Design and Modelling of Generator for Wave Energy Conversion System in Malaysia

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Abstract — This paper presents the design and modelling of generator for wave energy conversion system in Malaysia. This paper aims to identify the most promising topology to be used and to propose initial designs of the generator. Literature review on the previous technologies, power take-offs and linear generator have been completed and from the review, the criteria for the proposed generator designs are acquired. Two designs have been proposed in which one of the designs utilizes alternate slot winding concept. Both of the designs are simulated using Finite Element software, Ansys Maxwell. The preliminary results of flux distribution, air gap flux density, flux linkage and induced back EMF are obtained. From the simulation results, air gap flux density of both designs is within the expected range. It is also found that by implementing alternate slot winding concept, even though the total number of turn is the same, the induced back EMF produces is slightly lower than the full slot winding.

Keywords - wave energy; Wave Energy Converter (WEC); linear generator; finite element method (FEM); alternate slot winding;

I. INTRODUCTION

World electricity consumption is growing over the years. In Malaysia, the electricity demand increases by 3% per year and this trend is predicted to continue until year 2030 [1]. This growth in world electricity consumption has led to vast researches being conducted in the exploitation of renewable energy as an alternative to fossil fuel in serving the demand.

Wave energy is renewable energy which has high potential to be developed as the alternative. Total wave energy resources estimated to be available in the open sea is 10 TW [2]. Malaysia which is surrounded by ocean has the potential for Wave Energy Converter (WEC) development. However, wave power availability in Malaysia is significantly lower than other countries with progressive research and development on WEC. Compared to United Kingdom which is reported to have 40 kW/m wave power, Malaysia has only around 6 kW/m [2]. This significant difference of ocean wave power availability indicates the need for WEC research that is conducted specially for Malaysia application.

In Malaysia, study on WEC application is still in early phase. The available research materials on this conversion is limited. Thus, this research aims to conduct study on generator designs for wave energy conversion that suit Malaysia application.

II. PROBLEM FORMULATION

Even though wave energy is one of the promising alternatives for energy generation, in Malaysia the study conducted on this topic is still limited. Among the researches conducted on WEC in Malaysia is as in [3]. Figure 1(a) shows the draft of the proposed design. The result of the experiment is mainly centred on the RPM produced in the turbine of the system which has been proven to be enough in converting the wave energy into useable energy [3].

Another project conducted on the topic of WEC in Malaysia has achieved full prototyping stage [4]. The device which is known as UMT Evo Wave Power utilizes oscillating bodies technology. The structure and design of the device is as shown in Figure 1(b). The conversion of the reciprocating motion into electricity is via gears which are connected to generator. The generator is expected to be able to produce up to 10kW [4].
Figure 1. WEC System Design of Previous Research (a) OWC System [3] (b) UMT Evo Wave Power [4]

Despite the fact that these studies focused on WEC development in Malaysia, nonetheless they address more on the design of the primary interface of the system. In addition, the generator used in the design especially the design in [3] is conventional rotary generator while another method of conversion can be considered as the Power Take-Off (PTO) of the system which is direct drive conversion.

Generator that specially suits the utilization of WEC in Malaysian ocean has to be designed in order to convert the low energy level of local wave into useable electricity. In WEC, the generator is included as part of the power take-off (PTO) mechanism that changes the mechanical energy to electrical energy. There are two types of generators that can be used which are rotary generator and linear generator. Thus, type of generator to be used in this study has to be selected first before the designing process.

III. POWER TAKE-OFF (PTO)

There are three classifications of PTO which are turbine, hydraulic and direct drive [5]. Both turbine and hydraulic are applied to rotary generator as the transmission system [6], [7]. Direct drive method is utilized by linear generator so that the mechanical energy can be directly converted into electrical energy without the need of any interface mechanism [5], [8]. Table 1 shows the comparison between these two types of generator.

<table>
<thead>
<tr>
<th>Linear Generator</th>
<th>Rotary Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huge size but provide simpler system</td>
<td>Small in size but complex construction</td>
</tr>
<tr>
<td>Required less maintenance with longer lifetime</td>
<td>Required more maintenance</td>
</tr>
<tr>
<td>Higher efficiency</td>
<td>Low efficiency</td>
</tr>
<tr>
<td>Large construction cost</td>
<td>Require transmission system</td>
</tr>
</tbody>
</table>

From the comparison, it can be concluded that direct drive linear generator has advantages over conventional rotary generator in term of efficiency and overall cost. High efficiency deployed by direct drive PTO can be a benefit in increasing the efficiency of low ocean wave power in Malaysia.

Direct drive linear generator system can be used with point absorber oscillating bodies technology. This technology extracts the heaving motion of the wave and transfers it directly to the generator. Figure 2 shows the concept of point absorber technology which utilizes buoy as the primary interface to capture the wave motion.

Figure 2. Linear Generator with Permanent Magnets [6]

In this paper, generator is designed to be applied with this available technology and only permanent magnet (PM) linear generator will be considered. The generator is expected to be able to supply electricity to a residential located along the coastline of Malaysia. Hence, 1.5 kW power with one-phase 240 V generator is desired to be designed.

IV. DESIGN METHODOLOGY

A. Machine Specifications

The data of ocean wave in Malaysia have been taken from [10] in which the wave height and wave period are 0.8 m and 3.5 s respectively. The rated translator speed calculated is 0.4 m/s. These wave data are used during the simulation and testing of the proposed designs. The electrical energy produced from wave energy in this research is aimed to be able to power up one residential house located along the coast of Malaysia. The overall power requirement of the generator is 1.5 kW with rated output single phase voltage of 240 V.

