WAVE ENERGY CONVERTER USING ELECTROMAGNETIC INDUCTION

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ABSTRACT

The purpose of this study is to design an optimum Wave Energy Converter (WEC) device, which suits Malaysian wave characteristics based on the concept of electromagnetic induction. The existing WEC technologies are unsuitable for Malaysia wave characteristics as they are built for large waves with small frequency whilst Malaysian waves are small with high frequency. Besides, the available devices are massive and expensive in terms of fabrication and maintenance. Furthermore, a proper analysis was not conducted for the existing technologies as some of the previous works were scrapped due to inefficiency. A new device was designed using the theory of electromagnetic induction, which involves a magnet and a coil of wire. When a magnet moves through a coil, an induced current is produced in the coil. Performance estimation analysis was conducted to determine the system's specifications. Wave characteristics such as significant height, \( H_s \), and period, \( T \) influence the generated output. Thus, calculations between these two characteristics and the output characteristics, namely peak induced voltage, root mean square (RMS) induced voltage, RMS induced current and power generated were made. The relationships between these characteristics were then tabulated and presented in this paper. The conceptual design of this device has been completed. The next step is to fabricate the device, conduct performance analysis and compare with the performance estimation analysis.

Key words: Wave energy converter, wave energy, ocean energy, power take-off, electromagnetic induction
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1. INTRODUCTION
Ocean energy is a type of renewable energy which are harnessed from the sea. The energy obtained will be converted into electrical energy and distributed for our daily usage. Essentially, there are two main types of ocean energy, namely mechanical and thermal. The moon's gravitational force and the Earth's rotational force create mechanical force. Waves are formed by the wind on the ocean surface, which are created from the Earth's rotation. In contrast, tides and currents are formed by the moon's gravitational force [1]. The conversion of waves and tides to electrical energy involves typically mechanical devices. Meanwhile, electrical energy from thermal energy is obtained from the difference between the temperature at the ocean's surface and beneath the surface. The sun heats the surface while the water underneath remains cold. Several technologies of ocean energy include tidal stream, tidal range, deep ocean current, salinity gradient, thermal energy, and wave energy [2]. Each of these technologies uses a different approach to harness ocean energy. However, this research only focuses on wave energy, hence the title Wave Energy Converter.

Wave Energy Converter (WEC) converts the wave kinetic and potential energy into useful mechanical or electrical energy. For WEC, two essential types of waves are wind waves and swell waves. Waves are formed when the wind blows over the ocean surface area. Local wind waves are generated closer to the point of interest, while swell waves are generated from distant storms. The wave sizes are influenced by the wind speed in the storm area, size of the storm area and duration of the storm [2-3]. As the waves grow their speed increases and eventually this will exceed the speed of the storm, and so swell waves will arrive at a coastline before the storm arrives.

Wave energy is generated by the movement of a device either floating on the surface of the ocean or moored to the ocean floor. The energy created depends on the speed, height, and frequency of the wave, as well as water density. Ocean density varies because it is affected by salinity and temperature.

One of the crucial components of a WEC device is the power take-off (PTO) system. PTO is the system where the potential and kinetic energy of ocean waves are converted into electrical or mechanical energy. Each device has different PTO, which uses turbines, hydraulic systems, direct electrical drives and direct mechanical drive systems [1].

The hydraulic system inside a WEC device contains pistons, accumulator and motor. Wave movements cause the pistons to move, which will push high-pressure hydraulic oil into motors, pumps, accumulator and generator. Meanwhile, for PTO systems which use turbines, there are two types which are used in WEC devices, namely air turbine and hydro turbine. Figure 2 summarises on the main paths of the PTO systems.
Figure 1 Path of PTO systems [2]

WEC devices can be applied at three locations – onshore, nearshore and offshore. These terms represent the depth where the WEC is positioned at [1].

Onshore: The device is designed for onshore locations which are often incorporated into an existing structure.

Nearshore: The device is usually mounted in shallow, nearshore wave areas usually close to the coastline and in which some of the energy in the emerging ocean waves has started to disperse through bottom friction [3].

Offshore: The device is meant to be in deep, offshore wave environments, typically further from the shoreline and where bottom friction has a negligible effect in the incoming wave energy. This corresponds roughly to a site where the depth is greater than about half the wavelength of the ocean waves [4-5].

