Webology (ISSN: 1735-188X)
Volume 18, Number 6, 2021

Modeling And Simulations Of Wave Energy Converter Using MATLAB WEC Toolbox

[1]Mr. Dhananjay Khankal , [2]Dr. R. L. Edlabadkar

[1]Research Scholar, Department of Mechanical Engineering, Sinhgad College of Engineering, Vadgaon (Bk.), Pune, Maharashtra, India.

[2]Professor, Department of Mechanical Engineering, PVGs College of Engineering Technology, Pune.

Abstract

Ocean waves have the potential to help meet the world's electrical demand. Wave energy converters are used to transform energy from the waves into useful electrical power. The wave energy converter must be modelled in order to assess different features of the device without having to create the system in real time. MATLAB was used to model the Novi Ocean wave energy converter. The goal of this thesis is to use WEC-Sim, an open-source code that is a Simulink extension, to simulate this device. It was discovered that modelling the device in WEC-Sim was easier than in MATLAB. The WEC-Sim model yielded results that were similar to those of the MATLAB model. A basic controller was also used to control the turbine's output torque. It was also learned that WEC-Sim provides for smooth controller integration with the device model.

1. Introduction

Wave Energy Converter: A Brief Overview

Energy is one of the major inputs for the economic development of any country. In the case of the developing countries, the energy sector assumes a critical importance in view of the ever-increasing energy needs requiring huge investments to meet them. There are numerous sources of electricity production such as coal, oil, and natural gas, which contributes to one-third of global greenhouse gas emissions. Emission of greenhouse gas ultimately affects global warming and environmental changes. To reduce this effect, it is necessary using cleaner form energy source which further raises standard of living. Many countries have started to install facilities that use renewable energy sources for power generation. The importance of alternative energy sources comes together with climate changechallenges associated with the excessive use of fossil fuels. There are three primary motivators that stimulate the growth of renewable energytechnologies: energy security, economic impacts and carbon dioxide emission reduction [1,2]. Wave energy is one of the reliable and plenty available sources of energy in terms of sea waves. New technology development is based on the utilization of energy; hence every country needs more energy [3,4]. In fulfilling the need of energy requirement wave, energy extraction is the best choice. This wave energy is available in infinite amounts, and only one location is sufficient to extract the energy, so in the upcoming year, this area can play a crucial role in the countries development. In the world number of oceans are available such as Indian, Antarctic, Atlantic, Arctic, Pacific; in this ocean, the best energy resources are available in extracting energy. Each oceanic energy source has a relevant potential for human applications; however, as shown in Table 1.1, sea waves and marine currents have the highest energy potentials

Table 1.1. Potential installable capacity and energy production from marine energy sources.

Ocean Energy	**Capacity (GW)**	**Potential Generation (TWh/y)**
Tide	90	800
Marine currents	5000	50,000
Osmotic salinity	20	2000
OTEC (Ocean Thermal EnergyConversion)	1000	10,000
Sea wave	1000–9000	8000–80,000

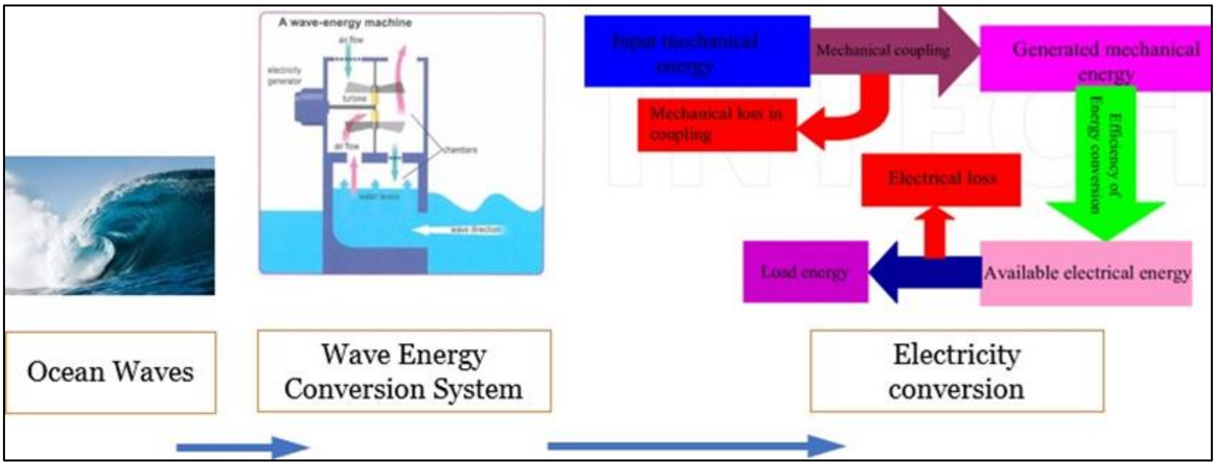

Figure 1.1 Typical Energy flow in sea wave energy conversion Wave energy converters are devices that converts the kinetic

energy and potential energy with moving ocean waves into usefulmechanical or electrical energy. Figure 1.1 shows the typical conversion of sea wave energy into useful electricity [6].
In-line with above concepts various WECs (Wave Energy Converter) Devices developed and tested at different locations across the world. It's difficult to extract the full capacity of the sea wave and convert it into electricity or any other useful form of energy. The wave energy field will play a crucial role in the upcoming year because waves traveling at long distances and negligible losses; hence energy generation is easy. Up to the present year, minimal wave energy has been extracted [7][8]. In recent years different onshore and offshore project is designed and developed. In this developed project, water column motion has been transformed into electrical power. The large-scale wave farms are not generating; hence it is hard to envisage the future of this manufacturing [9]. In the wave energy industry, to accelerate the development, it is necessary to replace the wind parks with wave energy convertor device. The influence of wave farms onthe nearshore process generally occurs and impacts the nearshore waves, and coastal processes study is necessary [10]. Also, evaluating the coastal impact

of wave farms is necessary for energy generation [11].
Due to extreme conditions present in the Antarctic and the Arctic Ocean, it is not easy to extract the wave's energy. Also, installed projects in this ocean are currently facing the issue regarding the generation of energy. In this area, the generation of wave energy found that these areas are not suitable for energy generation[12]. Due to the availability of larger water surface and marine resources, it can use it largely in the entire world. Many energy extraction options are available in energy generation, including tidal, wave, ocean thermal energy, marine biomass, and submerged geothermal energy[13]. Hence, wave power has many advantages: waves are abundant and widely available and provide an almost limitless source of energy without producing greenhouse gases.

Literature Review

Wave energy conversion (WEC) devices are classified by various categories which are outlined as below

Location Specific: WEC's are typically separated into shoreline, near- shore, submerged, and offshore devices. Cable costs and incident wave power intensity are competing economic factors because they both decrease with proximity to shore. Although shoreline devices fit well with breakwater structures, they typically require more structural material than floating devices, due to the impact stresses from breaking waves, and suffer from "not-in-my-back-yard" (NIMBY) issues due to the requirement for particularly unattractive structures in coastal locations. Since the kinetic energy part of the wave power transport decays exponentially with water depth, submerged devices are exposed to less incident wave power and are expected to suffer from complex deployment and maintenance procedures [26].

Operating Principle Specific: WEC's can be separated into oscillatingwater columns (OWC), over-topping devices (OTD), and wave- activated bodies (WAB). OWC devices are afflicted with thermodynamic losses resulting from the pressurization of air, and noise issues with large air turbines. OTD's offer relatively smoothpower output but tend to be extremely large devices that require huge capital investments. WAB's, a category that encompasses a diverse range of devices that operate from single modes or combinations of translational and rotational modes, are typically the most compact and efficient devices.

Directional Characteristics specific: WEC's are typically separated into point-absorbers, attenuators, and terminators. Point absorbers, attenuators, and terminators, absorb energy from a single point, from a line parallel with the direction of 3 wave propagation, and from a line perpendicular to the direction of wave propagation respectively [28].

Tidal energy: The energy from the tides is extracted from a rise and fall of the water due to the gravitational action of the moon and the sun.This energy occurs as the potential energy of the tides, which is pulled by building dams and as the energy of the tidal current, which isextracted using different types of turbines. The difference in height thatcan be reached varies from one meter up to twenty meters, depending on the place, but the one needed to produce economically sustainable energy corresponds to just over 3 meters [28,29].

