development pace of this industry a bit slow-moving.

Various wave energy technologies and conversion ideas are currently being developed and a significant variation of configurations have been theorised. Fig. 1 and Table 1 present examples of the main wave energy configuration systems currently available in industry and literature. The complexity of the technical options and configurations has, so far, limited the success of wave energy generation. High initial project cost, especially for offshore devices, has been found in the past to be a significant barrier to the development of prototypes (Goda, 2000).

Most of the wave energy technologies listed above seem highly complex, lack flexibility and use energy conversion techniques that by their nature require large and expensive devices with a poor mass to power output ratio, and in most cases they are difficult to scale down or use off-shore and on shorelines.

The following sections of this paper will describe the work strategy and the wave energy generation system design, the experimental results followed by a thorough analysis and discussion. Conclusion of the findings is then presented.

Wave energy extraction history spans over more than two hundred years. Yoshio Masuda is regarded as the father of modern wave energy conversion technology (Hosna and Mohamed, 2014). His developed

Table 1
Summary of the most common wave energy configurations (see Fig. 1).

System number Figure (1)	Technology	Description	Commercial success	Limitations	Ref.
(a)	Pelamis	Hydraulic; hinged contour device for deployment offshore	Implemented in Portugal, but never became commercially viable for expansion. The firm went to administration in November 2014.	Directional, not scalable and sensitive to wavelength. Maintenance issues of hydraulic systems. Too large and too costly, no clear way to reduce costs	http://www.bbc.co.uk/news/uk-scotland-scotland-business-30151276 and accessed on 21 (1512)
(b)	Wave Dragon	A floating, moored energy converter of the overtopping type.	Demonstrated in Wales (UK) for 7MW device and tested in Denmark. It is a joint EU research project, including partners from Austria, Denmark, Germany, Ireland, Portugal, Sweden, and the UK. No evidence of commercial viability.	Maintenance issues, Scalability and flexibility subject to high loading due to sheer size and consequent survivability issues	http://www.wavedragon.net/and accessed on 14 (2022)
(c)	LIMPET	Shoreline, Oscillating Water Column (OWC)	The LIMPET wave energy device has been operating since November 2000 supplying approx. 75kW of power to the grid on the Scottish island of Islay.	Infrastructure and not scalable, lack of flexibility and not applicable off-shore. Has to be extra robust to work in very destructive environment (Breaking waves) cost likely to be too high.	Heath (2000)
(d)	Edinburgh Duck	Stubby aerofoil cross section	No records of commercialisation.	Extremely complex PTO and large scale.	http://science.howstuffworks.com/environmental/green-science/salters-duck1.htm and accessed on 21 (2022)
(e)	Oyster	Oscillating wave surge converter as a pendulum	BBC reported in 2013 that the investment is more than anticipated. No evidence of commercial viability yet. The firm has been in administration since November 2015.	Complex and would require resonance to achieve the required reaction.	Cameron et al. (2010) BBC (1133)
(f)	FlanSea	Point Absorber	Demonstrator only	Cable technology and generator not enough information on cable fatigue	https://www.seascapesubsea.com/wp-content/uploads/2017/03/nCentric-Flansea.pdf (2017)
(g)	Carnegie	Oscillating wave surge converter a pendulum	Has been connected to the grid and tested in Australia. No evidence of commercial viability	Hydraulics systems and Complex anchoring technology sub surface nature of mooring could prove technically challenging in difficult environments, no information on power production capability	http://www.carnegiewave.com/and accessed on 21 (2022)
(h)	Wallace Energy System	direct-drive wave energy generators	Prototype. No evidence of commercial viability	Limited power and usual issues of direct drive.	http://eecs.oregonstate.edu/wesrf/and accessed on 21 (2022)
(i)	Wavestar	A float connected to the end of a mechanical arm is set in motion by the waves.	Systems have been tested in the North Sea and the Danish fjords. No evidence of commercial viability has been found.	Lacks the flexibility in relation to the need for significant supporting structure.	http://wavestarenergy.com/and accessed on 21 (2022)
(j)	Ocean Power Technology	Point Absorber with mechanical gearing system.	No evidence of commercial viability.	System reacts WAB against Central column, poor control and poor power output for complexity of system.	https://oceanpowertechnologies.com/(2022)

navigation buoy powered by wind energy has been commercialised by Japan since 1965 and later by the USA (Falcao, 2010). In 2000, the world's first commercial wave plant was installed on the island of Islay (Muller et al., 2013). However, the world's first wave farm was developed in the UK and installed in Portugal (https://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/and accessed on 21, 2022) at the Aguçadoura Wave Farm, which consists of three 750 kW Pelamis wave energy converter devices. This was just the beginning. Recent years have seen several worldwide developments in energy generation from waves as one of the most interesting hotspots in the field of renewable energy. For instance, in the last decade, UK has shown an ongoing effort for making marine energy a reality and developing a wave power on a commercial scale. It is believed that the UK has excellent wave resources and advanced techniques that need to be rapidly developed to achieve the target of 22 GW of installed capacity by 2050 (Jin and Greaves, 2021). On the other hand, different and many designs, technologies, methods and technical improvements for the wave energy generation systems have been presented in literature. For example, Y. Fan et al. (2016) studied the wave energy when it is captured and converted into hydraulic energy by a piston pump module,

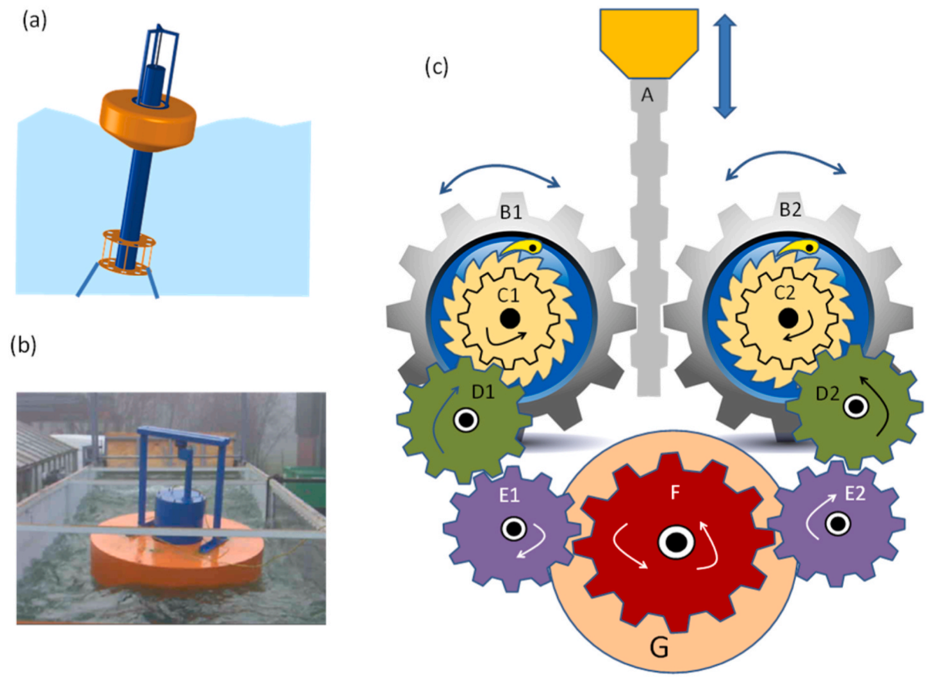

Fig. 2. The proposed system (a) a schematic diagram of the concept; (b) the first proof of concept demonstrator; (c) the rack, clutch and gear box concept.

which is combined with a wind turbine floating platform, and then the hydraulic energy is converted into electricity energy by a variable displacement hydraulic motor and induction generator. Another method based on the power take-off mechanism, which is developed by utilising an array of buoys connected with a flexible runway, is presented by H.C. Zhang et al. (2016). Also, K.M. Tsang et al. (Tsang and Chan, 2015), proposed a direct AC-AC electricity power conversion to improve the power efficiency and the electricity production of the wave energy converter instead of the widely-used AC-DC conversion method. Additionally, a study by R. Guanche et al. (2015) contains an analysis of suitable locations for the development of wave energy farms based on representative operation and maintenance parameters. In the next section, we will explain our work strategy and describe fully the design of the wave energy generation system.