2. PROBLEM STATEMENT

Existing Wave Energy Converter technologies are unsuitable for Malaysian wave characteristics. This is because they are mostly designed for waves with low frequency and great height. However, the waves in Malaysian seas are high in frequency and low height [2]. Thus, the existing technologies are unsuitable to be applied directly in Malaysia. Besides, available system designs are costly and massive. Most WEC devices available have a massive construction, which will be difficult to install and maintain. They are also quite expensive to be developed. Furthermore, proper preliminary analyses might not be conducted for existing technologies as some of the previous works on WEC have been scraped as they are inefficient. The electricity generated could not cover the cost of manufacturing the devices in a short period. Hence, this project aims to conceptually design an optimum wave energy converter system to generate electricity by considering wave characteristics as well as utilising ocean energy potential. In order to fulfil this, the appropriate wave energy converter technologies must be identified first. Next, the conceptual design of the wave energy converter system was developed. Finally, preliminary performance analysis on the proposed design was performed.
3. LITERATURE REVIEW

3.1. Existing Technologies

Thus far, WEC devices have been applied in several locations throughout the world. These devices can be categorised by their orientation, namely terminator, attenuator, and point absorber. The following are some information on the existing WEC technologies that have been developed.

3.1.1. Terminator

The principal axis of the devices categorised in this orientation is parallel to the front of incoming waves where it will intercept the wave physically [3]. Devices that fall under the terminator orientation are oscillating water column, overtopping and oscillating wave surge converter device.

3.1.2. Oscillating Water Column Device

Oscillating water column (OWC) device consists of an air chamber with its lower end open to the ocean and its top connected to the surrounding atmosphere via an air turbine. As the waves oscillate within the chamber, the air is pushed through the turbine, forcing it to spin and drive an electric generator [8]. The PTO for this device is a turbine system. Several types of turbines are used in this device. However, Wells turbine is the most commonly used because this turbine can rotate in one direction regardless of whether the air is being pushed up or pulled back into the column [9]. The world’s first commercial OWC was the Islay LIMPET (Land Installed Marine Power Energy Transmitter) located on the shoreline of the Isle of Islay, Scotland, United Kingdom. It was developed by Wavegen Limited which is now known as Voith Hydro Wavegen Limited and was commissioned in 2000. This device was capable of generating 250kW of power. However, the Islay LIMPET was deactivated in 2012.

3.1.3. Wave Overtopping Device

Wave overtopping devices use the action of the waves to deposit water into a reservoir above the mean water level and sometimes uses a collector to concentrate the wave energy. The collected water is then returned to the sea via a low head turbine which converts the potential energy to electricity [8]. An example of a wave overtopping device is the Wave Dragon, developed by a Danish company, Wave Dragon Aps. The first prototype was tested in 2003 at the Danish Wave Energy Test Centre located in Nissum Bredning fjord and became the world’s first offshore grid-connected wave energy device. There are four sizes of Wave Dragon available with different energy generated by each device which as can be seen in Table 2.1.

3.1.4. Oscillating Wave Surge Converter

The oscillating wave surge converter (OWSC) also known as an inverted pendulum, consists of a paddle rotating about a horizontal axis above the water surface and perpendicular to the direction of wave propagation. The paddle hangs at the mouth of a gully, effectively forming a 'water column' between the paddle and gully back wall [10]. The Oyster is one of the examples of the OWSC device. It was developed by Aquamarine Power. They deployed and tested two full-scale Oyster devices at the European Marine Energy Centre (EMEC) test site: Oyster 1 and Oyster 800. The power generated by the Oyster 1 was 315kW while Oyster 800 produced 800kW. These devices were placed offshore, on the seabed with about 10 metres deep and around 500 meters from the shore. However, the test programme had ended in 2015 when the company ceased trading [11-12].
3.2. Terminator

Devices under attenuator orientation have their principal axis perpendicular to the incoming wave direction. Therefore, as the wave moves along the WEC device, wave energy will be captured. There are three WEC devices that can be categorised as an attenuator, namely a floating wave attenuator, bulge wave device and rotating mass device [8].

3.2.1. Floating Wave Attenuator

A floating wave attenuator consists of a long floating structure with several sections joined and floats parallel to the waves. The joints bend as various wave height occur. The sections drive hydraulic pumps or other connected energy converters. Then, electrical energy is fed from a transformer placed in the structure's nose to a cable in the ocean floor to the shore to be put on the grid [13-14]. Pelamis Wave Energy Converter developed by a Scottish company Pelamis Wave Power is the first offshore wave attenuator to generate electricity to the grid when it was connected to the UK grid in 2004. The first full-scale prototype, P1, was deployed at the EMEC test site. The device has four sections with a total length of 120m and a diameter of 3.5m. They then develop a second-generation device, the P2 based on the testing results of the P1. The P2 has five sections measured 180m long, four metres wide and weight about 1,350 tonnes. In 2014, Wave Energy Scotland has taken over the project from Pelamis Wave Power and owned their assets and intellectual property [15].