Waves energy: Wave energy is taken under the magnification lens in this thesis work. It is considered to have the highest density on earth, even higher than solar and wind energy. It highlights how the farther are from the equator, the greater the concentrated energy. The principleof energy generation derives from the force of friction that the wind exerts on the surface of the sea. Unlike other renewable technologies, despite the seasonal variability, it is possible to satisfy the demand for electricity and, finally, the waves have a negligible energy loss even though they cover several kilometers [26,27].

Heliothermic energy or temperature gradient (OTEC): The difference in temperature between the surface and the depths of the sea/ocean better works when there is a delta of at least 20 ° C. Three types of OTEC systems can be used: closed cycle, a low boiling point fluid is used which evaporates with the surface water and condenses with that taken in depth; open cycle, uses low pressure steam which is pure because the water evaporating deposits the salt in a low-pressure vessel; hybrid, it is a mix between the two previous cases that synergistically exploits the thermal difference for the production of electricity or desalination of the water.

Salinity gradient: Energy from the salt gradient, or osmotic power, in exploiting the different concentration of salt between fresh (or brackish) water and sea water [28]. The operating principle is based on the difference in concentration of the salts dissolved in the water. Whenthe two liquids mix, a ionic current is formed with the purpose of balancing the salt concentration between the two masses of water in contact. This is because salt water, unlike fresh water, has a highconcentration of positive ions (protons) and negative ions (electrons).A membrane is then inserted which has the task of controlling this process and which allows, always in a controlled manner, the passageof positive and negative ions only in a certain direction. Two pilot-scale ocean salinity gradient (SGO) technologies have been developed: reverse electrodialysis (RED) and pressure-delayed osmosis (PRO) Earth's surface is covered with 70% moving and oscillating water (tides and waves), these tides and waves have the potential as an environmentally friendly energy source [29]. Ocean surface gravity waves, generated by the transfer of wind energy to the ocean surface,
are a vast source of clean and renewable energy. The total wave power incident on all the world's coastlines has been estimated to be 10 TW, the same order of magnitude as the world's total current power demand. As wind energy is transferred to wave energy, the energy density improves. The spatial concentration increases from an average wind power intensity of 0.5 kW per square meter of area perpendicular to the wind direction, at a height of 20 meters above the sea surface, to an average of 2-3 kW per square meter perpendicular to direction of wave propagation just below the sea surface. An increased public awareness of environmental and energy issues has stimulated a world- wide increase in support for the development of renewable energytechnologies. As a result, a proliferation of wave energy device developers is occurring globally [30,31]. However, immediate public acceptance of wave energy has not occurred because wave energyconversion technology and government policy are relatively immature compared to wind energy parallels, and there are no fully commercialized wave energy devices at this time. Nevertheless, all these concepts can be classified depending on different criteria. If the criteria used to classify WECs is location, three different groups can be identified.

Recent development in WEC

In recent years much research is happening in wave energy converter design, modelling, and simulation. In the present section, recent development in WEC has been discussed.

The dissimilar structures of a five-device array of spar-buoy oscillating-water-column WEC are in a wave basin, aiming at the investigation of the device's motion plus the mooring line loads. In extreme

and moderate wave conditions, tests were conducted. Results confirmed that in moderate wave conditions, results are good. The peaktension was observed in extreme wave conditions. With obtained results, strategies for the design of mooring system in compressed WEC array were implemented [40].The replacement of the traditional approach, i.e., an orifice plate with an axial flow turbine on an oscillating water column (OWC). In regular wave, condition experiments were performed with OWC. During experimentation, air pressure variations and torque output of the turbine were recorded. In various wave conditions, primary and secondary stage efficiencies werecalculated [41]. Numerical analysis and experimental validation were carried out for two-body point absorber WEC using mechanical motionrectifier-based power take-off. The experimental study shows that two body WEC produce twice power than single body WEC. Frequencyand time-domain analysis of wave simulation were compared in the present study [42].The experimental analysis of power conversion of wave energy convertor using hydraulic power take-off mechanism. In improving performance in this system, control strategy and modification of accumulator pre-charged pressure were used. Results confirmed that the system works in the best condition under different input wave conditions [43].For the onset of parametric resonance in WEC's real time detection system, this study was developed. With the help of a case study, detection system performance was validated. The results show that the detection system achieves 95% accuracy for nearly 7000 sea states. For monochromatic waves, 99% accuracy was obtained [44]. Simulation and experimental method were used to investigate the influence of the ram shape parameters on the overtopping wave discharge. In Malaysia's wave condition, seven different ram shapes were tested. This new ram parameter allows maximizing overtopping waves on the overtopping breakwater for energy conversion [45]. In the US Navy's wave energy test site in
Hawaii, numerical wave modelling for operational and survival analyses of wave energy convertors was carried out [46].

Renewable energy sources are essential to our future, not only because they generally minimize harm to our environment but are also a relatively free source of energy that are available for generations to come. Wind and solar energy are proven sources of renewable energy, but both are highly variable [47,48,49]. On the other hand, water wave energy is relatively persistent in locations around the world. Many researchers have tried to capture the energy of ocean waves, some were successful, but most were not. Harnessing wave energy is not a simple matter [50,52]. One must design systems thatcan withstand the extreme forces of waves, the corrosive nature of salt water, and biofouling effects that can impact the system, while safely extracting energy from waves.

Description of the Research Work

Sea wave energy converters involves various research activities such as design, model (mathematical as well as CAD models), simulatethe developed models and identify the performance in terms of efficacies and output. Previous section clearly mentions four objectives of current research work and are achieved through specific methodology and is outlined as below,

2. Research Methodology

Renewable energy is a practical way to produce more energyfor humans to use. There are many ways that power can be produced from natural phenomena. The general process is to take a force that occurs naturally then turn that force into rotational motion to turn a generator. Another way is to use solar energy to gather the sun’s rays and send that energy to the grid. A problem that occurs with both ways is that the power produced is very inconsistent. To accomplish the aim and objectives mentioned in the previous mentioned Section, the following methodology is proposed. This methodology is subdivided into four major tasks as below Various systems are developed for extracting the energy from sea waves. This task one east devoted for collecting research articles on investigations on drive energy generation utilization

Task 1: Study of WEC (Wave Energy Converter) systems
Task 1 is devoted to the study of WEC systems developed for extracting sea wave energy. When initiating studies in this field andlooking for references, there is a clear lack of suitable textbooks which simultaneously approach wave theory, modelling techniques and results from technology developers. Thus, there is a need to address in detail the main energy conversion possibilities and exemplify themwith the concepts that have endured through all stages of development, reaching full-scale. Additionally, an account of the operationalexperience gathered by the technology developers is of great value to engineers and scientists who wish to work in the area or increase their knowledge of the subject. This task conducts literature review andcompiles information about WEC systems and identifies possible research gaps and future scope of the work.

Task 2: Mathematical Modeling of WEC Device
Wave energy is created by wind, as a by-product of the atmosphere's redistribution of solar energy. Deep water surface waves are oscillations of the sea surface layer under gravity and, to a good approximation, they consist of the linear superposition of a large number of simple components. The fundamental modelling strategies and results are referenced to the key papers in the discipline and thefew existing review articles are referenced whenever possible. Task 2 involves mathematical modeling of hydrodynamics of sea waves andits effect on WEC systems. Task 3 further involves modeling of sea waves, kinematic modeling of WEC devices and interactions of sea waves and kinematic modeling using the first principle of modeling.

Task 3: Theoretical Investigation of WEC System using MATLAB Simulink Toolbox
WEC-Sim (Wave Energy Converter-Simulator) is an open- source wave energy converter (WEC) code capable of simulating WECs of arbitrary device geometry subject to operational waves. The code is developed in MATLAB/Simulink using the multi-bodydynamics solver Sim Mechanics, and relies on Boundary Element Method (BEM) codes to obtain hydrodynamic coefficients such asadded mass, radiation damping, and wave excitation. Wave energy converters are designed to operate in certain wave climates or sea- states, and most of the device developers today have machines designed for Atlantic conditions where the wave energy potential is the greatest. The wave conditions do not only set the size of the WEC, it also determines the characteristics of the PTO point absorber devices can be designed (using MATLAB-WEC Simulink Toolbox) to work at nearshore and offshore sites and at most sea states and can be designed for short or long wave periods. Task 3 involves modeling of PTO system using MATLAB Toolbox and simulate using Boundary Element Method and identify the performance of PTO systems.