The point absorber wave energy converters have seen great interest recently in industry and academia s they are scalable and have better flexibility towards wave heights and frequencies.

In (Yang et al., 2023), a simulation to evaluate the performance of a wave energy converter (WEC) which provides a better understanding of the buoy design. another mathematical modelling method has been also reported in (Li et al., 2022), where performance of an adaptive bistable point absorber wave energy converter in evaluated in irregular waves. The results show that adaptive bistable wave energy converter performs better than the standard bistable counterparts in irregular waves. In (Tan et al., 2023) a linear permanent-magnet generator was experimentally tested successfully and the results show that generator efficiency is improved by the adjustable draft system.

This paper provides an innovative systematic and experimental approach of the design of a point absorber WEC. The novelty of this paper is the design of a power take-off system that has a gearing system which allows the bi-directional linear motion to be transferred to one directional rotational motion, hence allows the use of low cost components from the wind energy industry. The second innovate point is the methodology adopted to experimentally valuate the forces needed for the power-take-off (PTO) for an optimised design of the buoy system for regular waves. The next section will describe the proposed point absorber wave energy converter and its novelty and previous work that lead to this stage of development.

2. The suggested point absorber

This paper is a continuation to the work detailed in (Al-Habaibeh et al., 2010); in his paper we present an innovative design methodology via a new configuration of a point absorber wave energy convertor (WEC) that addresses most of the negative issues in other systems such as efficiency, scalability and simplicity, both in manufacture and maintenance, and introduces a modular design approach that gives flexibility in scale and accurate output power determination. This work studies the characteristics and behaviour of the PTO of a point absorber wave energy generation system, i.e., mechanical and electrical, that are caused by a hydraulic wave simulator based on sea wave patterns collected from real sites in the UK to capture common amplitude and frequency. Ultrasound sensor was used for this exercise. This helps not only in estimating the electrical efficiency and the output power generated when converting the mechanical energy from simulated waves into electrical energy, but also supports the determination of the forces that acts on the system that are produced by the wave simulator from different types of linear movement that generate different types of wave patterns. This yields to draw a better picture of the dimensions, weight and shape of the buoy (float) and other design features that are expected to react of wave patterns to produce the expected PTO movement. Fig. 2-a presents a simplified 3D CAD design of the proposed system. It consist of a floating buoy that is attached to a rack system the enables the movement of the PTO unit. Fig. 2-b presents the first working proof of concept prototype in action. Based on the initial exploration, a systematic design methodology was needed for a step-by-step design and assessment process. To explain how the gearing system of the PTO works, consider Fig. 2-c. Fig. 2-c presents a schematic diagram of the rack linear movement, gears and the electric generator. The rack system (A) moves up and down as a results of the buoy movement. Two pinions are engaged permanently with the rack system (B1 and B2).

The linear motion in the rack (A) will generate bi-rotational motion in the pinions B1 and B2. B1 and B2 are attached to a combined rachet (clutch) and gear mechanism, C1 and C2 respectively. The yellow components of the rachet mechanisms are attached to (B1 and B2) to engage (C1 and C2) or smoothly slide based on the direction of rotation.

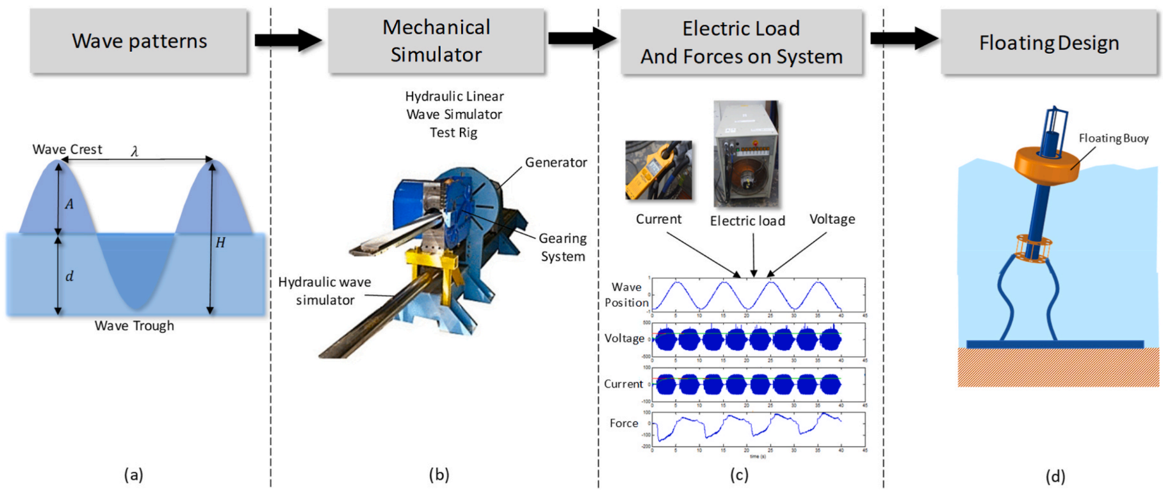

Fig. 3. A simplified illustration of the work strategy followed in this paper. (a) is the wave pattern where λ is the wavelength, A is the wave amplitude, H is the wave height and d is the water depth. The mechanical power in (b) contains primarily of the hydraulic linear wave simulator test rig that simulates the wave movement. In (c), the electric power; current and voltage, are measured and the resulted force is calculated. (d) is a floating buoy on the water surface connected to a core that is moored to the seabed.