3.2.2. Bulge Wave Device

Bulge wave device comprises of a water-filled rubber tube, placed perpendicular to the waves, and moored to the seabed. Water enters via the front, and the travelling wave induces changes in pressure around the tube length, producing a 'bulge'. The bulge grows as it travels through the tube, accumulating energy that can be used to operate a standard low-head turbine located at the end, at which water then returns to the sea [16]. A bulge wave device named Anaconda is a distensible rubber tube with closed ends. It is placed just below the water surface where one end faces the wave direction. When a wave passes, water enters the tube and bulge waves are created. This bulge wave will move along the tube until the end where a turbine in the PTO system will be driven. This device has been proven in laboratory tests using a smaller-scale prototype, which were 0.25 metres and 0.5 metres in diameter. However, the full-scale device will be 200 metres long, and 7 metres in diameter where it will be placed 40 to 100 metres in the ocean. The estimated power generation is 1 MW per unit [17-18].

3.2.3. Rotating Mass Device

Two forms of rotation are used to capture energy by the movement of the device heaving and swaying in the waves. This motion drives either an eccentric weight or a gyroscope causes precession. In both cases, the movement is attached to an electric generator inside the device [16]. Wello Oy, a Finnish company, developed a rotating mass device called the Penguin. The first full-scale prototype named Penguin WEC 1 weight 1600 tonne, 30 metres long, nine metres high with a draft of seven metres. However, it was semi-submerged, and only two metres were visible above the sea surface. The power generated by the Penguin WEC 1 was 500kW. This device was deployed at EMEC test site in 2012. It was reinstalled in 2017 and has been on-site for more than two years, enduring several storms including wave heights up to 18.7 m encountered during the Storm Caroline [19]. Nonetheless, on 22 March 2019, the prototype was taking on water and sank at the test site. A new model named Penguin WEC 2 has been developed. The incident of the Penguin WEC 1 will influence the future design, operations and maintenance plans [20].
3.3. Point Absorber
Commonly, point absorbers feature small dimensions corresponding to the incident wavelength, and capture wave energy from the ocean in all directions. Point absorbers can be placed on the water surface and underwater. In this report, floating-point absorber refers to the one on the water surface while submerged pressure differential is for the underwater structure [8].

3.3.1. Floating Point Absorber
A point absorber is a buoyant device that captures the energy from most directions via its motions on the surface of the ocean. The movement of the buoyant top corresponding to the base is transformed into electrical energy. Depending on the configuration of the displacers or reactors, the power take-off system will take different forms [16]. PowerBuoy is an example of a floating point absorber device developed by Ocean Power Technologies Inc. Their latest device, PB3, is 13.3 metres high, 2.65 metres of float diameter, 1.0 metres of spar diameter and weighs 8,300 kg. The average power produced by this device is 8.4 kWh per day. The electricity generated using a direct drive generator is stored in onboard Energy Storage System, which is in the device's spar. Maintenance works are done every three years. The PB3 has its own monitoring and management system consists of data collection, processing and transmission, which are by self-monitored to facilitate an effective maintenance plan, thereby increasing its operational performance [21].

3.3.2. Submerged Pressure Differential
Submerged pressure differential devices are typically located near shore and attached to the seabed. The motion of the waves causes the sea level to rise and fall above the device, inducing a pressure differential in the device. The alternating pressure pumps fluid through a system to generate electricity. AWS is an example of a submerged pressure differential device. It responds to subsea water pressure changes from incoming waves and transforms the corresponding motion into electricity through a direct drive generator. Currently owned by AWS Ocean Energy Ltd, the AWS is designed for offshore applications with water depths over 25 metres. The output power is between 25kW and 250kW [22].

3.4. Previous Studies
Table 1 shows a summary of some previous studies on wave energy converter. These studies are related to the existing technologies mentioned earlier.
This paper presents a brief overview of the design, benefits, risk, and environmental impact of a sea wave power plant. This accomplishment in wave energy concepts for small-scale electricity generation. The two considered and modelled concepts are an oscillating water column (OWC) and a heaving point absorber. This paper explained about The Anaconda, which is a new concept for wave energy conversion that is made of rubber filled with water which utilises the pressure built up and extracted through the power take-off system.
### Methdology

The study begins with a literature review on WEC technologies and material. The purpose of this stage is to identify appropriate WEC technology that can be applied to this project. Existing WEC technologies are massive and complex to fabricate. Thus, the fabrication and maintenance cost became expensive. In addition, during the potential site survey and data collection process, it was found that the wave height in Malaysian seas are small but are high in frequency. Compared to where the existing WEC devices were deployed, the waves are large but low in frequency.
These factors make the current technologies became incompatible to be applied in Malaysia. Due to these challenges, the conceptual design of a WEC device based on the principle of electromagnetic induction was introduced. Initial calculations were made to determine the specifications, size, and expected output of the device.

5. CONCEPTUAL DESIGN

5.1. Theoretical Concept

Based on the research done on available WEC devices, their working principles, characteristics, PTOs and wave characteristics suitable for each device, a simple solution has been chosen. The WEC device to be invented will use the concept of electromagnetic induction to generate electricity.