Task 4: Validation of simulated WEC Systems
The results obtained from (output. Mat) MATLAB data fileis shown in the power matrix. Power matrix is a means of representing the output power values when there are two input variables as height and period. Task 4 involves simulation of various PTO systems and comparing its performance in terms of its power generation capacity, efficiency and effect of waves (different types of sea waves

as input)on the PTO device. These simulated (using WEC-sim MATLAB toolbox) results are further compared with available literature. Comparison will help in future to optimize the design according to available location, sea wave patterns.

Outcomes:

Following tangible outcomes would be derived from thisresearch work related with objectives
A detailed review on the accuracies and limitations of previously derived and implemented WECs and PTOs will be presented. Various PTO systems are mathematically modeled and further simulated using the MATLAB toolbox WEC-Sim. The results obtained from the PTO models will be compared against research articles and performance of the wave energy converter will be validated. The results obtained from the simulation will be compared against previously published results and performance of thewave energy converter will be evaluated and its cost effectiveness will be analyzed.

3. Result And Discussion

The WEC WEC-Sim model was simulated in regular and irregular wave conditions with and without latching control and the results are presented. The simulation was performed for a time span of 300 s. A high-level view of the WEC-Sim's function can be seen in the figure 3.1. A WEC- Sim model requires a set of input files. The outer surface of the float of the device must be defined in the WEC geometryfile. The hydrodynamic coefficients need to be generated using a boundary element method (BEM) code. Using the WEC-Sim library blocks the WEC should be modelled as a Simulink/Sim scape file. If theWEC uses a hydraulic PTO system, this can also be designed using the library blocks in the Simulink/Sim scape model.

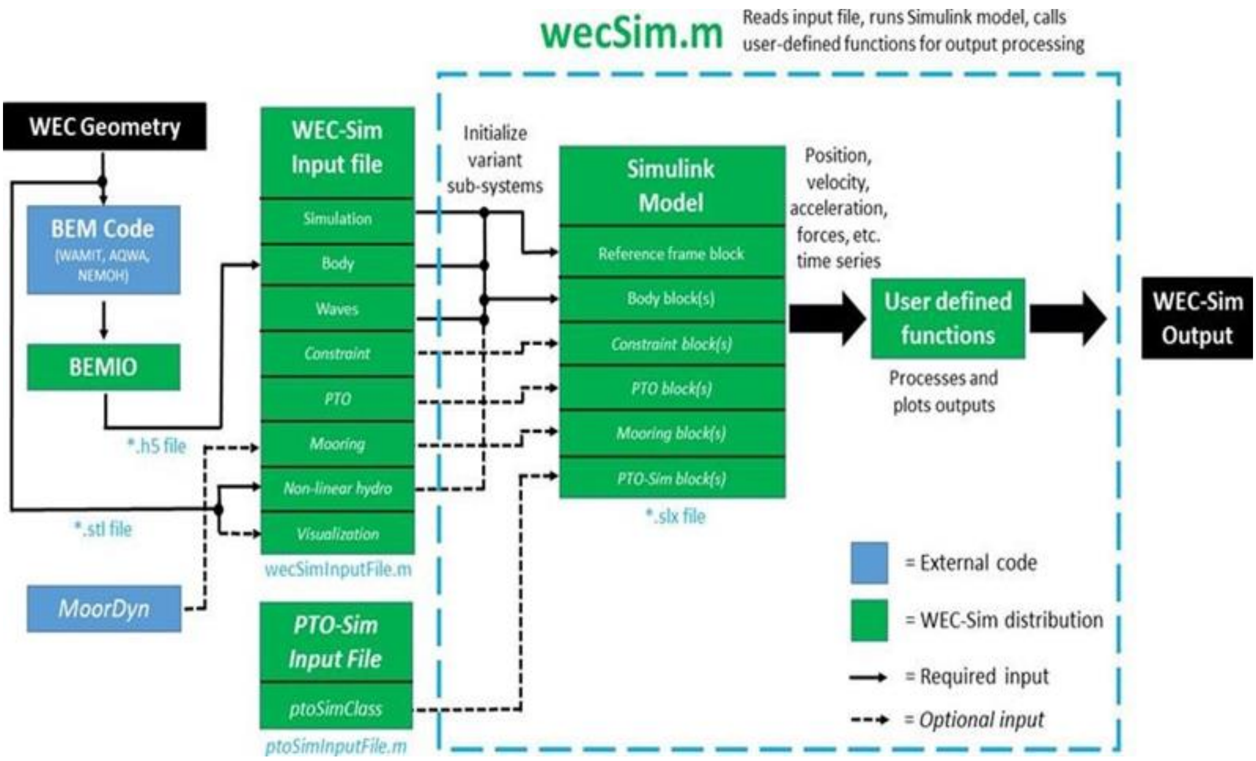

Figure 3.1 WEC-Sim workflow diagram

WEC-SIM Input Files

Geometry File

WEC-Sim requires the geometry of the float in the Stereolithography (.stl) file format. This can be done using any computer-aided design (CAD) program. The float can be modelled using a CAD program and later exported to the required .stl file format. WEC-Sim requires the geometry file only for the Sim scape Mechanics Explorer visualization when linear buoyancy is assumed. The rectangular float of the WEC has a surfboard design. For the ease of designing, the float was designed to be rectangular without thecurved edges resembling a cuboid as in figure 3.2.

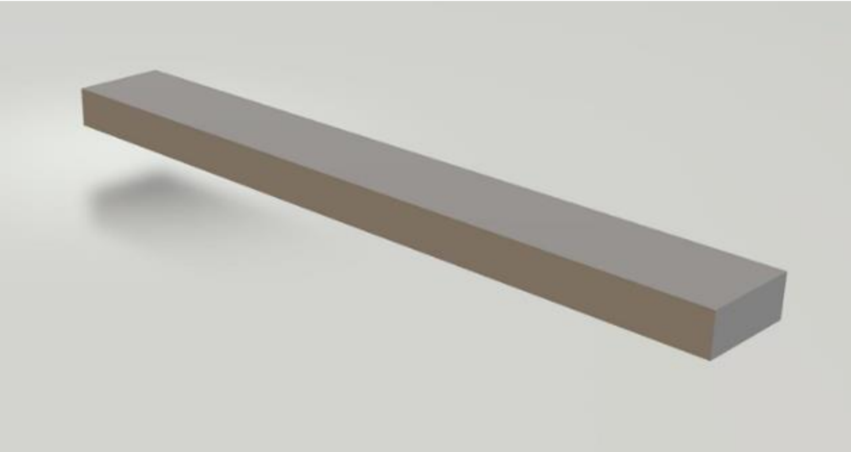

Figure 3.2 The rectangular float modelled using Free CAD.

Hydrodynamic Data

The hydrodynamic coefficients required by WEC-Sim can begenerated using any program that uses BEM code. WAMIT was the program used in this research work. The float was assumed to be rectangular similar to the geometry file. Among the possible output files from WAMIT, only the added mass and damping coefficients and the exciting forces from diffraction potentials are needed by WEC-Sim.Also, the hydrodynamic coefficients need to be generated with respect to wave periods and not wave frequencies. WEC-Sim only requires the .OUT file that is acquired from WAMIT.
The .OUT file needs to be converted into the hierarchical data format 5 (HDF5) in order to be accessible to WEC-Sim. To make this possible, WEC-Sim has developed a pre-processor code called boundary element method input/output (BEMIO). The BEMIO code reads the hydrodynamic data from WAMIT and calculates the radiationand excitation impulse response functions. It also calculates the state space realization for the radiation impulse response functions. This BEMIO code then saves the results in the HDF5 format (.h5 file).

SIMULINK MODEL

WEC-Sim requires a Simulink/Sim scape model (.slx) file, which can be created using the additional WEC-Sim library blocks as seen in figure 3.3 and 3.4. The geometry of the float can be coupled to the model using the rigid body block. In every model the global reference frame is important as it acts as the seabed. The PTO system can be designed using simple translational PTO block if they are linear systems. If the WEC has a mechanical drivetrain or a hydraulic drivetrain as a part of the PTO system, PTO-Sim can be used.