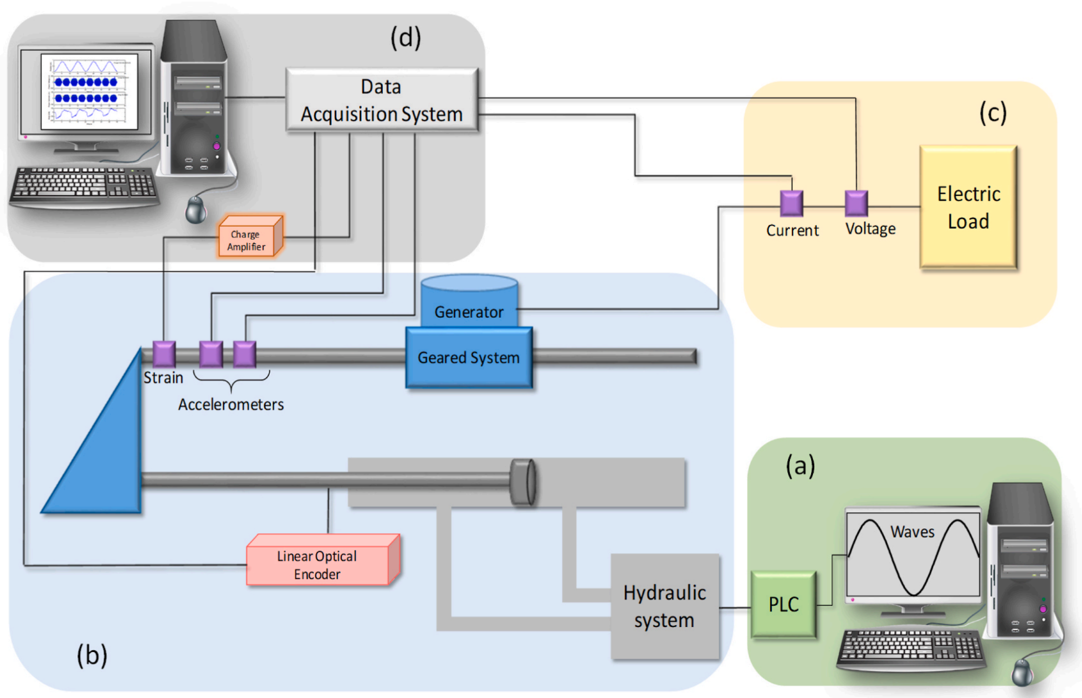

Fig. 4. Schematic description of the project design. (a) is the wave patterns fed into the hydraulic simulator; (b) the hydraulic simulator moves based on the wave patterns to power the power-take-off (generator and gear system); (c) the power generated is absorbed by the load; (d) data from the sensors attached to the system is captured for analysis.

The ratchet mechanisms will only allow either C1 or C2 to be engaged, and the other will be disengaged (neutral) due to the locking mechanism in the rachet. Let's assume the rack (A) is going downward. This means C2 and B2 will be engaged due to the yellow part of the rachet being locked) and the right hand side of the assembly will be the active one. The movement of C2 will allow the movement of D2, E2 and F; leading to the rotation of the generator counter clockwise. However, F is still engaged with E1, D1 and C1 which will force them to rotate in the directions specified. But since C1 is not engaged with B1; the gear system will successfully rotate the generator as described. If the rack is moving with the wave upwards, the left side of the gears will be engaged and the right hand side gears will be disengaged (neutral). But this will still allow gear F to rotate counter clockwise and hence allow the motor to rotate in the same direction as in the previous case. Gears D1, D2, E1 and E2 are mainly to change gearing ratio, but might not be necessary for the functionality of the gear box depending on the speed and toque requirements. The up-and-down linear motions of the buoy changes to rotational motion in one direction using a novel patented clutch system described in patent number WO2011104561A3.

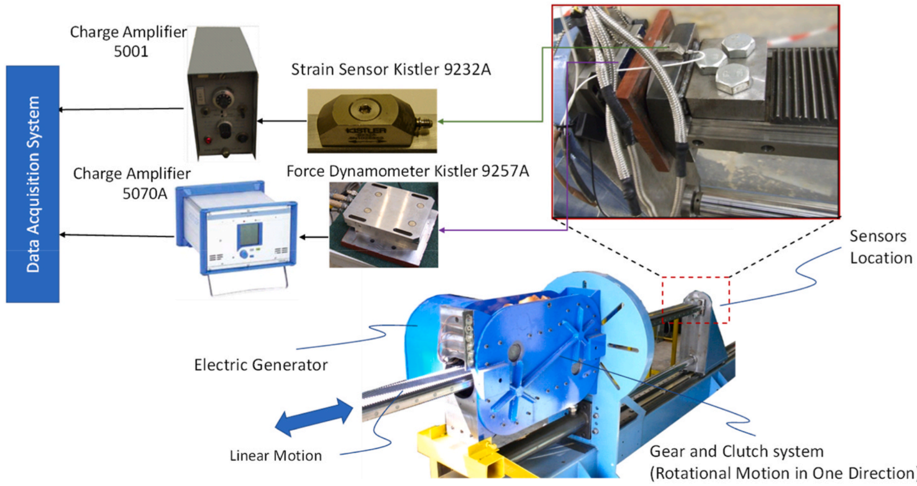

Fig. 5. The strain sensor connected to the hydraulic wave simulator test rig and the force dynamometer is used for in-situ calibration.

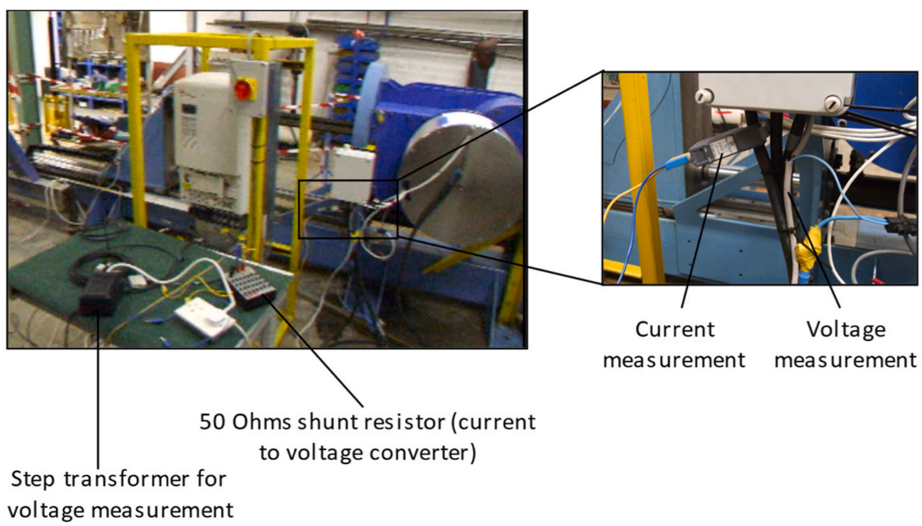

Fig. 6. The experimental system for measuring the current and voltage.

Table 2
Test values with fixed wave cycle time, wave height, electrical frequency and the electric load.

Fixed	Wave Cycle Time (sec)	10
	Wave Height (m)	± 0.8
	Electrical Frequency (Hz)	61
	Electric Load Bank (kW)	27.5
Generated	Phase Voltage V(RMS /volts)	187.6
	Phase Current I (RMS /A)	35.94
	Power $= 3 \times I \times V$ (kW)	20.23
		Assuming $\cos\theta = 1$ and balanced load
	Force (kN)	87.7 − 89.5

3. Work strategy and project design

The previous work by the authors (Al-Habaibeh et al., 2010) mainly presented the idea as a proof of concept. The system under consideration is a floating buoy (point absorber) that transforms the energy from waves into useable mechanical energy. In this paper, a detailed design methodology and results are presented. It is difficult to simultaneously deign all aspects of the WEC without the use of systematic methodology that allows proper investigation and assessment prior to the full investment in manufacturing the full system. The performance of WECs lies in the combined efficiency of different sub-systems that it contains. It was important to assess the PTO prior to the design of the floating buoy system to allow the design based on the required forces for the upward and downwards movements at different wave patterns. For example, the buoy design will require a specific shape, volume and weight to allow the generation of electricity for a wide range of wave patterns and electrical load. This means the design will need the full understanding of the forces on the PTO for the selected generator and gearing system. Once this is well-understood, the next stage will be to use Finite Element Analysis and fluid dynamics to simulate the response of the PTO relative to the response of the buoy to the expected wave patterns. Only then, a full system can be designed and manufactured. This methodological approach is critical for the scalability and success of the system for each location based on available wave patterns.