Faraday’s Law of Electromagnetic Induction was introduced by Michael Faraday in the 1830s. This law predicts how electromotive force (emf) or voltage is produced from the interaction between a magnetic field and an electrical circuit. This phenomenon is known as electromagnetic induction [23]. Faraday’s First Law states that the change in a wire coil’s magnetic field can induce emf in the coil. The emf is called induced emf. If the conductor circuit is closed, the current will also circulate through the circuit, and this current is called induced current. Faraday’s Second Law states that the magnitude of emf induced in the coil is equal to the rate of change of flux that linkages with the coil. The flux linkage of the coil is the product of the number of turns in the coil and flux associated with the coil [24].

5.2. Design Specification

There are four ways to change the magnetic field. The first method is by moving a magnet towards or away from the coil. Second is by moving the coil into or out of the magnetic field. Third is by changing the area of a coil placed in the magnetic field. Fourth, by rotating the coil relative to the magnet [24].

In this project, the first method will be applied. The magnet will be placed inside a waterproof cylindrical case. Another ring-shaped case containing the coil will be placed outside the magnet case. A floater will be attached below the magnet case while the coil case
will be fixed to the device's structure. When waves hit the device, the magnet will float up and down the coil and theoretically will generate emf. In order to maximise electricity production, there will be five units of electromagnetic induction generators in a single device. The design drawing of the whole device is shown in Figure 4. Meanwhile, Figure 5 shows the detailed design of each generator unit.

Figure 3 Design drawing of an electromagnetic induction generator device

Figure 4 Detail design of the electromagnetic induction generator unit

Figure 5 AC to DC converter circuit
This device is expected to produce 12Vac. However, the targeted outputs; the warning light and the storage battery requires 12Vdc. To solve this, electricity generated should pass through an AC to DC converter circuit comprises a rectifier circuit, a filter circuit, and a regulator circuit. Figure 6 shows the block diagram of the whole system.

5.3. Performance Estimation Analysis

Some calculations have been made to determine the type of magnet suitable to be used for this project. The magnetic field strength and area of the coil will affect the induced voltage produced. Table 2 shows the approximate magnetic field strength according to their respective magnet types. A type of magnet called neodymium magnet was considered to be the most suitable. Neodymium magnet is a permanent magnet made from an alloy of neodymium, iron and boron. It has powerful magnetic strength and low relative permeability.

<table>
<thead>
<tr>
<th>Source</th>
<th>Approximate Magnetic Field Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neuron depolarisation (imaged by MEG)</td>
<td>0.5 pT (5 x 10^-13 T)</td>
</tr>
<tr>
<td>Earth’s magnetic field</td>
<td>0.5 G (50 µT)</td>
</tr>
<tr>
<td>Refrigerator magnet</td>
<td>50 G (5 mT)</td>
</tr>
<tr>
<td>Junkyard electromagnet</td>
<td>1 T</td>
</tr>
<tr>
<td>Clinical MRI scanners</td>
<td>0.5 – 3.0 T (typical)</td>
</tr>
<tr>
<td>Research MRI scanners (human)</td>
<td>7.0 T – 11.7 T</td>
</tr>
<tr>
<td>Laboratory NMR spectrometers</td>
<td>6 – 23 T</td>
</tr>
<tr>
<td>Largest pulsed-field created in a laboratory non-destructively</td>
<td>97 T</td>
</tr>
<tr>
<td>Largest pulsed-field created in a laboratory (destroying equipment but not the lab)</td>
<td>730 T</td>
</tr>
</tbody>
</table>

In order to estimate the performance of the wave energy converter, a simple modelling equation was derived from Faraday's Law of electromagnetic induction. The specification of the WEC system is shown in Table 3. Several assumptions were made to ease the creation of the model.

<table>
<thead>
<tr>
<th>Parameters (Unit)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of Coil, (d) (m)</td>
<td>0.025</td>
</tr>
<tr>
<td>Length of coil, (l) (m)</td>
<td>0.5</td>
</tr>
<tr>
<td>Number of turns of coil, (N)</td>
<td>22000</td>
</tr>
<tr>
<td>Flux density, (B) (T)</td>
<td>1.1</td>
</tr>
<tr>
<td>Magnetic flux, (\Phi) (Wb)</td>
<td>0.000540031</td>
</tr>
<tr>
<td>Time, (t) (s)</td>
<td>1</td>
</tr>
<tr>
<td>Rate of change of flux, (\Delta\Phi) (T/s)</td>
<td>1.1</td>
</tr>
</tbody>
</table>

From the specification of the conceptual design of WEC, the peak induced voltage can be estimated. Using Faraday's Law of Electromagnetic Induction and specifications in Table 3, the peak induced voltage is calculated. However, this does not take into consideration the average output of the AC system, the properties of wave motion and the changing condition of the waves.
Wave Energy Converter using Electromagnetic Induction

*Peak Induced Voltage* $\varepsilon$,

$$\varepsilon = -N \frac{\Delta BA}{\Delta t} = 11.88V \tag{1}$$

The properties of the wave will influence the induced voltage, as shown in (1). Significant height, $H_s$ and period, $T$ would influence the rate of change of flux in equation (1). The influence of the rate of change of flux on the estimated peak induced voltage, $\varepsilon$ and root mean square voltage, $V_{rms}$ is shown in Table 4 and Figure 7. The rms value is shown as it is more representative of the obtained voltage of the WEC as an Alternating Current (AC) system.