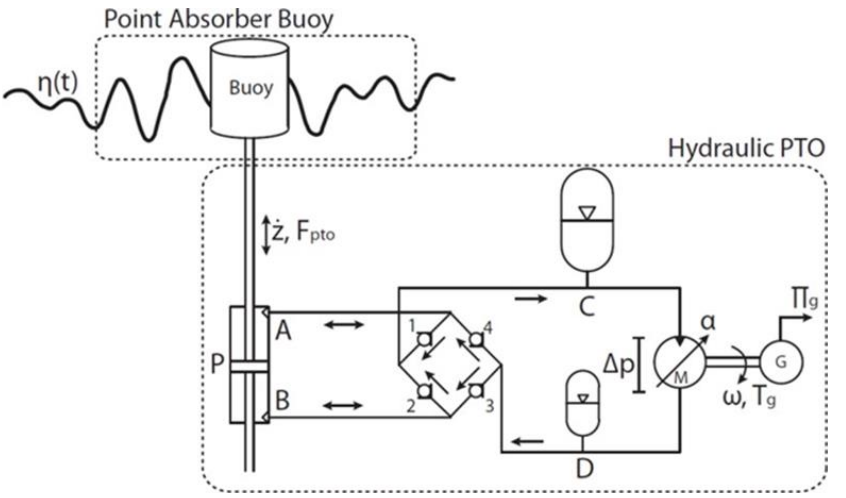

Figure 3.3 Schematic of the PTO-Sim hydraulic model. The arrow indicate thedirection of flow.

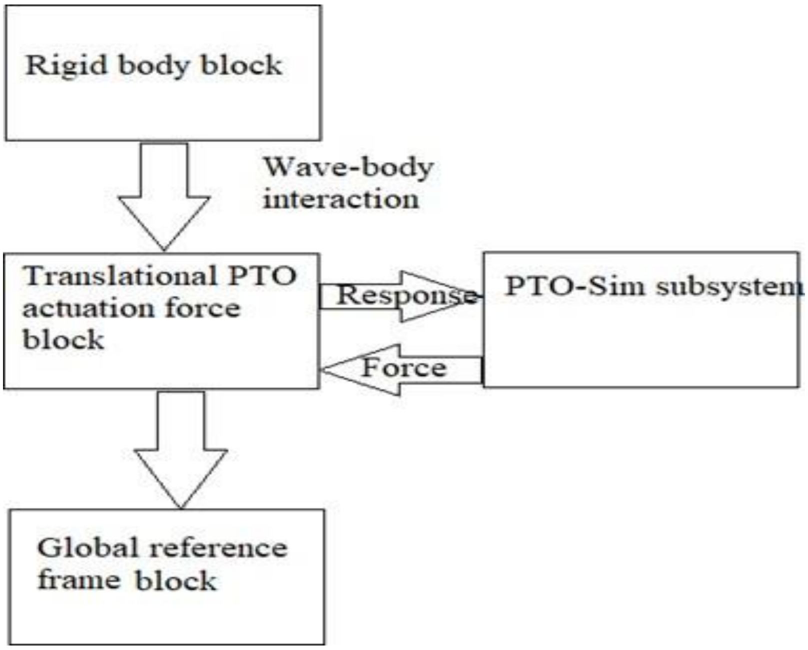

Figure 3.4 Schematic showing the implementation of the Simulink model for theNovi Ocean WEC.

PTO-Sim is an additional WEC-Sim module that is used to model more complex PTO systems. The PTO-Sim library has many additional blocks that can be used, or new subsystem blocks as required can be created. In the case of the WEC, the inverted hydropower plant PTO system needed to be modelled. This was done by using a combination of the PTO-Sim library blocks and other subsystems that were designed specifically as described in figure 3.5.

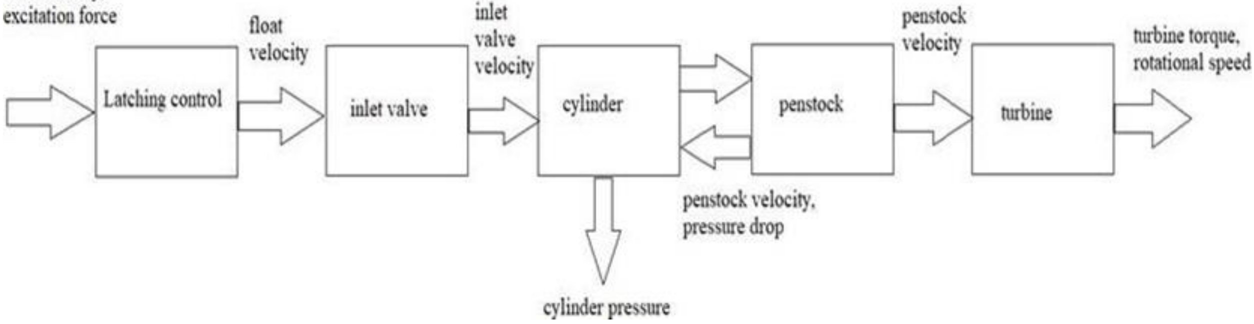

Figure 3.5 Schematic showing the implementation of the PTO system of the NoviOcean WEC.

WEC-SIM INPUT FILE

For every run, WEC-Sim requires a WEC-Sim input file that specifies the simulation parameters, wave conditions and bodyproperties. This file must be named 'wec Sim Input File. m'. This input file is divided into classes which initialize the objects required and also describe the components that are required to run WEC-Sim. The simulation parameters and the solver settings that are required to run the WEC-Sim model are initiated in the simulationclass. The simulation model also needs to be specified in the simulationclass.

The wave class defines the wave types and wave parameters.It helps in stating if the waves are regular or irregular and also the wavespectrum used. It is also possible to use any type of wave spectrum by feeding in a data file defining the wave spectrum. The body class defines the mass and hydrodynamic properties of each body in the WEC. This also specifies the location of the hydrodynamic data file and the geometry file. The different parameters in the body class are presented in Table 3.1. The moment of inertia of the float was calculated using (3.1),(3.2), (3.3) which are the equations that calculate the moment of inertia for a solid cuboid along the 3 axes.

$$I_h = \frac{1}{12} m(w^2 + l^2) \tag{3.1}$$

$$I_l = \frac{1}{12} m(h^2 + w^2) \tag{3.2}$$

$$I_w = \frac{1}{12} m(l^2 + h^2) \tag{3.3}$$

where m is the mass of the solid cuboid, h, l, w are the height, length and width of the solid cuboid respectively and I_h, I_l, I_w are the moment of inertia of the solid cuboid along the 3 axes. Similar to the other classes, the PTO class defines the properties of the PTO system. The specified input parameters values are fixed in each simulation process, but each time the height and period of waves are changed according to the data listed in Table below. Thus, each simulation contains wave data in a particular month of the year to measure the average power.

Table 3.1 Mean values for Height and period of sea wave

Mean Wave Height(m)					
JAN	**FEB**	**Mar**	**APR**	**MAY**	**JUN**
0.57-1.07	0.63-1.13	0.5-1	0.5-1	0.45-0.95	0.43-0.92
JUL	**AUG**	**SEPT**	**OCT**	**NOV**	**DEC**
0.41-0.91	0.43-0.93	0.42-0.92	0.44-0.94	0.55-1	0.54-1
Mean Wave Height(s)					
JAN	**FEB**	**Mar**	**APR**	**MAY**	**JUN**
4.1-5.7	4.2-5.8	3.8-5.4	3.7-5.3	3.6-5.2	3.5-5.1
JUL	**AUG**	**SEPT**	**OCT**	**NOV**	**DEC**
3.4-5	3.5-5.1	3.4-5	3.5-5.1	3.9-5.5	3.9-5.5

Simulation Results

WEC-Sim Matlab tool is used in the simulations of project for (3600) seconds in each simulation and step time (1) s, PTO Stiffness Coeff. K equal zero N/m, PTO Damping Coeff. c (1200000) KNs/m in the irregular waves environment with (BS) wave spectrum type. The results obtained from (output.mat) Matlab data file is shown in the power matrix Table 3.2. power matrix is a means of representingthe output power values when there is two input variables as height andperiod.

Table 3.2 Power Generated in PTO model i.e., Power matrix (in watt).