Generally speaking, wave energy conversion consists of two steps. It first converts wave energy into mechanical energy and then mechanical energy into electrical energy through generators (Kim et al., 2017). Fig. 3 explains the suggested novel design methodology in this paper. Our study starts by collecting wave patterns from real sites Fig. 3-a, which are very useful to impose the type of wavy-motion the hydraulic linear wave simulator follows. The patterns tested are regular patterns in this paper. As we know, random sea conditions off-shore will be waves of different heights and frequencies; but at any moment in time at least a

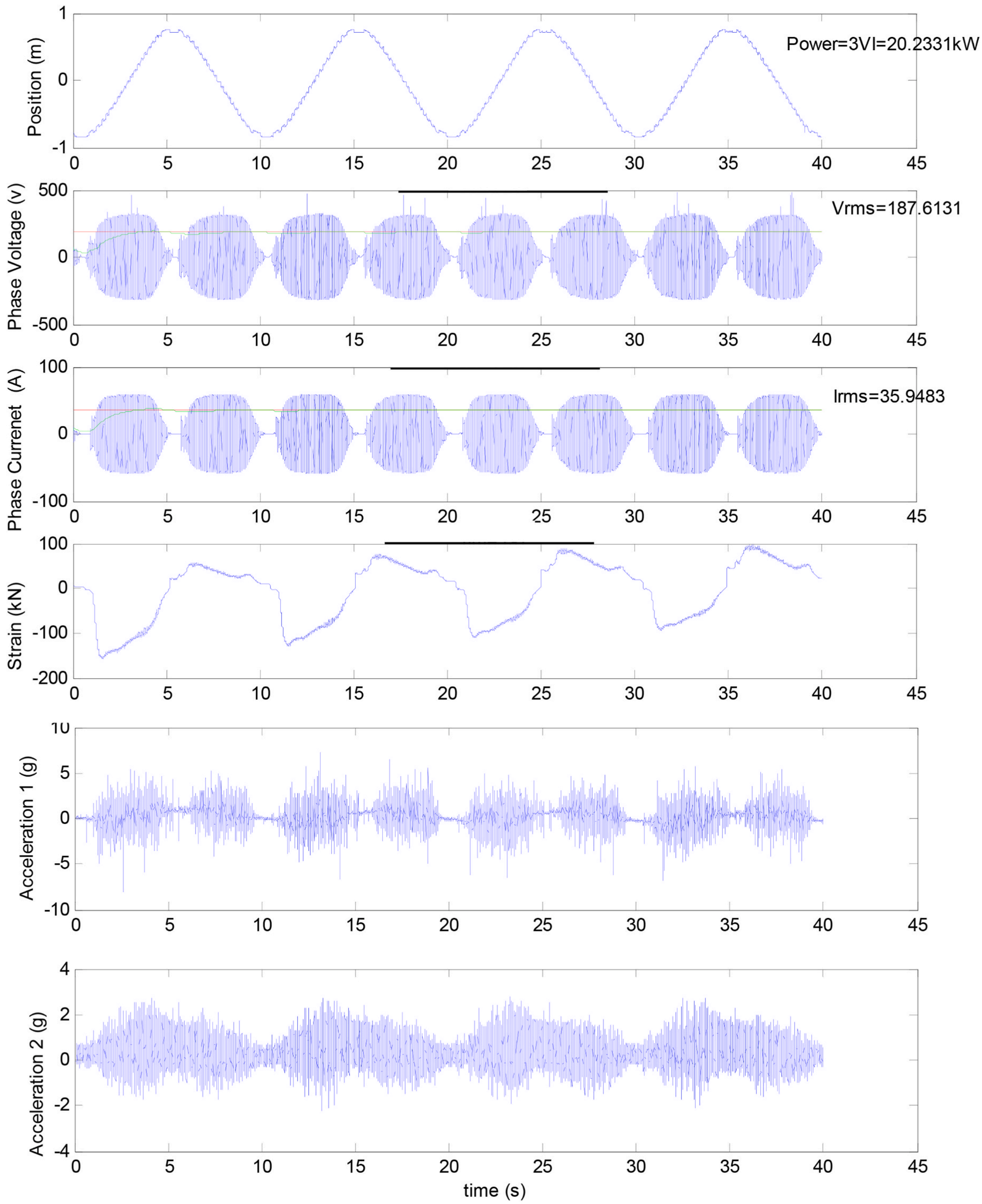

Fig. 7. The phase voltage and current, strain and acceleration signals in the case of: wave Cycle Time = 10 sec, wave Height = ±0.8 m, electrical frequency = 61 Hz and the electric load bank = 27.5 Kw . The green line represents the average RMS values and the red line refers to the actual RMS values.

quarter of an ideal sinusoidal cycle will be present. The purpose of the design of the experiment is to evaluate the gearing system and the generator for ideal sinusoidal waves. Wave with more randomness and variation will be tested in a following stage of the design process following the design of the buoy to respond to the a specific range of waves and frequencies. Fig. 3-b presented the hydraulic simulator that will follow the regular wave patterns. As a result of the mechanical movement, an electric power is generated and measured, and the produced power and the force on the system are measured as in Fig. 3-c. Based on the captured data, load and forces, the next stage will be to design the floating buoy system to provide the required movement from the PTO as close as possible to the simulation process of the hydraulic system, see Fig. 3-d. The floating mechanism design in consideration is a floating buoy on the water surface connected to a core that is moored to the seabed. The linear up- and down-motion of the floating buoy is transferred via a gearing and a clutch system, as described previously, to one-directional rotation to generate electricity from the up- and down motion of the buoy. The up- and down-motion of the floating buoy mimics exactly the movement of the hydraulic linear wave simulator in this study. The exact gearing system and generator design is a

Table 3
Test 1 fixed (wave cycle time, wave height and electrical frequency), changing (electric load, current and voltage) and generated (power and force) values.

Fixed Parameters					
Wave Cycle Time = 10 sec		Wave Height = ±0.8 m	Electrical Frequency = 65.4 Hz		
Changing			Generated		
Electric Load Bank (kW)	Phase Voltage (RMS /volts)	Phase Current (RMS /A)	Power[a] (kW)	Max force in each direction (kN)	
29.5	177.2	34.9	18.6	100.4	−74.0
27.5	187.6	35.94	20.23	87.7	−89.5
19.5	191.07	26.7	21.04	113	−87.0
1.5	204.5	6.6	4.05	20.2	−2.8
0	206.4	6.2	3.87	12.1	−1.1

[a] Assuming $\cos\theta = 1$ and balanced load.

Table 4
Test 2 fixed (wave cycle time, wave height and electrical frequency), changing (electric load, current and voltage) and generated (power and force) values (for power, $\cos\theta = 1$ and balanced load are assumed).

Fixed					
Wave Cycle Time = 10 sec	Wave Height = ±1 m		Electrical Frequency = 73 Hz		
Changing			Generated		
Electric Load Bank (kW)	Phase Voltage (RMS /volts)	Phase Current (RMS /A)	Power (kW)	Max force in each direction (kN)	
0	253	8.2	6.22	3.31	−2.95
1.5	250	8.6	6.4	4.50	−3.95
3	244.5	9.37	6.8	7.45	−9.27
7	223.4	11.3	7.58	19.45	−13.63
11	238.2	16.7	11.98	36.23	−26.08
21	232.2	30.8	21.4	135.90	−93.18
22.5	221.4	42.1	28.0	201.0	−170
26.5	221	42.7	28.3	217.27	−159.09
29.5	169.5	34.2	17.39	87.50	−76.13

proprietary design with details that could not be shared in detail due to its commercial sensitivity.

The novel idea of the PTO is to function by taking bidirectional linear energy and turning it into a single direction rotation energy using a specially designed clutch system.

As shown schematically in Fig. 4, the experimental PTO and the hydraulic simulator have four main sub-systems. The hydraulic wave simulator is used mainly to: (1) test the PTO (drivetrain); and (2) estimated the forces that are needed in order to design the buoy.