### Table 4 Rate of change of flux on induced peak and RMS voltage

<table>
<thead>
<tr>
<th>Rate of Change of Flux (T/s)</th>
<th>Peak Voltage, $\varepsilon$ (V)</th>
<th>RMS Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.080</td>
<td>0.764</td>
</tr>
<tr>
<td>0.2</td>
<td>2.160</td>
<td>1.527</td>
</tr>
<tr>
<td>0.3</td>
<td>3.240</td>
<td>2.291</td>
</tr>
<tr>
<td>0.4</td>
<td>4.320</td>
<td>3.055</td>
</tr>
<tr>
<td>0.5</td>
<td>5.400</td>
<td>3.819</td>
</tr>
<tr>
<td>0.6</td>
<td>6.480</td>
<td>4.582</td>
</tr>
<tr>
<td>0.7</td>
<td>7.560</td>
<td>5.346</td>
</tr>
<tr>
<td>0.8</td>
<td>8.641</td>
<td>6.110</td>
</tr>
<tr>
<td>0.9</td>
<td>9.721</td>
<td>6.873</td>
</tr>
<tr>
<td>1.0</td>
<td>10.801</td>
<td>7.637</td>
</tr>
<tr>
<td>1.1</td>
<td>11.881</td>
<td>8.401</td>
</tr>
</tbody>
</table>

**Figure 6** Flux rate against induced peak voltage and rms voltage

To better visualise the influence of wave properties $H_s$ and $T$ on the expected performance of WEC, a two-variable data table was constructed based on the parameters of the WEC in Table 3. The table shows the expected output from different values of $H_s$ and $T$. Based on significant height, $H_s$ and period, $T$ of the wave, the magnet velocity can be found, and the induced voltage can be calculated from equation (2).

*Induced voltage relative to $H_s$ and $T$*,

$$\varepsilon = -N \frac{BA}{l/T_{mean}} \tag{2}$$

The influence of wave properties, significant height $H_s$ and Period, $T$ on the peak induced voltage and rms voltage, $V_{rms}$ is shown in Table 5 and Table 6. The results in the data table are colour coded to make it easier to understand the data. The obtained value is colour coded.
with 30th percentile in red, 50th percentile in yellow and 90th percentile in green. The reason for the uneven distribution of colour coding is because the obtained results are not distributed normally, and the colour green is considered the best case use or scenario. In contrast, the colour yellow is considered the more probable results from the average of wave conditions in Malaysia [26].