T\H	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1	1.5
3.5	198	252	312	377	452	524	613	704	798	903	1009	1134	1252	2815
3.7	3.4	386	478	579	688	811	941	1071	1213	1372	1528	1706	1910	4300
3.9	442	566	609	839	995	1181	1362	1570	1776	2011	2248	2518	2780	6285
4.1	624	789	963	1161	1393	1626	1887	2174	2468	2786	3145	3504	3849	8802
4.3	826	1052	1300	1566	1854	2200	2549	2943	3303	3730	4219	4711	5182	11657
4.5	1074	1364	1673	2030	2427	2833	3298	3737	4265	4783	5383	6015	6704	15030
4.7	1351	1687	2093	2523	3047	3534	4087	4726	5363	6064	6823	7572	8370	18981
4.9	1644	2055	2526	3083	3649	4304	5004	5690	6506	7374	8255	9123	10281	2277
5.1	1941	2420	3011	3664	4345	5091	5943	6813	7819	8667	9770	10892	12021	27009
5.3	2244	2831	3478	4212	5069	5921	6795	7921	8951	10085	11185	12627	13929	31502

Figure 3.6 demonstrate the average electrical output power available for each month of a year. It is observed that, the month of February will provide more available power compared to other months in the year.

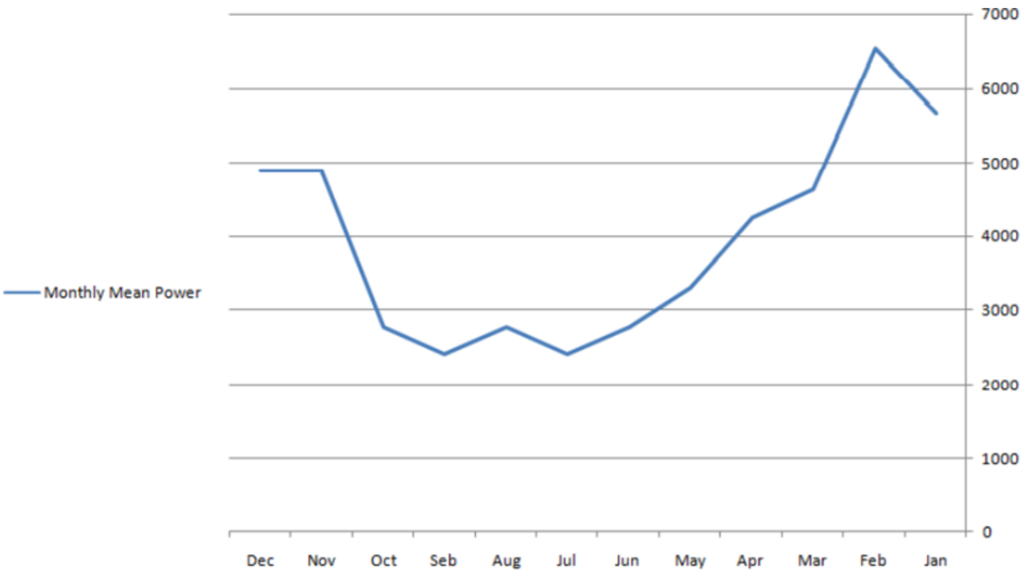

Figure 3.6 Monthly mean power of the results in the power matrix

Figure 3.6 shows the monthly mean power of the results in the power matrix according to the values of waves height and period ineach month. From the power matrix we note that the highest value that can be obtained from the device is 31.5 kW when T=5.3 s and H=1.5 m during January and February. At the same time, when the monthly average is taken, we find that it doesn't exceed the 6.5 kW which is capable of lighting about 5 homes. While in the lower average, we findthat it doesn't exceed the 2.4 kW which is capable of lighting about 2 homes only. These results mean that the output power produced from the device can be up to average 6.5 kW during the winter and 2.4 kW during the summer. In the autumn and spring, the output ranges between 2.4-6.5 kW; however, there are a vast difference.

Since the wave height and period are the two main input variables on the output power. Figure 3.7 shows the relationship between each of them and the output. From Figure 3.8 and 3.9 it is clear that the output power is proportional to the two input variables height and period for waves. However, it is noted that there is a difference in effect degree of each on the power output. When height ismore than 1 meter rise there is a greater difference in the outputincreasing, while the output increases regularly with increasing period.

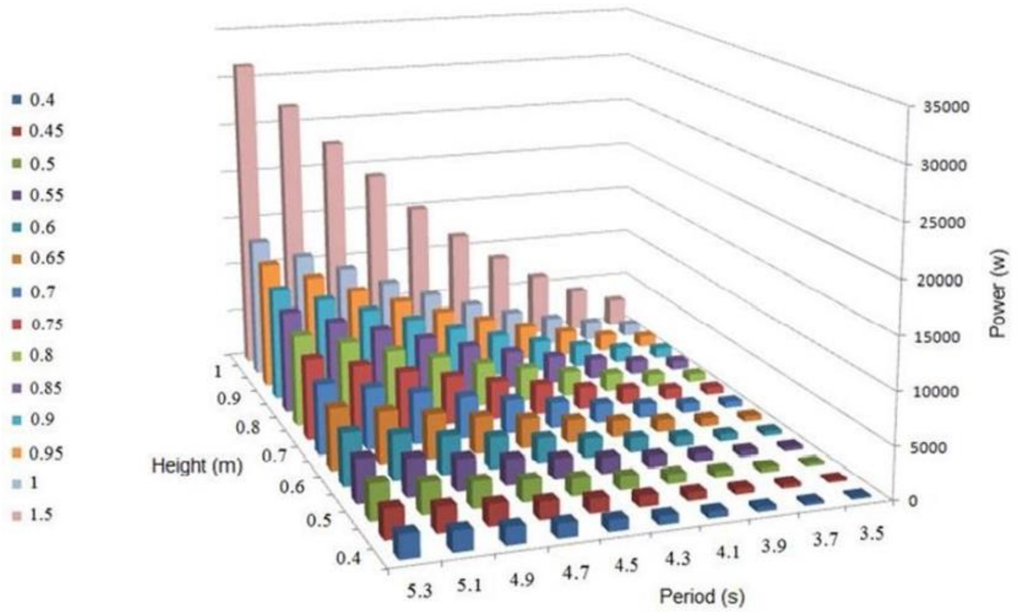

Figure 3.7 The impact of the height and period of waves on the power output

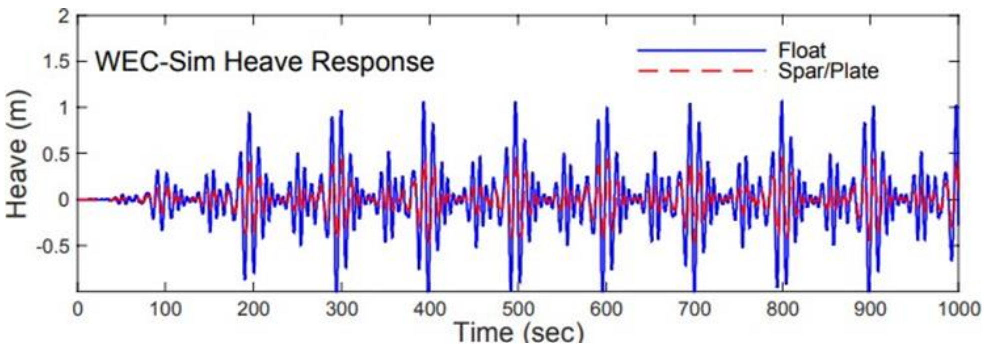

Figure 3.8 Performance of WEC and heave response of float and spar/plate

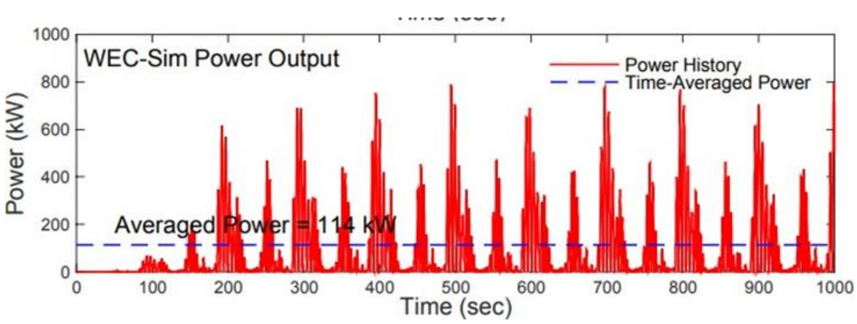

Figure 3.9 Performance of WEC device output is measured as power history and time averaged power.