3.1. a. Input wave data

Fig. 4-a presents the input wave data to the simulator. An instrumentation digital system has been designed and built to read wave data collected from real sites in the UK using ultrasound sensor and converts the collected data through the linear wave simulator into linear motion that simulates the actions of a floating buoy attached to the wave energy generation system. These wave patterns control the motion of the subsequent sub-systems, i.e., the hydraulic linear wave simulator.

3.2. b. Hydraulic linear wave simulator

As presented in Fig. 4-b, this part contains a mechanical geared system connected to a permanent magnet generator. The mechanical motion of the wave simulator is controlled by the data captured from the real wave patterns, as mentioned earlier. Three sensors are connected to the hydraulic linear wave simulator: A Strain sensor, Kistler 9232A, as shown in Fig. 5 which is used to measure the force strength resulted from the compression and tension on the rack. The strain sensor is calibrated in-situ to measure force using a force dynamometer type Kistler 9257A, see Fig. 5. Two accelerometers are also used to measure the acceleration of the linear carriage. Fig. 4-b presents the location of the sensors on the schematic drawing. The reason of not using the force dynamometer for the full test is to protect the force dynamometer from any damage caused by excessive forces during the full testing process. The strain sensor will not have this problem as it measures strain that is calibrated to force values without having to endure any direct forces and stress.

3.3. c. Electric energy unit

Fig. 4-c shows the electrical energy unit. Following the mechanical movement of the hydraulic linear wave simulator, an electric current and voltage are generated and measured, as shown in Fig. 6, and consequently the output power is estimated. In order to measure the high voltage of the electric generator for one phase using the computer data acquisition system with ±10 V levels, a step-down transformer circuit is implemented and data was calibrated accordingly. A voltage divider and parallel capacitor are implemented for accurate calibration and for noise cancellation respectively. On the other hand, the current is measured using a clamp-on current sensor with which gives 1 mA sensory measurement for each 1 A current value.

3.4. d. Data acquisition system

As shown in Fig. 4-d, this sub-system receives all the complete information and signals from the previous sub-systems, i.e., current, voltage, strain and vibration. All data is captured using a data acquisition card from National Instruments where the sampling rate for all tests is 1000 sample per second per channel. By examining all the results caused by different simulated wave patterns, we can develop a well-planned and business-like float mechanism design that is efficient and productive for each location.

In the following section, we will investigate how by changing the electric load, the output power of the system changes in return and how it leads to different force values and consequently to different system efficiencies.

4. Experimental evaluation

The aim of the experimental work is to measure the forces exerted by the hydraulic system as a result of the compression and tension on the rack and consumed by the electric generator and the gearing system. A force platform dynamometer (Kistler 9257A), as shown in Fig. 5, was sandwiched within the system to measure the actual forces exerted by the hydraulic system. However, the forces acting on the rack of the wave simulator are estimated to exceed 100 kN; and the maximum load on the force dynamometer is estimated to be 50 kN. To solve this problem, a strain sensor (Kistler 9232A) will be used to measure the force. The sensor needs to be calibrated in position by satisfying the calibration equation which is given by:

$$\text{Strain Force (N)} = \left[1.487\, v^3 + 3.6988\, v^2 + 4.468\, v - 0.1733\right] \times 10^3 \quad (1)$$

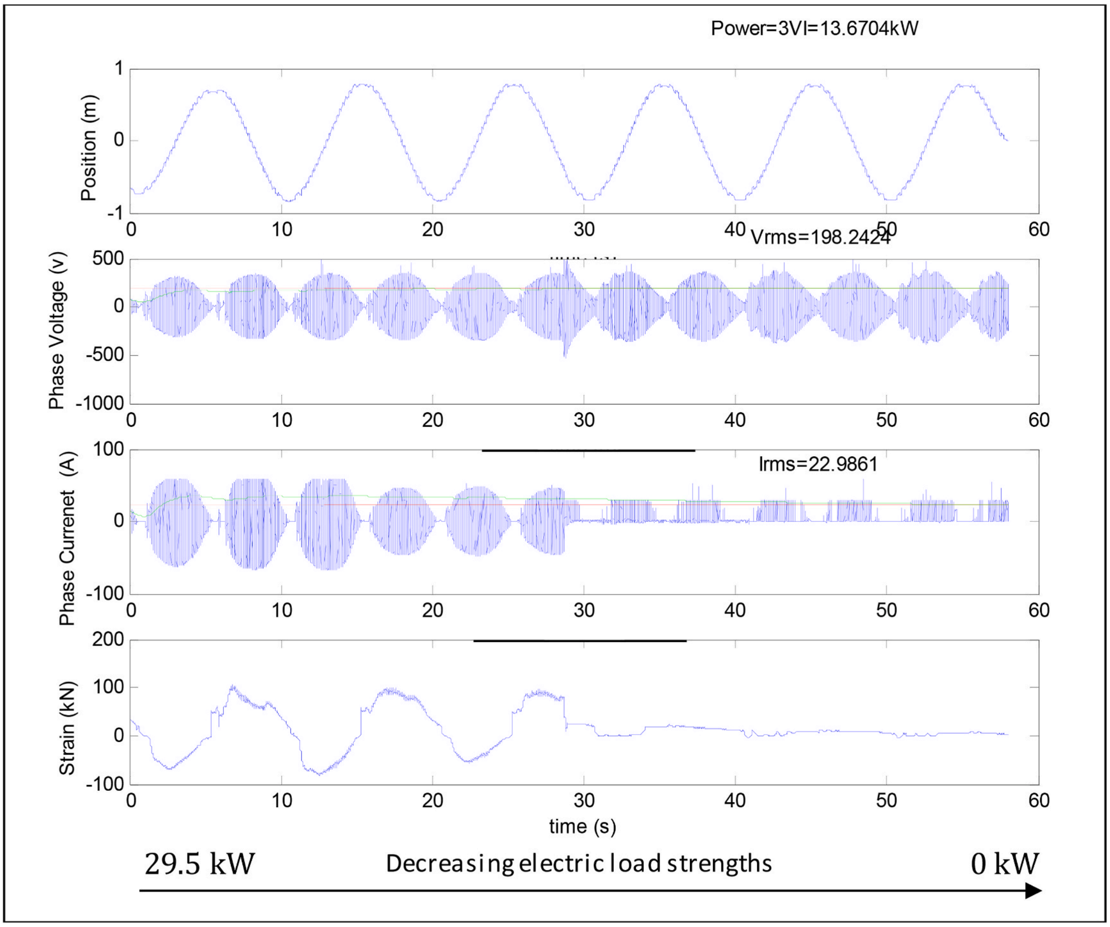

Fig. 8. The complete change in load from maximum to minimum during Test 1 in the case of wave cycle time = 10 sec, wave height = ±0.8 m and electrical frequency = 65.4 Hz with changing electric loads. The green line represents the average RMS values and the red line refers to the actual RMS values.

ii. Test 2 with Wave Height = ±**1 m**.

Where v (volts) is the voltage output of the strain sensor based on the current amplification of the charge amplifier of 2×10 mechanical units per volts. As the sensor is calibrated, the system is ready for calibrated measurement. Our work falls into two parts, the first one examines the generated power and force as a result of fixed parameters, i.e., wave time cycle (wave period), wave height, electrical frequency from the generator and the electric load bank. The second part, however, deals with studying the force and power values as a consequence of varying the electric load strengths with keeping the other parameters fixed.

4.1. a. Fixed electric load at fixed parameters

As a starting step, the parameters of the wave time cycle (wave period), wave height, frequency and the electric load bank strength are fixed; and the generated power and force values are examined. The performance values are summarised in Table 2.

