DESIGN AND MODELLING OF WAVE ENERGY CONVERTER AND POWER TAKE-OFF SYSTEM

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ABSTRACT: Ocean wave energy contains the largest energy density amongst all renewable energy. In Malaysia, the highest wave energy in the South China Sea is 12kW with maximum wave amplitude of 2 meters. This paper presents the design and modelling of wave energy converter and power take-off system that suitable for Malaysia in order to obtain the highest output of electrical power. A point absorber made up of a floating buoy connected by a fibre rope is used as wave energy converter. Linear permanent magnet generator has been used as the power-take-off system. This generator exploits directly the incoming sea wave vertical motion. This wave energy converter and power-take-off model have been developed and implement in Matlab. The model included wave energy, buoy water interaction, and linear generator. To extract highest wave energy, different parameters have been applied to the linear generator. Simulation results are presented showing three effects of three different parameters; winding coil turns, magnetic field strength and tooth width of the stator.

KEYWORDS: *Wave Energy Harvesting; Alternative Energy*

1.0 INTRODUCTION

Since the Industrial Revolution, humans use fossil fuels such as coal, natural gas, and petroleum to generate electrical energy. Continuous extraction of these non-renewable energy resources will eventually cause the depletion of fossil fuel [1]. Referring to the United States Environmental Protection Agency, 26% of greenhouse gases are emitted from energy supply [2]. It is considered the largest source of the global greenhouse gas emission. The energy supply mentioned is the burning of fossil fuel for the purpose of electricity and heat generation. According to the Country Synthesis Report On Urban Air Quality Management report, Malaysian power plant emits about 10% nitrogen oxide, 60% sulphur dioxide and 40% of the particular matter in 2004 [3].

Along with the growth of industry and economy, the demand for electrical energy has increased [4]. To generate more electrical energy, the burning of fossil fuels also increased. In Malaysia, the electricity generation is produced through the construction of open and combined cycle gas turbines, dual-fired gas or oil thermal power station, coal-fired thermal power stations and hydroelectric power station [5]. In 1999, a fossil fuel that used to generate electricity is 73.3% natural gas, 7.8% petroleum gas and 7.5% coal [5].

According to U.S Energy Information Administration report, petroleum and natural gas liquids are the primary energy sources consumed in Malaysia followed by natural gas and coal [6]. This report also stated that due to the economic development and population growth in Malaysia, it resulted in substantially higher electricity generation landing at 134 billion kilowatt hours in 2012 according to Malaysia Energy Information Hub (MEIH) data [6]. In addition, fossil fuel consumption in Malaysia is quite high about 94.5% in the year 2012 according to The World Bank data [6].

Fossil fuels are non-renewable and have limited amount in the world. Because of the energy consumption increasing over the world, renewable energy has been introduced. There are a few of renewable energy source such as solar, tidal and hydro. In Malaysia, the most commonly renewable energy is hydro and followed by solar and biomass. Although Malaysia is located at the equator and has a tropical climate, due to its seasonal rainfall variation in peninsular Malaysia, solar may not be the best solution. In contrast, the hydroelectric power plant has a lot of disadvantage. It may affect the environment and disturb the ecosystem and habitat of living beings [8].

Amongst renewable energy sources, ocean waves contain the highest energy density [9]. Wave energy has a high availability factor compare with other resources, resource predictability, high power density and low environmental and visual impact [9]. There are research and development program on wave energy in other countries to investigate the availability of wave power energy conversion even though there is no any exploitation of wave energy to any significant extent in Malaysia [10]. Ocean covers about more than 70% of the earth. As waves roll through the ocean, they contain kinetic energy. This kinetic energy can be harness and converted into electricity or power. There are varieties of ways to convert this energy into electricity. However, there are still many limits in harvesting wave energy such as high cost, low field experience, and limited technical skills [11]. Besides that, most of the wave energy converter devices are large in size and complicated in design. Usually, it is needed to be built offshore. Thus, research and engineering work have to be done to develop a reliable and cost efficient wave converter [12].

This project is conducted to study the feasibility of harvesting wave energy using modelling and simulation of a wave energy power generator. A wave energy generator consisting of a permanent magnet is mathematically modelled and simulated using Matlab. This model is analysed by conducting a parametric study to deduce the optimum configuration in terms of voltage, current and power production.

2.0 DESIGN OF WAVE ENERGY CONVERTER

The design of the wave energy converter (WEC) require a floating buoy to be located on the sea surface connected by a rope to the linear permanent magnet generator. The floating buoy acts as a "point absorber" device that absorbs the wave energy. The location of this floating buoy could be in the ocean shoreline, near the shore or offshore [13]. In shoreline, WEC can be easily installed and maintenance. They do not require any mooring and long length underwater electrical cables. However, this device does not experience high wave energy compared with other two locations. Near the shore region is the transition region between shallow and deep water. In this region, WEC has similar advantages with shoreline but experience higher powered waves than shoreline. The offshore region will let WEC devices experience more powerful wave in due to the deep waters. In this region, WEC requires a mooring system to keep the device at the desired location [14].