Table 5 Peak Induced Voltage (V) at different $H_s$ and $T$

<table>
<thead>
<tr>
<th>Significant Height, $H_s$ (m)</th>
<th>0.2</th>
<th>0.25</th>
<th>0.3</th>
<th>0.35</th>
<th>0.4</th>
<th>0.45</th>
<th>0.5</th>
<th>0.55</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.188</td>
<td>1.465</td>
<td>1.783</td>
<td>2.079</td>
<td>2.374</td>
<td>2.673</td>
<td>2.970</td>
<td>3.267</td>
<td>3.564</td>
<td>3.861</td>
<td>4.158</td>
<td>4.455</td>
<td>4.752</td>
<td>5.049</td>
<td>5.346</td>
<td>5.643</td>
<td>5.940</td>
</tr>
<tr>
<td>5</td>
<td>0.950</td>
<td>1.188</td>
<td>1.426</td>
<td>1.663</td>
<td>1.901</td>
<td>2.139</td>
<td>2.376</td>
<td>2.614</td>
<td>2.851</td>
<td>3.089</td>
<td>3.327</td>
<td>3.564</td>
<td>3.802</td>
<td>4.039</td>
<td>4.277</td>
<td>4.515</td>
<td>4.752</td>
</tr>
<tr>
<td>6</td>
<td>0.792</td>
<td>0.990</td>
<td>1.188</td>
<td>1.336</td>
<td>1.484</td>
<td>1.782</td>
<td>2.080</td>
<td>2.376</td>
<td>2.673</td>
<td>2.970</td>
<td>3.108</td>
<td>3.306</td>
<td>3.504</td>
<td>3.702</td>
<td>3.900</td>
<td>4.098</td>
<td>4.296</td>
</tr>
<tr>
<td>7</td>
<td>0.679</td>
<td>0.849</td>
<td>1.018</td>
<td>1.188</td>
<td>1.358</td>
<td>1.528</td>
<td>1.697</td>
<td>1.867</td>
<td>2.037</td>
<td>2.206</td>
<td>2.376</td>
<td>2.546</td>
<td>2.716</td>
<td>2.885</td>
<td>3.055</td>
<td>3.225</td>
<td>3.394</td>
</tr>
<tr>
<td>8</td>
<td>0.594</td>
<td>0.743</td>
<td>0.891</td>
<td>1.040</td>
<td>1.188</td>
<td>1.337</td>
<td>1.485</td>
<td>1.634</td>
<td>1.782</td>
<td>1.931</td>
<td>2.079</td>
<td>2.228</td>
<td>2.376</td>
<td>2.525</td>
<td>2.673</td>
<td>2.822</td>
<td>2.970</td>
</tr>
<tr>
<td>9</td>
<td>0.528</td>
<td>0.669</td>
<td>0.792</td>
<td>0.924</td>
<td>1.056</td>
<td>1.188</td>
<td>1.320</td>
<td>1.445</td>
<td>1.566</td>
<td>1.680</td>
<td>1.794</td>
<td>1.908</td>
<td>2.022</td>
<td>2.136</td>
<td>2.246</td>
<td>2.350</td>
<td>2.450</td>
</tr>
<tr>
<td>10</td>
<td>0.475</td>
<td>0.594</td>
<td>0.713</td>
<td>0.812</td>
<td>0.950</td>
<td>1.069</td>
<td>1.188</td>
<td>1.307</td>
<td>1.426</td>
<td>1.544</td>
<td>1.663</td>
<td>1.782</td>
<td>1.901</td>
<td>2.020</td>
<td>2.139</td>
<td>2.257</td>
<td>2.376</td>
</tr>
</tbody>
</table>

Table 6 RMS Induced Voltage (V) at different $H_s$ and $T$

<table>
<thead>
<tr>
<th>Significant Height, $H_s$ (m)</th>
<th>0.2</th>
<th>0.25</th>
<th>0.3</th>
<th>0.35</th>
<th>0.4</th>
<th>0.45</th>
<th>0.5</th>
<th>0.55</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.840</td>
<td>1.050</td>
<td>1.266</td>
<td>1.470</td>
<td>1.680</td>
<td>1.890</td>
<td>2.100</td>
<td>2.310</td>
<td>2.520</td>
<td>2.730</td>
<td>2.940</td>
<td>3.150</td>
<td>3.360</td>
<td>3.570</td>
<td>3.780</td>
<td>3.990</td>
<td>4.200</td>
</tr>
<tr>
<td>5</td>
<td>0.672</td>
<td>0.840</td>
<td>1.008</td>
<td>1.176</td>
<td>1.344</td>
<td>1.512</td>
<td>1.680</td>
<td>1.848</td>
<td>2.016</td>
<td>2.184</td>
<td>2.352</td>
<td>2.520</td>
<td>2.688</td>
<td>2.856</td>
<td>3.024</td>
<td>3.192</td>
<td>3.360</td>
</tr>
<tr>
<td>6</td>
<td>0.560</td>
<td>0.700</td>
<td>0.840</td>
<td>0.980</td>
<td>1.120</td>
<td>1.260</td>
<td>1.400</td>
<td>1.546</td>
<td>1.690</td>
<td>1.832</td>
<td>1.960</td>
<td>2.100</td>
<td>2.240</td>
<td>2.380</td>
<td>2.520</td>
<td>2.660</td>
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<tr>
<td>7</td>
<td>0.450</td>
<td>0.600</td>
<td>0.720</td>
<td>0.840</td>
<td>0.960</td>
<td>1.080</td>
<td>1.200</td>
<td>1.328</td>
<td>1.456</td>
<td>1.590</td>
<td>1.725</td>
<td>1.860</td>
<td>2.000</td>
<td>2.136</td>
<td>2.272</td>
<td>2.408</td>
<td>2.544</td>
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<td>8</td>
<td>0.375</td>
<td>0.467</td>
<td>0.568</td>
<td>0.663</td>
<td>0.757</td>
<td>0.850</td>
<td>0.945</td>
<td>1.038</td>
<td>1.130</td>
<td>1.223</td>
<td>1.316</td>
<td>1.409</td>
<td>1.502</td>
<td>1.595</td>
<td>1.688</td>
<td>1.781</td>
<td>1.874</td>
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<tr>
<td>9</td>
<td>0.336</td>
<td>0.420</td>
<td>0.504</td>
<td>0.588</td>
<td>0.672</td>
<td>0.756</td>
<td>0.840</td>
<td>0.924</td>
<td>1.008</td>
<td>1.092</td>
<td>1.176</td>
<td>1.260</td>
<td>1.344</td>
<td>1.428</td>
<td>1.512</td>
<td>1.596</td>
<td>1.680</td>
</tr>
<tr>
<td>10</td>
<td>0.317</td>
<td>0.398</td>
<td>0.482</td>
<td>0.566</td>
<td>0.650</td>
<td>0.734</td>
<td>0.818</td>
<td>0.904</td>
<td>0.990</td>
<td>1.076</td>
<td>1.162</td>
<td>1.248</td>
<td>1.334</td>
<td>1.420</td>
<td>1.506</td>
<td>1.592</td>
<td>1.678</td>
</tr>
</tbody>
</table>