Fig. 7 shows the change in phase voltage, phase current, strain and acceleration signals as a function of time. It can be noticed that the phase voltage and current signals disappear when the wave position reaches its maximum height (peak) or minimum height (trough). However, when the wave changes its location between these two positions, both signals start to have a value. This mechanism appears periodically along the time axis creating a signal pattern (two signal patterns per wave period). On the other hand, the strain signal follows the wave position shape where it reaches its highest point when the wave at its peak, and it goes to its lowest point when the wave at its trough. There is a lag observed between the simulated wave position and the reading of the strain sensor and the readings are not symmetric. This could be as a result of the load and the strain sensor; as will be discussed in the following sections of this paper.

4.2. b. Changing the electric load at fixed parameters

Here, we study the case of fixed parameters of the wave time cycle (wave period), wave height and electrical frequency with varying the electric loads and then probe the resulting power and force values that are generated. To achieve this, two different tests; Test 1 and Test 2, are conducted that have two different fixed wave time cycles (wave period), wave heights and frequencies, as presented in Table 3 and Table 4, with several electric load strengths.

i. Test 1, Wave Height = ±**0.8 m**.

In this test, we use a ±0.8 m wave height and 10 sec time period with a 65.4 Hz frequency. Five values of the electric load strengths are tested, as listed in Table 3.

The complete change in electric load is exhibited in Fig. 8. It can be noticed that the system can reach a power up to 21.04 kW which corresponds to an electric load equals to 19.5 kW. Interestingly, with decreasing the electric load strengths, both the force and the current signals decrease as well. At a certain threshold of the electric load (∼ 15 kW in this case), however, the force signal fades out and the current produces only noisy signals. Moreover, the voltage signal is not affected by this situation, as the voltage and the current are not related.

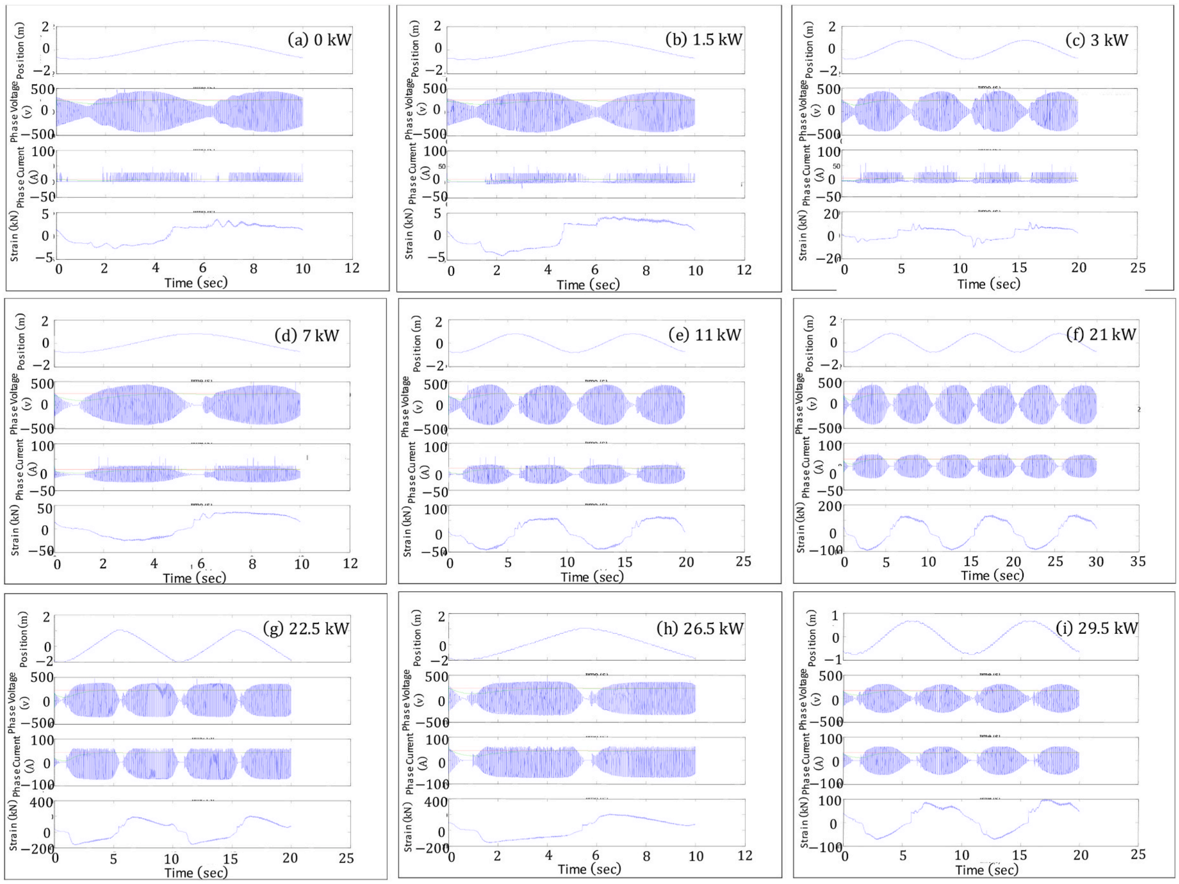

Fig. 9. The results for Test 2 in the case of wave Cycle Time = 10 sec, wave Height = ±1 m and frequency = 73 Hz with changing electric loads where: (a) load = 0 kW, (b) load = 1.5 kW, (c) load = 3 kW, (d) load = 7 kW, (e) load = 11 kW, (f) load = 21 kW, (g) load = 22.5 kW, (h) load = 26.5 kW and (i) load = 29.5 kW.

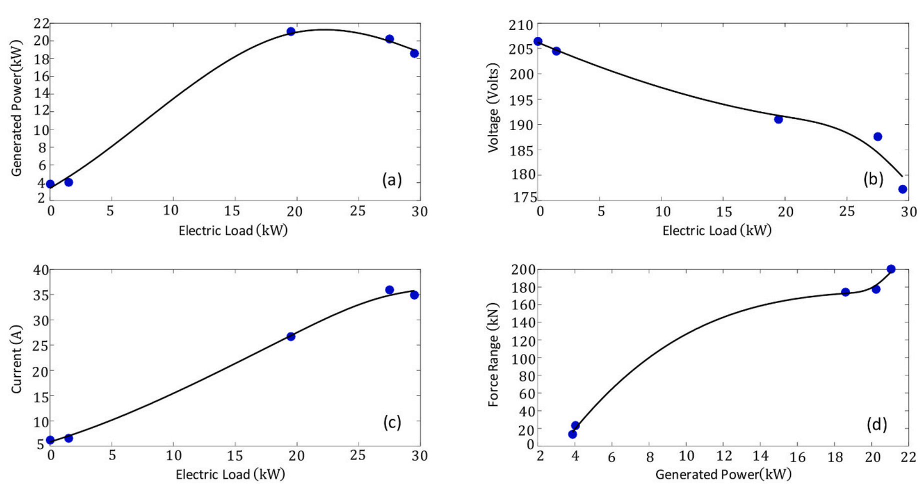

Fig. 10. Results of Test 1 (Wave Cycle Time = 10 sec, Wave Height = ±0.8 m and Frequency = 65.4 Hz) where: (a), (b), and (c) represent the change of the generated power, voltage and current as a function of the electric load, respectively. However, (d) shows the change of the force range as a function of the generated power.

In this test, we use a ±1 m wave height and 10 sec time period with a 73 Hz frequency. Nine values of the electric load strengths are tested, as in Table 4.