Besides that, the stability of the floating buoy is also considered to make sure it resists overturning moments and can withstand various external loads such as the wind, current and waves. In designing, all the weights of the floating buoy are accounted for while calculating the centre of gravity [13]. The condition for the stable equilibrium of a floating buoy required a restoring couple to return to its original position following angular perturbation. A floating buoy is considered stable when all the resultant force acting on it is zero. In addition, the size of the floating buoy needs to be determined to increase the performance of the floating buoy. The size of the floating buoy should be much smaller than the incoming wavelengths so that it will capture the wave energy effectively [14]. The steepness of the incoming wave is very important as it may affect the output power and the lifespan if the floating buoy. If the diameter of the floating buoy is larger than or equal with the steepness of wave, the floating buoy could be submerged more than it is required and some parts could be damaged. This will affect the output power. So, the floating device should be small in size so that it will be able to operate in most of the conditions.

On the other hand, to obtain optimal output power from the floating buoy, the incident of wave frequencies must be closer to or correspond to the natural frequency of the floating buoy. The natural frequencies of the floating buoy are calculated by considering the total mass of the system and spring constant. The natural frequencies are then tuned by varying the mass of the system and spring constant. A mooring system maintains the floating buoy at the desired position [15]. There are three categories of materials that used in mooring: metals (wire or chain), synthetic materials (nylon line), and natural non-metallic. The common materials used for energy conversion is a chain, wire ropes, and fiber ropes. These materials will provide optimum performance for the floating buoy in a wide range of water depths. The chain is the heaviest, has highest break strength and elasticity while fiber rope has light weight, lower break strength and elasticity compare with chain. The choice for choosing this material depends on the water depth, the seabed material and slope and the cost [15].

3.0 MATHEMATICAL MODELLING

Ocean waves motion are normally generated by the different type of force such as bodies moving on the surface of the ocean, winds push the sea surface and create different pressure between the air and water. The differences of distances between earth and the moon will also generate waves. The important parameters that describe wave are wavelength, wave amplitude, period, and water depth. Higher wave energy can be obtained in deep water as compared to shallow water. This is because ocean waves travel slowly in shallow water with small wavelength. Wave fluctuation that causes by only one frequency in vertical direction can be presented as:

$$\mathrm{x} = A \sin \mathrm{w}t \tag{1}$$

where A is wave amplitude and ω is angular frequency. In deep water, approximation expression for wave power, P_{wave} can be described as:

$$\mathrm{P}_{wave} = \frac{pg^2 H_s{}^2 T}{64\pi} \tag{2}$$

Here ρ is the seawater density, g is gravitational acceleration, H_s is wave significant height and T is wave period.

Table 1: Northeast monsoon wave data [8]

Northeast monsoon	Value
Wave amplitude	2.0 m
Wave time period	6.0 s
Wavelength	56.2 m

Referring to wave data given by Table 1, the approximation maximum wave power that Malaysia can experience by using the Equation 2 is 11.77kW. According to Malaysian Meteorological Department, Malaysia experiences northeast monsoon and southeast monsoon. The overall highest wave height is during northeast monsoon in the South China Sea.

The potential energy of wave will lift the floating buoy as illustrated in Figure 1. This floating buoy is the main converter that converts wave energy into kinetic energy to move the translator that mounted with a permanent magnet. The total forces acting on the floating buoy consists of buoyancy force F_b, drag force F_d, radiated force F_r, excitation force F_e, spring force F_s and generator force F_g. The buoy movement is then controlled by the following equation:

$$M\ddot{z} = F_b + F_d + F_r + F_e + F_s + F_g \tag{3}$$

where M is the total mass of buoy-translator system and $\ddot{z}$ is the acceleration.

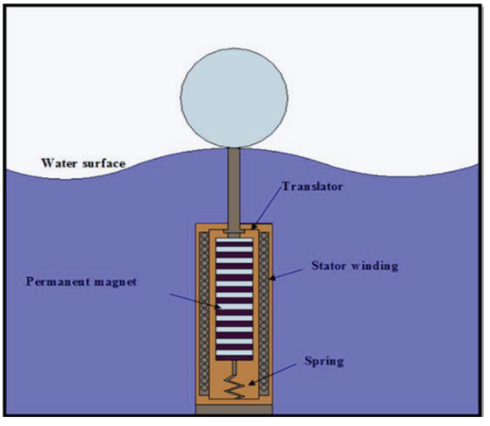

Figure 1: Schematic diagram of wave energy converter

Buoyant force is the upward force that acting on the buoy when the buoy is fully or partially submerged in the water. The buoyant force can then be calculated as:

$$F_b = -S_b z \tag{4}$$

The S_b is hydrostatic stiffness and z is vertical displacement,

$$S_b = \rho g A_w \tag{5}$$

where ρ is seawater density, g is gravitational acceleration, and A_w is the area of floating buoy. Drag force also known as fluid resistance is the force that acting opposite to the relative motion of the floating buoy with respect to the surrounding fluid. Drag force can be expressed as:

$$F_d = -\frac{1}{2}\rho C_d A_w \dot{z} \tag{6}$$

where, ρ is seawater density, $C_d$is drag coefficient and $\dot{z}$ is velocity. Radiated force appears due to the wave which is radiated by the buoy motion itself in the absence of incident wave. Radiated force can define as:

$$F_r = -m_r(\omega)\ddot{z} - R_r(\omega)\dot{z} \tag{7}$$

Here m_r is added mass, R_r is radiated resistance and can be computed as:

$$m_r = \mu_r m_m \tag{8}$$

$$R_r(\omega) = \varepsilon_r \omega \rho a^3 \, 2\pi/3 \tag{9}$$

where m_m is mass of the buoy, ω is the angular frequency of the incident wave, μ_r and ε_r are coefficients. Excitation force is the wave progress in the positive x-direction to the floating buoy which can move in the surge, heave and pitch motion. For simplicity, the excitation force can be calculated as follow:

$$F_e = \kappa \rho g \pi a^2 x \tag{10}$$

in which κ is non-dimension excitation force which depends on ka ($k = 2\pi/\lambda$), λ is the wavelength. A spring that connects the floating buoy to the bottom structure functions as an energy storing mechanism. When the buoy is lifted by a wave, some energy is converted into electrical energy while some energy is stored in spring. When the buoy moves downward, the stored energy is converted into electrical energy.

$$F_s = -k_s z \tag{11}$$

where k_s is the spring constant and z is vertical displacement. The electromagnetic force (emf) produced by the linear permanent magnet generator in one phase can compute from the equation below:

$$E_i = \frac{d\lambda_{im}}{dz}\frac{dz}{dt} \tag{12}$$

where λ_{im} is the flux linkage in phase i due to permanent magnet and z is vertical displacement. The flux linkage can be expressed as:

$$\lambda_{im} = N_i \phi_i \cos\left(\frac{\pi}{w_p} z\right) \tag{13}$$

where N_i is number of turns in phase- i, $\emptyset_i$ is maximum flux and w_p is pole pitch. Therefore, the generator force that provided by the linear permanent magnet generator which opposing the movement of the buoy can be given as:

$$F_g = N_i \phi_i \sin\left(\frac{\pi}{w_p} z\right) i_i \tag{14}$$

where i_i is the current in the phase- i. The per-phase inductance, L_s of the generator can be computed by:

$$L_s = \frac{6\mu_0 l_s w_p \left(k_w N_i\right)^2}{N_p \pi^2 g_{eff}} \tag{15}$$

where μ_0 is air permeability, l_s is stator length, k_w is winding factor, N_p is the number of poles and g_{eff} is effective air gap length and can be calculated from:

$$g_{eff} = K_c g_1 \tag{16}$$

where g_1 is air gap length and K_c is the Carter's coefficient and is calculated from the equation:

$$K_c = \frac{T_t(5g_1 + b_s)}{T_t(5g_1 + b_s) - b_s^{\ 2}} \tag{17}$$

where b_s is the slot width and T_t is the tooth pitch and can be calculate from:

$$T_t = b_s + b_t \tag{18}$$

where b_t is the tooth width. The generator phase resistance is:

$$R_s = \rho_{cu} \frac{2N_i^{\ 2}(l_s + 2w_p)}{N_p h_s b_s k_{sfil}} \tag{19}$$

where ρ_{cu} is copper resistivity, h_s is slot length, k_{sfil} is copper filling factor. The output phase current, I_{ph} is then calculated from equation:

$$I_{ph} = \frac{v_{ph}}{R_s + L_s} \tag{20}$$

where V_{ph} is the output phase voltage. Therefore, the three-phase output power that produced by the linear permanent magnet generator can then be calculated as

$$P_{out} = \sqrt{3V_{line}} I_{line} \tag{21}$$

where $I_{line} = I_{ph}$ and V_{line} can be calculated as:

$$V_{line} = \sqrt{3V_{ph}} \tag{22}$$

4.0 OUTPUT POWER DUE TO VARIOUS PARAMETERS

Three different parameters are studied via simulation to obtain the highest electrical output power. The parameters are the number of winding coil turns, magnetic field strength and tooth width of the stator. The default values for these parameters are 2000, 0.55T and 75mm respectively. One of the values is changed while the others remain a constant. The ranges chosen for these parameters are so that the wave generators size remains realistic and economic.