The current and power generated by the system can be estimated by calculating the total impedance. The impedance is determined from coil inductance and wire resistivity of the system, as shown in equation (3) and (4).

**Inductance of Coil L,**

\[ L = \frac{\mu N^2 A}{l} \]  # (3)

**Resistance of Wire R,**

\[ R = \frac{\rho L}{A} \]  #(4)

The capacitive reactance is determined from inductance in (5). The impedance and current induced by the system are shown in equation (6) and (7).
Wave Energy Converter using Electromagnetic Induction

*Inductive Reactance* $X_L$,

$$X_L = 2\pi f L \# (5)$$

*Impedance* $Z$,

$$Z = \sqrt{R^2 + X_L^2} \# (6)$$

*RMS Current* $I$,

$$I = \frac{V_{rms}}{\sqrt{R^2 + X_L^2}} \# (7)$$

The power generated by the system was then determined by the product of rms voltage, current and power factor $\cos \varphi$ (8) (9).

*Average Power Generated* $P_{ave}$,

$$P_{ave} = V_{rms} I_{rms} \cos \varphi \# (8)$$

where Power Factor $\cos \varphi$,

$$\cos \varphi = \frac{R}{Z} \# (9)$$

From the above equation, a data table was constructed relating to the induced rms voltage from the WEC system in Table 6, and wave properties $H_s$ and $T$. The two variable data Table 7 and Table 8 shows the estimated current and power generated by the WEC system with respect to the wave properties $H_s$ and $T$.

<table>
<thead>
<tr>
<th>Significant Height, $H_s$ (m)</th>
<th>0.2</th>
<th>0.25</th>
<th>0.3</th>
<th>0.35</th>
<th>0.4</th>
<th>0.45</th>
<th>0.5</th>
<th>0.55</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
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</tr>
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<tbody>
<tr>
<td>0.940</td>
<td>0.925</td>
<td>1.110</td>
<td>1.295</td>
<td>1.486</td>
<td>1.658</td>
<td>1.850</td>
<td>2.053</td>
<td>2.259</td>
<td>2.449</td>
<td>2.638</td>
<td>2.827</td>
<td>3.014</td>
<td>3.202</td>
<td>3.391</td>
<td>3.579</td>
<td>3.766</td>
<td></td>
</tr>
<tr>
<td>1.434</td>
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<td>1.110</td>
<td>1.261</td>
<td>1.417</td>
<td>1.568</td>
<td>1.714</td>
<td>1.853</td>
<td>2.017</td>
<td>2.173</td>
<td>2.337</td>
<td>2.501</td>
<td>2.662</td>
<td>2.823</td>
<td>2.984</td>
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<td>3.307</td>
</tr>
<tr>
<td>0.555</td>
<td>0.694</td>
<td>0.832</td>
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<td>1.248</td>
<td>1.387</td>
<td>1.526</td>
<td>1.655</td>
<td>1.803</td>
<td>1.942</td>
<td>2.081</td>
<td>2.219</td>
<td>2.358</td>
<td>2.497</td>
<td>2.636</td>
<td>2.774</td>
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<tr>
<td>0.493</td>
<td>0.617</td>
<td>0.740</td>
<td>0.863</td>
<td>0.984</td>
<td>1.100</td>
<td>1.213</td>
<td>1.318</td>
<td>1.410</td>
<td>1.503</td>
<td>1.596</td>
<td>1.689</td>
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<td>1.863</td>
<td>1.950</td>
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<tr>
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<td>0.777</td>
<td>0.888</td>
<td>0.999</td>
<td>1.110</td>
<td>1.211</td>
<td>1.312</td>
<td>1.413</td>
<td>1.514</td>
<td>1.615</td>
<td>1.717</td>
<td>1.819</td>
<td>1.920</td>
<td>2.021</td>
<td>2.129</td>
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</tr>
</tbody>
</table>