Detailed results are presented in Fig. 9, where it can be observed that this system can generate power up to 28.3 kW which corresponds to maximum force values in each direction of 87.50 kN and − 76.13 kN when the electric load is equal to 26.5 kW. The noise level in voltage and current was cancelled using a filtering algorithm, but some noise could still contribute to the power's calculations. Also, the extrapolation of force could influence the accuracy of the force measurement. It is assumed that the 3 phase system includes only balanced resistive loads and that the current and voltage are in phase. The strain force is not symmetric which could be as a result of the movement of the generator in one direction which could be the influence of the gearing system. Fig. 9 presents at least one wave and fore cycles for each test to estimate the power generated and absolute maximum forces on the PTO.

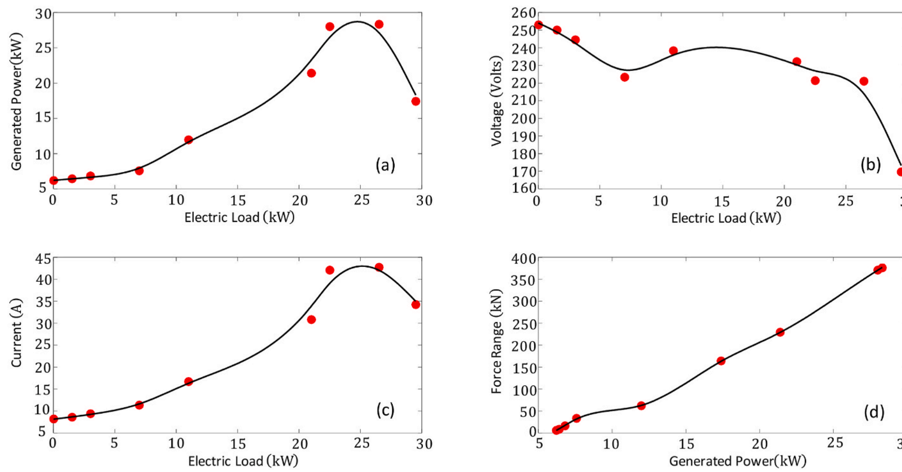

Fig. 11. Results of Test 2 (Wave Cycle Time = 10 sec, Wave Height = ±1 m and Frequency = 73 Hz) where: (a), (b), and (c) represent the change of the generated power, voltage and current as a function of the electric load, respectively. However, (d) shows the change of the force range as a function of the generated power.

5. Discussion and analysis

Based on the previous experimental results in the sections above, it is noticeable that by changing the electric load values, the generated power and the force change accordingly producing varied efficiencies. Figs. 10 and 11 show the relation between the parameters for both tests; Test 1 and Test 2. It can be observed clearly, from Fig. 10-a and Fig. 11-a that the generated power increases with increasing the values of the electric load. However, the system shows in both tests a decreasing efficiency at specific higher electric load thresholds. In the case of Test 1, we can see that when the electric load reaches the value of ∼ 19.5 kW, the system's efficiency is in its highest performance where it can generate power up to 21.04 kW. After this value, i.e., with increasing the electric load, the generated power and consequently the force decrease significantly indicating that the system cannot perform as good as before this point. Similarly, for Test 2, when the electric load is in the range of ∼ 26.5 kW, the system's efficiency in its best and produces power up to 28.3 kW. However, with increasing the load, the efficiency drops down drastically. Fig. 10-b,c and Fig. 11-b,c show the change of the current and voltage as a function of the electric load. It can be seen that the voltage always drops with increasing the electric load values and the current, on the other hand, increases with increasing the electric load until it reaches a specific limit where it decreases notably. Additionally, as illustrated in Fig. 10-d and Fig. 11-d, the force range increases with the power generated and their relation is almost linear in Test 2 for high generated power values.

Finally, among the most interesting ideas for further experimental work is to estimate the power generated from waves that are created inside a water energy tank. The results of this experiment and the full design of the system will be presented in a future publication.

6. Limitations of this work

This work has some limitations which are discussed in this section.

One of the key limitations is of this study is that the generated energy from the PTO assumes ideal movement of the linear motion (the rack) relative to the wave. This is the maximum expected power, but experimentally after the design of the buoy and the complete system, this is expected to be less than the ideal power due to the delay time needed by the buoy to react to the waves. However, this approach should estimate the maximum ideal conditions at any specific wave patterns.

Another limitation is that there is a lag observed between the simulated wave position and the reading of the strain sensor and the readings are not symmetric. This could be as a result of the load and the strain sensor. It is assumed that the 3 phase system includes only balanced resistive loads and that the current and voltage are in phase. The strain force is not symmetric which could be as a result of the movement of the generator in one direction which could be the influence of the gearing system. The strain in the test-rig structure is transferred to the sensor via two contact surfaces resulting in a change in distance. The sensor's casing represents an elastic transmission element and converts the change in distance into a shear force. This shear force produces a proportional electric charge Q (pC) in piezoelectric element. Although the sensor is calibrated in situ using a force dynamometer, there are several sources of error such as hysteresis and sensor linearity (3% and 2% FSO respectively). However, the surface roughness of installation should be Ra = 1.6 μm with flatness of 0.05 μm. In compression, due to short length of the part, the signal was not symmetric between compression and tension due to the possible deformation of the part. However, the absolute value of the maximum reading was the main objective of the study. This is one of the limitations of the experimental work.

7. Conclusion

Wave energy generation technology is still at its infancy. Research is still on-going to produce a practical and cost-effective wave energy system with suitable reliability to become commercially viable. Wave energy converters (WEC) present a complex systems with significant interaction and interdependency between the mechanical system, wave motion and the electricity generated. The paper has presented a novel approach for the design of WEC system to develop full understanding of the relationship between the mechanical motion, electric power generated and the forces exerted on the system. This will support the design of the power take off (PTO) system and from which the floating buoy mechanism can be simulated and designed. Such forces are critical when designing the interaction of the system with water based on the selected configuration. This paper simulates the ideal absolute maximum forces and electricity generated caused by a point absorber WEC configuration on the water surface connected to a core that is moored to the seabed. The linear up- and down-motion of the floating buoy is transferred via a gearing and a clutch system to one-directional rotation to generate electricity from the expected up- and down ideal motion of the buoy. The suggested test-rig and the instrumentation system has been found successful in experimentally simulating the performance of the PTO system. It has been shown that for fixed wave height and wave cycle time, different power and force values can be generated and consequently different efficiencies. This helps in, not only optimising the best design characteristics of the buoy floating mechanism on water, but also in estimating the price of the generated electricity over the life time of the wave energy generation system. Based on which, we can evaluate the commercial viability of the system. Also, the change in the load forces on the system would mean different interactions between the floating buoy and the waves, which could add complexity of the dynamic response of the complete system which will be covered in future research work.

CRediT authorship contribution statement

Amin Al-Habaibeh: Supervision, Investigation, Conceptualization, Methodology, Data curation, Formal analysis, Validation, Software, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Lama Hamadeh:** Writing – original draft, Writing – review & editing, Validation, Visualization, Formal analysis. **James McCague:** Conceptualization, Methodology, Investigation, Validation, Visualization, Software, Resources, Data curation.

Declaration of competing interest

The authors declare that there is no conflict of interest including any financial, personal or other relationships with other people or organizations that could inappropriately influence, or be perceived to influence, their work.