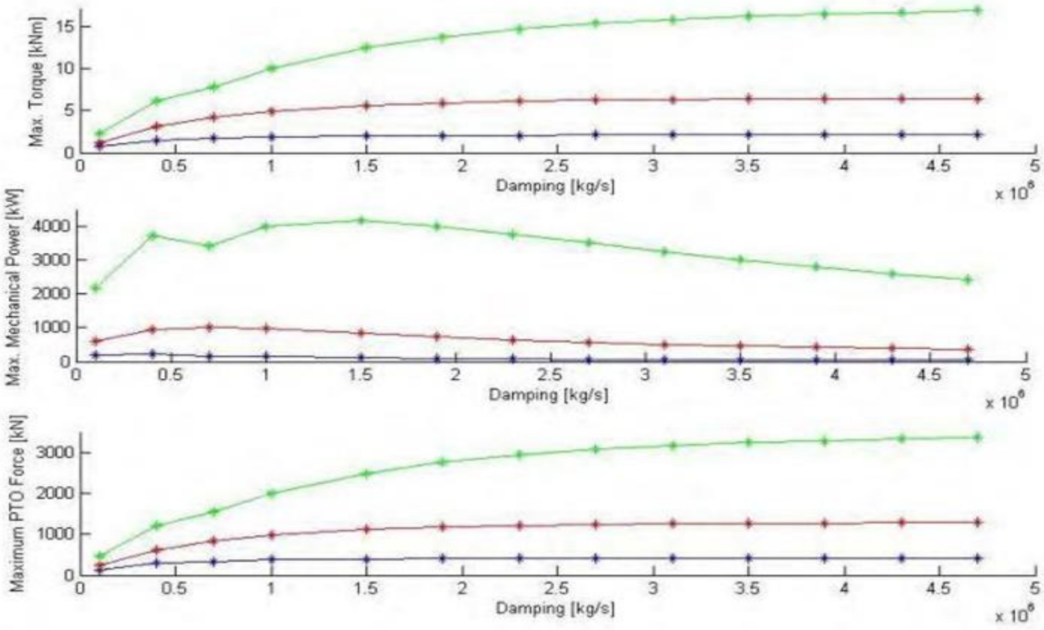

Figure 3.10 Maximum values of Torque, Mechanical Power, PTO force

Figure 3.10 shows the behavior of the maximum torque in module, maximum mechanical power and maximum PTO force inmodule reached during the 900 seconds of simulation. The trend of the torque is equal to the PTO force, because the PTO force multiplied for the `pinion radius (rw=0.1 m) and divided the gear ratio (ng=20) is equal to the torque. Increasing the BL coefficient, the PTO force increases and achieves an asymptote (different for each energy sea state). The diagrams in figure are useful to understand better the sizing of the electrical machine.

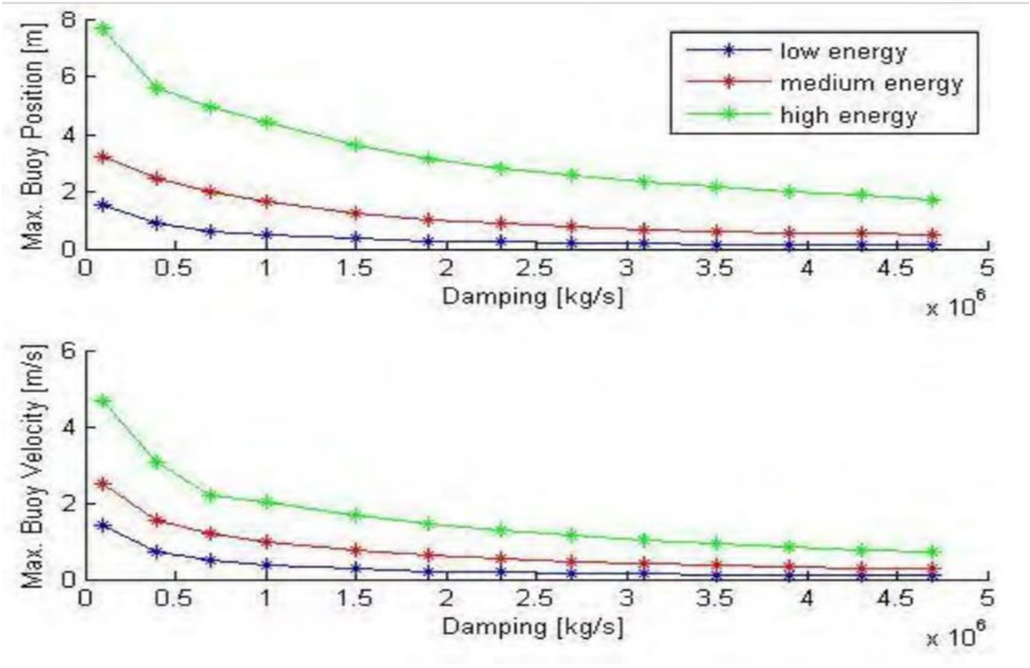

Figure 3.11 Maximum Values of Buoy Position and Velocity

In figure 3.1 the maximum values of buoy position and velocity are shown. As expected, if the damping coefficient increases the position and the velocity of the buoy decrease, this effect is due to high values of PTO force applied that force the buoy to have a lower oscillation. Furthermore, wave-wire model is developed using MATLAB-Simulink and shown in Figure 3.12, that has the task to connect the integrated wave-to-wire model to the grid, is added. In figure the integrated wave-to-wire model with the grid connection is represented (AFE stands for active front end). For understanding betterthe behavior of the system, the simplified model of the point absorber wave energy converter

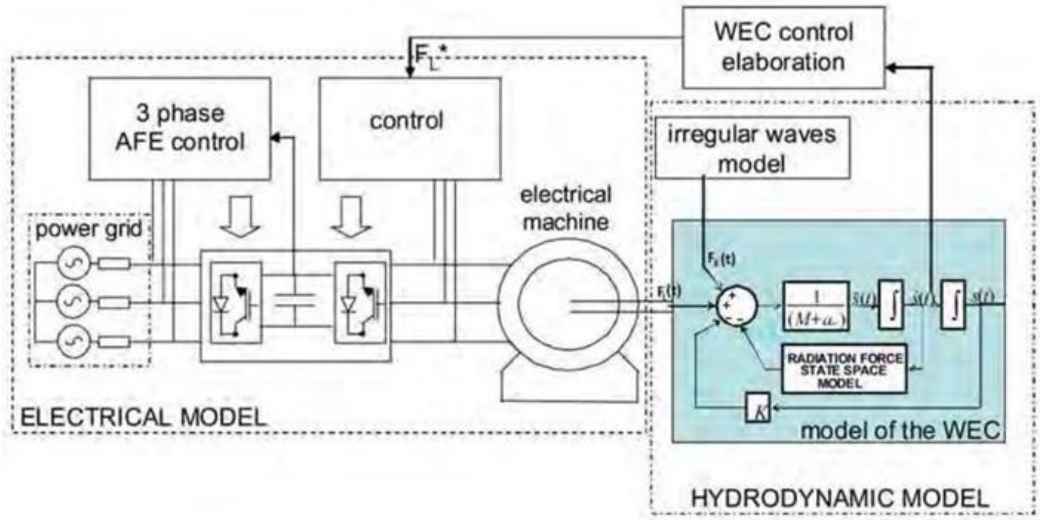

Figure 3.12 Wave – wire model (grid connected model for WEC)

In figure 3.13, it is seen that the wave-to-wire model, up to the DC link, is equal to the model used in the simulations. The mediumenergy sea state is tested with the damping coefficient equals to 4300000 kg/s. In the next table the data of the grid connection, which have been used in the simulation, are shown in table 3.3 model with grid connection Both the inverters are considered ideal and the switching frequency of the grid side inverter has been chosen equal to the switching frequency of the inverter that controls the PMSG. The filter resistance, the filter inductance, the capacity of the capacitor and the DC link voltage have been chosen. The goals of the simulation of the wave-to-wire model with the grid connection are: find the trend over the time of several important quantities of the system, prove that the power generated by the PTO can be effectively injected into the grid and prove that the current is injected into the grid with a unity power factor. The simulation time of 50 s has been considered enough to prove the goals. In figure above the trend over the time of the position of the buoy, the torque of the generator, the generator speed, the mechanical power, the DC link voltage and the grid current are plotted.it can be noticed in figure a correlation between the DC link voltage, the grid current and the low-frequency oscillations of the sea waves. It can be seen that the oscillations of the generator speed correspond to fluctuations in the DC link voltage and in the grid current waveform. Also, the trend over the time of the generator torque, generator speed and mechanical power are plotted. As expected, the torque and the speed of the generator have always the same sign and the mechanical power produced is always positive. It can be seen clearly the influence of the torque limit and the power limit on the trend of the waveforms.