4.1 Number of winding coil turns

The simulation is carried out with the number of winding coil turns is increased from 500 to 3500. Based on Figure 2, it shows that the output phase voltage increases and output phase current decreases as winding turn increased. As the winding turn increased, the inductance is also increased. This resulted in more voltage being induced and current is decreased. Overall, the output voltage is directly proportional the number of turns of the coil and the output power always remain unchanged.

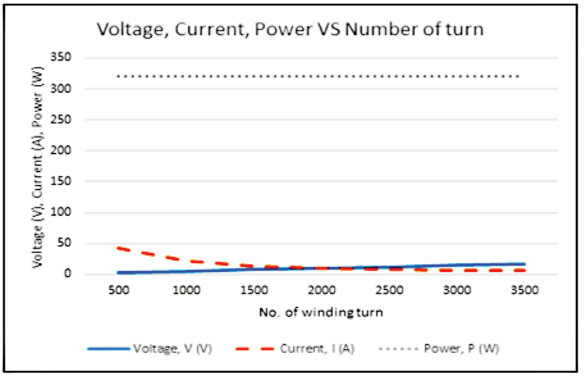

Figure 2: Voltage, Current and Power vs No. of turns

4.2 Magnetic field strength

The second simulation is carried out to evaluate the optimum magnetic field strength for the purpose of obtaining higher output power. This magnetic field strength of the magnet is set from 0.45T to 0.7T. From the Figure 3, it is observed that the phase output voltage, phase output current, and output power is increased linearly with the increment value of magnetic field strength. The reason is due to the stronger magnetic field density that produced a higher induced voltage when more magnetic flux cut through the winding coils. This will result in a greater current flow through the coils. Therefore, output power increases as voltage and current increases. Overall, it can be concluded that output phase voltage, phase current, and output power is directly proportional to the magnetic field strength.

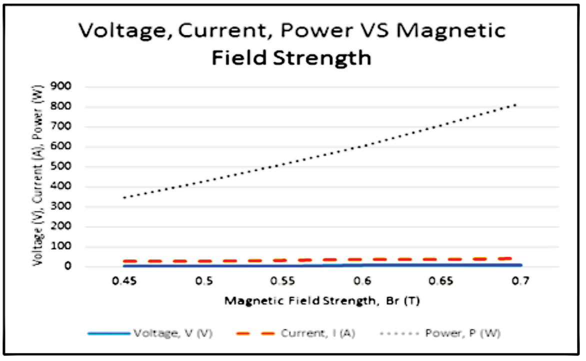

Figure 3: Voltage, Current and Power vs Magnetic Field Strength

4.3 Tooth width of stator

The third simulation is carried out to determine the output power with different tooth width of the stator. The winding coils are tied in the tooth width of the stator. By changing the tooth width diameter, the winding coils diameter also changed. In the simulation, the tooth width diameter is increased from 65 mm to 85 mm.

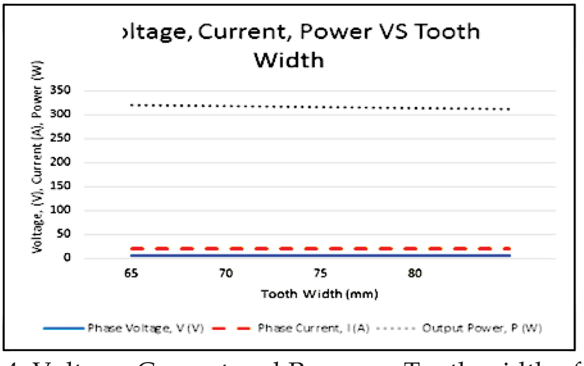

Figure 4: Voltage, Current and Power vs Tooth width of stator

Based on Figure 4, it can be seen that output power and phase current decreases as tooth width of stator increased. However, the value of phase voltage remains constant at 5V with the change of tooth width. This shows that the value of tooth width must be as small as possible. By decreasing tooth width of the stator, larger contact areas between teeth and the permanent magnet allow the output performance to be increased. However, the tooth width should not be too small as it may affect the carrying of magnetic flux with the coil. Anyways it can be concluded that output power decreases gradually with the increase of tooth width.

5.0 CONCLUSION

In conclusion, the present work meet the expectation to be able to simulate the optimum configuration of the wave energy power generator in terms of voltage, current and power production. Through the parametric analysis conducted it can be deduced that the winding coil of 3500, magnetic field strength of 0.7T and tooth width of 65 mm produced the highest output power is 777.5 W with an output phase voltage of 27.5 V and an output phase current of 9.45 A.

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