Data availability

Will provide the data after the paper is published

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References

Al-Habaibeh, A., Su, D., McCague, J., Knight, A., 2010. An innovative approach for energy generation from waves". Energy Convers. Manag. 51 (8), 1664–1668.
BBC. http://www.bbc.co.uk/news/uk-scotland-scotland-business-34901133. (Accessed 25 April 2022).
Cameron, L., Doherty, R., Henry, A., Doherty, K., Van't Hoff, J., Kaye, D., Naylor, D., Bourdier, S., Whittaker, T., 2010. "Design of the next generation of the Oyster wave energy converter". In: 3rd International Conference on Ocean Energy, 6. ICOE Bilbao, Spain, p. 1e12.
deLlano-Paz, F., Calvo-Silvosa, A., Antelo, S.I., Soares, I., 2015. The European low-carbon mix for 2030: the role of renewable energy sources in an environmentally and socially efficient approach". Renew. Sustain. Energy Rev. 48, 49–61.
Elavarasan, R.M., Mudgal, V., Selvamanohar, L., Wang, K., Huang, G., Shafiullah, G.M., Markides, C.N., Reddy, K.S., Nadarajah, M., 2022. Pathways towards high-frequency solar photovoltaic thermal management for electrical, thermal and combined generation applications: a critical review". Energy Convers. Manag. 255, 115278.
Falcao, F.A.O., 2010. Wave energy utilization: a review of the technologies". Renew. Sustain. Energy Rev. 14 (3), 899–918.
Fan, Y., Mu, A., Ma, T., 2016. Design and control of a point absorber wave energy converter with an open loop hydraulic transmission". Energy Convers. Manag. 121 (1), 13–21.
Garcia Novo, P., Kyozuka, Y., 2021. Tidal Stream Energy as a Potential continuous power producer: a case study for West Japan". Energy Convers. Manag. 245, 114533.
Goda, Y., 2000. Random Seas and Design of Maritime Structures". World Scientific.
Guanche, R., de Andrés, A., Losada, I.J., Vidal, C., 2015. A global analysis of the operation and maintenance role on the placing of wave energy farms". Energy Convers. Manag. 106, 440–456.
Heath, T.V., 2000. Chapter 334 – *The Development and Installation of the LIMPET Wave Energy Converter*". World Renewable Energy Congress VI, pp. 1619–1622.
Hosna, T., Mohamed, B., 2014. IEEE Electron. Appl. Conf. Expo. (PEAC), France 338–342.
http://eecs.oregonstate.edu/wesrf/. (Accessed 21 April 2022).
http://science.howstuffworks.com/environmental/green-science/salters-duck1.htm. (Accessed 21 April 2022).
http://wavestarenergy.com/. (Accessed 21 April 2022).
http://www.bbc.co.uk/news/uk-scotland-scotland-business-30151276. (Accessed 21 April 2022).
http://www.carnegiewave.com/. (Accessed 21 April 2022).
http://www.dailymail.co.uk/wires/ap/article-3797174/Developers-face-challenges-capturing-wave-energy.html.
http://www.wavedragon.net/. (Accessed 14 February 2022).
https://oceanpowertechnologies.com/. (Accessed 21 April 2022).
https://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/. (Accessed 21 April 2022).
https://www.seascapesubsea.com/wp-content/uploads/2017/03/nCentric-Flansea.pdf. (Accessed 15 April 2022).
https://www.theguardian.com/environment/2017/jan/16/uk-wave-power-far-too-costly-warns-energy-research-body.
Hussain, A., Arif, S.M., Aslam, M., 2017. Emerging renewable and sustainable energy technologies: state of the art". Renew. Sustain. Energy Rev. 71, 12–28.
Jin, S., Greaves, D., 2021. Wave energy in the UK: Status review and future perspectives". Renew. Sustain. Energy Rev. 143, 110932.
Jung, S., Shetti, N.P., Reddy, K.R., Nadagouda, M.N., Park, Y.K., Aminabhavi, T.M., Kwon, E.E., 2021. Synthesis of different biofuels from livestock waste materials and their potential as sustainable feedsticks – a review". Energy Convers. Manag. 236, 114038.
Kim, J., Koh, H.J., Cho, I.H., Kim, M.H., Kweon, H.M., 2017. Experimental study of wave energy extraction by a dual-buoy heaving system". Int. J. Nav. Archit. Ocean Eng. 9 (1), 25–34.
Li, Y., Zhang, X., Xiao, L., 2022. Parametric study on power capture performance of an adaptive bistable point absorber wave energy converter in irregular waves. J. Ocean Eng. Sci. 7 (4), 383–398. https://doi.org/10.1016/j.joes.2021.09.011. ISSN 2468-0133.
Liang, B., Shao, Z., Wu, G., Shao, M., Sun, J., 2017. New equations of wave energy assessment accounting for the water depth". Appl. Energy 188 (15), 130–139.
Mehri, S., Shafie-Khah, M., Siano, P., Moallem, M., Mokhtari, M., Catalao, J.P.S., 2017. Contribution of tidal power generation system for damping inter-area oscillation". Energy Convers. Manag. 132, 136–146.
Muller, N., Kouro, S., Glaria, J., Malinowski, M., 2013. Medium-voltage power converter interface for Wave Dragon wave energy conversion system". In: Proceedings of the IEEE ECCE, Denver (USA), pp. 352–358.
Quaranta, E., Aggidis, G., Boes, R.M., Comoglio, C., De Michele, C., Patro, E.R., Georgievskaia, E., Harby, A., Kougias, I., Muntean, S., Perez-Diaz, J., Romero-Gomez, P., Rosa-Clot, M., Schleiss, A.J., Vagnoni, E., Wirth, M., Pistocchi, A., 2021. Assessing the energy potential of modernizing the Europeans hydropower fleet". Energy Convers. Manag. 246, 114655.
Raos, S., Hranic, J., Rajsl, I., Bar, K., 2022. An extended methodology for multi-criteria decision making process focused on enhanced geothermal systems". Energy Convers. Manag. 258, 115253.
Saidur, R., Rahim, N.A., Islam, M.R., Solangi, K.H., 2011. "Environmental impact of wind energy". Renew. Sustain. Energy Rev. 15 (5), 2423–2430.
Sher, F., Iqbal, S.Z., Imran, M., Snape, C.E., 2020. Thermal and kinetic analysis of diverse biomass fuels under different reaction environment: a way forward to renewable energy sources". Energy Convers. Manag. 203, 112266.
Tan, J., Polinder, H., Jarquin Laguna, A., Miedema, S., 2023. A wave-to-wire analysis of the adjustable draft point absorber wave energy converter coupled with a linear permanent-magnet generator. Ocean. Eng. 276, 114195 https://doi.org/10.1016/j.oceaneng.2023.114195. ISSN 0029-8018.
The international energy agency. https://www.iea.org/reports/global-energy-review-2020/renewables. April 2022.
Tsang, K.M., Chan, W.L., 2015. Direct AC–AC grid interface converter for ocean wave energy system". Energy Convers. Manag. 92 (1), 302–311.
Wave Energy/Technology Brief, Int. Renew. Energy Agency, http://www.irena.org/documentdownloads/publications/wave-energy_v4_web.pdf.
Weiss, C.V.C., Guanche, R., Ondiviela, B., Castellanos, O.F., Juanes, Jose, 2018. Marine Renewable Energy Potential: a global perspective for offshore wind and wave exploitation". Energy Convers. Manag. 177, 43–54.
Yang, Injun, Tezdogan, Tahsin, Incecik, Atilla, 2023. Numerical investigations of a pivoted point absorber wave energy converter integrated with breakwater using CFD. Ocean. Eng. 274, 114025 https://doi.org/10.1016/j.oceaneng.2023.114025. ISSN 0029-8018.
Zhang, H.C., Xu, D.L., Liu, C.R., Wu, Y.S., 2016. Wave energy absorption of a wave farm with an array of buoys and flexible runway". Energy 109 (15), 211–223.