Table 3.3 Data of the grid connection

Quantity	Value
Peak amplitude of the grid voltage, Vg	230 V
Grid frequency, f	50 Hz

Switching frequency of the inverters, f_s	2000Hz
Filter resistance, R_f	0.028 Ω
Filter inductance, L_f	0.0009 H
Capacity of the capacitor, C	0.033 F
DC link volage, V_{dc}	800 V

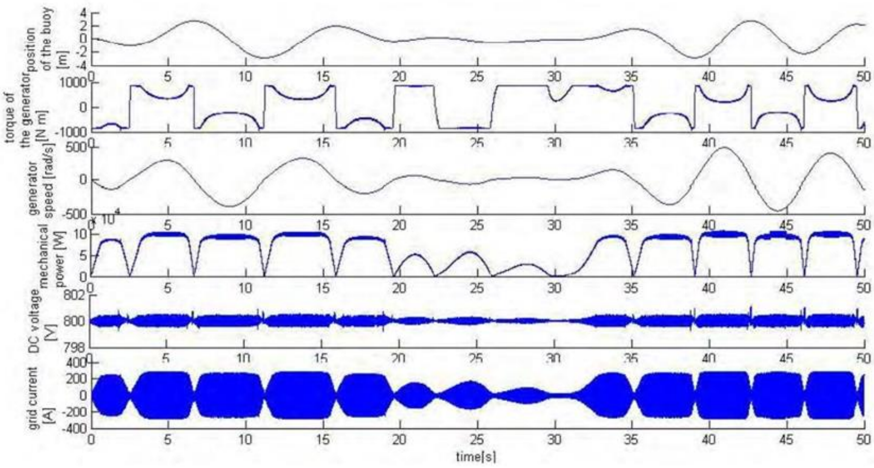

Figure 3.13 Trend over the time of important magnitudes of the wave-to-wire

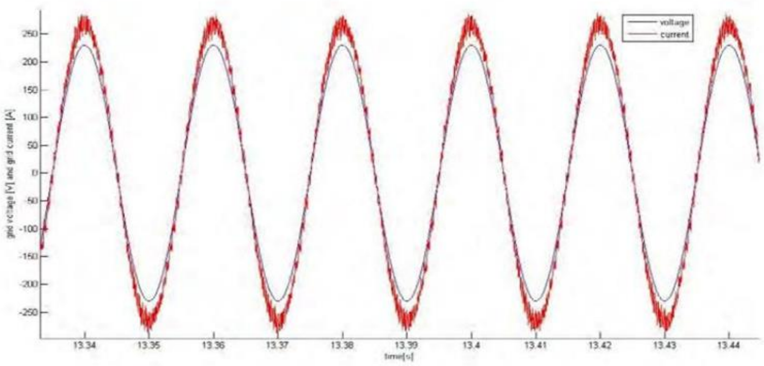

Figure 3.14 Detail of the grid voltage and grid current over the time

In figure 3.14 the voltage and the current of phase a at the grid section are plotted in detail in order to check the power factor. Thered line represents the current and the blue one the voltage. It can be seen that the two waveforms are sinusoidal and especially in phase. This proves that the current has been successfully injected into the grid with a unity power factor as expected.

4. Limitations

Wave energy conversion systems have certain limitations such as Suitable to Certain Locations. The biggest disadvantage togetting your energy from the waves is location. Only power plants and towns near the ocean will benefit directly from it. Because of its source, wave energy is not a viable power source for everyone. Landlocked nations and cities far from the sea haveto find alternate sources of power, so wave energy is not theclean energy solution for everyone. Effect on Marine Ecosystem.: As clean as wave energy is, it still creates hazards for some of the creatures near it. Large machines have to be put near and in the water to gather energy from the waves. These machines disturb the seafloor, change the habitatof near-shore creatures (like crabs and starfish) and create

noise that disturbs the sea life around them. There is also a danger of toxic chemicals that are used on wave energy platforms spilling and polluting the water near them.
Source of Disturbance for Private and Commercial Vessels.: Another downside is that it disturbs commercial and private vessels. Power plants that gather wave energy have to be placed by the coastline to do their job, and they have to be near cities and other populated areas to be of much use to anybody. Weak Performance in Rough Weather: The performance of wave power drops significantly during rough weather. They must withstand rough weather. Noise and Visual Pollution: Wave energy generators may be unpleasant for some who live close to coastal regions. They look like large machines working in the middle of the ocean and destroy the beauty of the ocean. They also generate noise pollution, but the noise is often covered by the noise of waves, which is much more than that of wave generators. The Costs of Production: Although wave energy is good on almost all sides, one of its crucial side effects is the enormous cost of production. Energy production from the waves requires a huge setup. Also, the lifespan of the technology used is quite uncertain in these cases. Since the waves are quite uncertain. Furthermore, WEC-Sim open-source MATLAB toolbox is widely used for simulation of wave energy converters. WEC-Sim can model both rigid bodies and flexible bodies with generalized body modes. Simulations are performed in the time-domain by solving the governing wave energy converter equations of motion in the 6 Cartesian degrees-of-freedom, plus any number of user-defined modes. WEC-Sim's capabilities include the ability to model both nonlinear hydrodynamic effects (Froude-Krylov forces and hydrostatic stiffness) and non-hydrodynamic bodies, body-to-body interactions, mooring systems, passive yawing. WEC-Sim contains numerous numerical options and ability to perform highly customizable batch simulations. WEC-Sim can take in data from a variety of boundary element method software using its BEMIO (BEM-in/out) functionality and can output para view files for visualization.

5. Future Scope

The observations and findings from the models investigated in this study call for a need for more complex models of the slidercrank WEC. Future research efforts should try and utilize models that employ other methods and strategies, such as flywheels, to help regulate the PTAR and the MP of the WEC. Additionally, workingwith a hardware in the loop system can possible help answer some questions that arose from this thesis. Namely, a cost analysis thatwould allow one to determine an estimated cost reduction from using less versatile electrical components. A study involving the energy savings a flywheel energy storage system would also be informative. This work was just the beginning of the design process of a WEC system.

- To continue this research, the following future steps are suggested:
- To evaluate the proposed ideas, and conclude with a final design
- To perform dimensional analysis from the wave data analyzed
- To experimentally test a small-scale model
- To verify experimental results with numerical modeling results
- To investigate different types of mooring configurations
- To evaluate the environmental impacts of the finalized prototype
- To estimate the LCOE of the proposed system

On the one hand, a quantification and study of the reflection in the real wave tank experimental setup by means of the water surface's height study along the tank. This way a better insight of the tank's

physical phenomena would be accomplished and a better comparison with the simulation results could be done.
In conclusion, wave-energy harvesting is a very dynamicresearch area, where different concepts and technologies are currently proposed and developed. Pilot plants and full-scale devices are sometimes tested. However, the number of operating devices is very limited

6. Conclusion

In the first part of the thesis the goal was to analyze the behavior of the WEC adopted considering an ideal PTO (without losses), The average mechanical power extracted and peak to average power ratio obtained for each case imply the following considerations. Many different types of wave energy converters have been tested and implemented up to date, however, only a few have been successful, and are currently supplying electricity to the power grid. Wave energy has the potential to contribute to the global energy demand, by overcoming both the environmental impact from fossil fuelresources, and the availability and predictability of other renewable energies such as wind and solar. Thesis illustrates the development and application of PTO- Sim, the WEC-Sim module responsible for accurately modeling the WEC's conversion of mechanical power to electrical power through itsPTO system (or power conversion chain, PCC). The point absorber technology was chosen to investigate the feasibility for production of electrical power from the reference model3 (RM3), using WEC-Sim, an open source numerical modeling tool fordesign and analysis of WEC devices. WEC-Sim allows users to simulate the device through building a device Simulink model, importing the necessary files and create WEC-Sim input file with the specified input parameters of the study area. The results in this thesis showed that the output power produced from a two point absorber device in Sea can produce up to average 6.5 kW during the winter and 2.4 kW during the summer, the autumn and spring ranges between them. A 20% increase or decrease in wave heights leads to 40% change in the produced power output. Also, a 20% increase in wave period leads to 100% increase in power output. Simulation of WEC system which takes account of pattern ofsea wave (height and width of wave), device parameters (geometric parameters) and simulates its mechanical performance and estimates output power, torque and speed of rotation. Simulation is conducted using WEC-Sim toolbox and conducts simulation using BEM method and results clearly shows expected results. This initial investigation can lead to the design of a WEC system with the potential to overcome previous challenges from unsuccessful devices, and to overcome the economic barrier that is slowing the development of these technologies