Table 7 RMS induced current (A) at different $H_s$ and $T$

<table>
<thead>
<tr>
<th>Significant Height, $H_s$ (m)</th>
<th>0.2</th>
<th>0.25</th>
<th>0.3</th>
<th>0.35</th>
<th>0.4</th>
<th>0.45</th>
<th>0.5</th>
<th>0.55</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
<th>1</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>0.328</td>
<td>0.513</td>
<td>0.738</td>
<td>1.005</td>
<td>1.313</td>
<td>1.651</td>
<td>2.051</td>
<td>2.442</td>
<td>2.954</td>
<td>3.467</td>
<td>4.020</td>
<td>4.661</td>
<td>5.251</td>
<td>5.928</td>
<td>6.646</td>
<td>7.405</td>
<td>8.265</td>
</tr>
<tr>
<td>3</td>
<td>0.146</td>
<td>0.238</td>
<td>0.329</td>
<td>0.447</td>
<td>0.583</td>
<td>0.733</td>
<td>0.842</td>
<td>1.013</td>
<td>1.181</td>
<td>1.314</td>
<td>1.541</td>
<td>1.789</td>
<td>2.061</td>
<td>2.334</td>
<td>2.606</td>
<td>2.890</td>
<td>3.194</td>
</tr>
<tr>
<td>0.082</td>
<td>0.128</td>
<td>0.185</td>
<td>0.251</td>
<td>0.328</td>
<td>0.415</td>
<td>0.513</td>
<td>0.620</td>
<td>0.723</td>
<td>0.815</td>
<td>0.911</td>
<td>1.015</td>
<td>1.118</td>
<td>1.224</td>
<td>1.332</td>
<td>1.441</td>
<td>1.552</td>
<td>1.665</td>
</tr>
<tr>
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<td>0.118</td>
<td>0.161</td>
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<td>0.264</td>
<td>0.328</td>
<td>0.397</td>
<td>0.473</td>
<td>0.555</td>
<td>0.643</td>
<td>0.734</td>
<td>0.824</td>
<td>0.914</td>
<td>1.004</td>
<td>1.095</td>
<td>1.186</td>
<td>1.278</td>
</tr>
<tr>
<td>0.636</td>
<td>0.057</td>
<td>0.082</td>
<td>0.112</td>
<td>0.146</td>
<td>0.183</td>
<td>0.223</td>
<td>0.276</td>
<td>0.329</td>
<td>0.385</td>
<td>0.447</td>
<td>0.511</td>
<td>0.578</td>
<td>0.659</td>
<td>0.734</td>
<td>0.823</td>
<td>0.912</td>
<td></td>
</tr>
<tr>
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<td>0.060</td>
<td>0.082</td>
<td>0.107</td>
<td>0.136</td>
<td>0.167</td>
<td>0.199</td>
<td>0.232</td>
<td>0.265</td>
<td>0.299</td>
<td>0.333</td>
<td>0.367</td>
<td>0.404</td>
<td>0.440</td>
<td>0.476</td>
<td>0.513</td>
<td>0.550</td>
</tr>
<tr>
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<td>0.048</td>
<td>0.063</td>
<td>0.082</td>
<td>0.104</td>
<td>0.128</td>
<td>0.155</td>
<td>0.181</td>
<td>0.207</td>
<td>0.233</td>
<td>0.258</td>
<td>0.284</td>
<td>0.309</td>
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<td>0.361</td>
<td>0.387</td>
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<td>0.050</td>
<td>0.065</td>
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<td>0.143</td>
<td>0.164</td>
<td>0.185</td>
<td>0.209</td>
<td>0.232</td>
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<td>0.354</td>
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<tr>
<td>0.613</td>
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<td>0.053</td>
<td>0.066</td>
<td>0.082</td>
<td>0.109</td>
<td>0.131</td>
<td>0.155</td>
<td>0.179</td>
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<td>0.226</td>
<td>0.249</td>
<td>0.273</td>
<td>0.297</td>
<td>0.320</td>
<td>0.344</td>
</tr>
</tbody>
</table>

Table 8 Power generated (W) by WEC system at different $H_s$ and $T$
6. CONCLUSION

Waves are generated by the wind on the ocean surface, which are created from the Earth's rotation. Energy from the wave motion can be harnessed and transformed into electrical or mechanical energies. The devices involved in this process are called Wave Energy Converters (WECs). There are various types of WEC technologies that have been developed and tested around the world. However, most devices are unsuitable to be applied in Malaysia due to the difference in the wave characteristics. In addition, most devices are expensive to develop, and the construction is large and heavy. Furthermore, some of the existing technologies are scrapped after a certain period of deployment, which shows that proper analyses might not be conducted prior to development.

This project targets to develop a conceptual design of an optimum WEC system which compliments the Malaysian wave characteristics. As of now, the conceptual design of the new WEC device has been completed. The next step is to fabricate the device and conduct performance analysis. The result of the actual device testing process will be evaluated and compared with the performance estimation analysis presented in this paper.

REFERENCES


Wave Energy Converter using Electromagnetic Induction