References

1. Q. Du and D. Y. C. Leung, "2D Numerical Simulation of Ocean Waves," Proc. World Renew. Energy Congr. – Sweden, 8–13 May, 2011, Linköping, Sweden, vol. 57, no. Wrec, pp. 2183–2189, 2011, doi: 10.3384/ecp110572183.
2. M. Castillo, G. Morales, and L. A. Loyola, "The alkaloids of L. paniculatum and the structure of paniculatine," Can. J. Chem., vol. 54, no. 18, pp. 2900– 2908, 1976, doi: 10.1139/v76-410.
3. E. Rusu, "Evaluation of the wave energy conversion efficiency in various coastal environments," Energies, vol. 7, no. 6, pp. 4002–4018, 2014, doi: 10.3390/en7064002.
4. L. Rusu and F. Onea, "The performance of some state-of-the-art wave energy converters in locations with the worldwide highest wave power," Renew. Sustain. Energy Rev., vol. 75, no. August 2015, pp. 1348–1362, 2017, doi: 10.1016/j.rser.2016.11.123.
5. Rusu and F. Onea, "Review Article A review of the technologies for wave energy extraction,"

vol. 2, no. 1, pp. 10–19, 2018, doi: 10.1093/ce/zky003.
6. D. Sorin, O. Florin, and R. Eugen, “Evaluation of the Nearshore Impact of a Hybrid Wave-Wind,” vol. 1, no. 2, pp. 1–28, 2013.
7. Kim et al., “An overview of ocean renewable energy resources in Korea,” Renew. Sustain. Energy Rev., vol. 16, no. 4, pp. 2278–2288, 2012, doi: 10.1016/j.rser.2012.01.040.
8. B. Zanuttigh, E. Angelelli, A. Kortenhaus, K. Koca, Y. Krontira, and P. Koundouri, “A methodology for multi-criteria design of multi-use offshore platforms for marine renewable energy harvesting,” Renew. Energy, vol. 85, pp. 1271–1289, 2016, doi: 10.1016/j.renene.2015.07.080.
9. S. Wang, P. Yuan, D. Li, and Y. Jiao, “An overview of ocean renewable energy in China,” Renew. Sustain. Energy Rev., vol. 15, no. 1, pp. 91–111, 2011, doi: 10.1016/j.rser.2010.09.040.
10. “IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation Summary for Policymakers,” no. May 2011, pp. 5–8.
11. M. Leybourne, W. M. J. Batten, A. S. Bahaj, N. Minns, and J. O. Nians, “Preliminary design of the OWEL wave energy converter pre-commercial demonstrator,” RENE, vol. 61, pp. 51–56, 2014, doi: 10.1016/j.renene.2012.08.019.
12. Cuadra, S. Salcedo-sanz, J. C. Nieto-borge, E. Alexandre, and G. Rodríguez, “Computational intelligence in wave energy : Comprehensive review and case study,” Renew. Sustain. Energy Rev., vol. 58, pp. 1223– 1246, 2016, doi: 10.1016/j.rser.2015.12.253.
13. E. C. De Nantes, J. Hals, A. Kurniawan, M. J. Muliawan, T. Moan, and J. Krokstad, “Numerical benchmarking study of a selection of Wave Energy Converters,” 2011.
14. E. Rusu, “Evaluation of the Wave Energy Conversion Efficiency in Various Coastal Environments,” pp. 1–17, 2014.
15. B. Chenari, S. Saadatian, and A. Ferreira, “Wave Energy Systems : An Overview Of Different Wave Energy Wave Energy Systems : An Overview Of Different Wave Energy Converters And Recommendation For Future,” no. March, 2014.
16. B. Z. Zhou, J. J. Hu, K. Sun, Y. Liu, and M. Collu, “Motion Response and Energy Conversion Performance of a Heaving Point Absorber Wave Energy Converter,” Front. Energy Res., vol. 8, no. September, pp. 1–12, 2020, doi: 10.3389/fenrg.2020.553295.
17. M. Brito, R. M. L. Ferreira, L. Teixeira, M. G. Neves, and R. B. Canelas, “Experimental investigation on the power capture of an oscillating wave surge converter in unidirectional waves,” Renew. Energy, 2019, doi: 10.1016/j.renene.2019.11.094.
18. H. H. Lee and C. Chen, “Parametric Study for an Oscillating Water Column Wave Energy Conversion System Installed on a Breakwater,” 2020.
19. S. Prakash et al., “Wave Energy Converter,” pp. 71–77, 2016, doi: 10.1109/APWC.on.CSE.2016.21.
20. M. A. Mueller, “Electrical generators for direct drive wave energy converters.”
21. Ackermann and L. So, “Wind energy technology and current status : a review,” vol. 4, 2000.
22. R. Thresher and N. Renewable, “Trends in the Evolution of Wind Turbine Generator Con ® gurations and Systems,” vol. 1824, no. February, 2018, doi: 10.1002/(SICI)1099-1824(199804)1.
23. Ireland and U. T. De Lisboa, “The energy conversion performance of several types of Wells turbine designs,” vol. 211, pp. 133–145, 2015.
24. P. Bari, S. M. Camporeale, P. Bari, and P. Bari, “Accurate numerical simulation of a high

solidity Wells turbine Accurate numerical simulation of a high solidity Wells turbine," no. April,2008, doi: 10.1016/j.renene.2007.04.006.

25. T. Kim, M. Takao, T. Setoguchi, K. Kaneko, and M. Inoue, "Performance comparison of turbines for wave power," vol. 0729, pp. 681–689, 2001.
26. R. Henderson, "Design , simulation , and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter," vol. 31, pp. 271– 283, 2006, doi: 10.1016/j.renene.2005.08.021.
27. M. A. Mueller, "Electrical generators for direct drive wave energy converters," vol. 149, no. 4, 2002, doi: 10.1049/ip-gtd.
28. U. A. Korde, "Efficient primary energy conversion in irregular waves," vol. 26, pp. 625–651, 1999.
29. U. A. Korde, "On providing a reaction for efficient wave energy absorption by floating devices," vol. 21, pp. 235–248, 1999.
30. H. Yavuz, A. Mccabe, G. Aggidis, and M. B. Widden, "Calculation of the performance of resonant wave energy converters in real seas," vol. 220, pp. 117–128, 2006, doi: 10.1243/14750902JEME44.
31. F. D. O. Falca, "Modelling and control of oscillating-body wave energy converters with hydraulic power take-off and gas accumulator," vol. 34, no. 2007, pp. 2021–2032, 2021, doi: 10.1016/j.oceaneng.2007.02.006.
32. R. P. F. Gomes et al., "Compact floating wave energy converters arrays : Mooring loads and survivability through scale physical modelling," Appl. Energy, vol. 280, no. September, p. 115982, 2020, doi: 10.1016/j.apenergy.2020.115982.
33. T. D. Dang, T. Cuong, D. Kyoung, and K. Ahn, "Experimental Assessment of the Power Conversion of a Wave Energy Converter Using Hydraulic Power Take - Off Mechanism," Int. J. Precis. Eng. Manuf. Technol., no. 0123456789, 2020, doi: 10.1007/s40684-020-00261-z.
34. M. A. Musa, M. F. Roslan, M. F. Ahmad, A. M. Muzathik, and M. A. Mustapa, "The Influence of Ramp Shape Parameters on Performance of Overtopping Breakwater for Energy Conversion," pp. 1–18.
35. N. Li, K. Fai, and P. Cross, "Numerical wave modeling for operational and survival analyses of wave energy converters at the US Navy Wave Energy Test Site in Hawaii," Renew. Energy, vol. 161, pp. 240–256, 2020, doi: 10.1016/j.renene.2020.06.089.
36. R. Waters et al., "Experimental results from sea trials of an offshore wave energy system Experimental results from sea trials of an offshore wave energy system," vol. 034105, no. 2007, pp. 2012–2015, 2014, doi: 10.1063/1.2432168.
37. U. A. Korde, "Phase control of ¯ oating bodies from an on-board reference," vol. 23, no. 2001, pp. 251–262, 2002.