B. Machine Topology

For WEC application at near shore of Malaysia, as the wave power level is low with slower wave speed, more weightage should be put into factors that affect the efficiency of the output power which are flux density, shear stress and power losses.

Thus, tubular longitudinal flux machine with slotted iron cored is chosen to be used. Tubular structure is opted as it
gives lower total power loss to the system and hence has higher power density [11]. The higher power density in slotted and iron cored structure becomes the main reason for the selection. Other than that, iron cored machine is capable of producing higher shear stress than air cored machine and thus contribute to smaller size of generator [12]. The proposed generator designs of the project will be modelled based on the selected criteria.

Two designs are proposed in this research. The difference of both designs is the winding arrangement concept in the stator. The concept of alternate teeth wound will be applied onto the second proposed design. The study on alternate teeth wound design has been conducted using PM brushless rotary motor [13]. Conventional winding arrangement of all teeth wound machine is compared with alternate teeth wound in this study. Figure 3 shows the illustration of the design used in the study in [13].

![Figure 3. Alternate Teeth Wound Design [13]](image)

The most significant difference in the results of these two machines is their winding inductance, in which higher self-inductance value is observed in alternate teeth wound [13]. Self-inductance value of winding will affect the induced back EMF of the machine.

As the study in [13] is focusing on rotary machine with the winding being wound around the teeth, which is different from tubular linear generator, the proposed design will implement alternate slot winding instead of teeth wound. The slots of the proposed design will be alternately wound. Number of turn per slot will be differ from the first design however the total turn of coil in both machines will be kept constant.

C. Stator and Translator Mechanical Design

Stator mechanical design consists of the stator’s core parameters and total length of the coil whereas the translator design includes the magnetic pole numbers and height of the magnet.

1) Length of coil and radius of stator

The length of the coil can be approximated using the formulas as follows;

\[
Induced\ EMF = B_g L v
\]  

\[
Output\ Power,\ P_{out} = \frac{1}{2} B_g A v
\]

\(B_g\) in the equation signifies the air-gap flux density in tesla, \(L\) is the coil total length in meters, \(v\) is the velocity in m/s and \(A\) is peak electrical loading in Ampere/m. From the calculation in (1) and (2), using the average output voltage of 240 V and output power of 1.5kW, the air gap flux density is approximately 0.7 T and the total length of coil must be more than 860 m. The initial radius of the stator is depending on the number of turns and its total length. The circumference of the stator must be approximately the same or more as the total length of coil per slot per turn.

2) Number of magnetic pole and height of magnet

In designing translator, the important parameters are number of magnetic pole and the height of the magnet. Number of pole of the machine must be high enough to yield better output voltage. However, too much magnetic pole will affect the stator losses. The losses will be higher due to higher magnetic frequency [14]. The value of slot per pole per phase (q) also will become smaller as number of pole increases that in return produce less sinusoidal voltage waveforms [14], [15].

Thus, the chosen pole number of the initial design is 4 poles aligned under the stator at any time of translation. Height of the magnet can be acquired from the following formula [16];

\[
B_g = B_r \left( \frac{h_m}{\mu_r v r_g} \right)
\]

where \(B_r\) is the magnet remnant flux density, \(h_m\) is the height of the magnet, \(\mu_r\) is the relative permeability (\(\approx 1.05\)) and \(r_g\) is the air gap diameter.

3) Initial Proposed Design Specification

Table 2 shows the initial designs parameters of the proposed generators while Figure 4 and Figure 5 show the full and stator-focused image of 2D Quarter symmetry of the designs respectively. The design parameters are designated from the design conditions, calculations and assumption.
Table 2. Initial Dimension of Proposed Designs

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of slot</td>
<td>11</td>
<td>Total turns of coil of the machine</td>
<td>2640</td>
</tr>
<tr>
<td>Length of stator, ( l_s )</td>
<td>440 mm</td>
<td>Air gap diameter, ( g )</td>
<td>4 mm</td>
</tr>
<tr>
<td>Height of back iron, ( h_{bi} )</td>
<td>20 mm</td>
<td>Length of magnet assembly, ( l_m )</td>
<td>1.48 m</td>
</tr>
<tr>
<td>Width of slot, ( w_{sl} )</td>
<td>23 mm</td>
<td>Width of magnet, ( h_m )</td>
<td>80 mm</td>
</tr>
<tr>
<td>Height of slot, ( h_{sl} )</td>
<td>40 mm</td>
<td>Height of magnet, ( h_{me} )</td>
<td>7 mm</td>
</tr>
<tr>
<td>Stator tooth width, ( w_t )</td>
<td>17 mm</td>
<td>Outer radius of magnet, ( r_m )</td>
<td>128 mm</td>
</tr>
<tr>
<td>Depression width (slot opening), ( w_{df} )</td>
<td>5 mm</td>
<td>Number of magnetic pole</td>
<td>4</td>
</tr>
<tr>
<td>Outer radius of stator, ( r_s )</td>
<td>200 mm</td>
<td>Magnetic Pole Pitch, ( \tau_s )</td>
<td>120 mm</td>
</tr>
<tr>
<td>Number of turns per slot ( \tau_s )</td>
<td>240°</td>
<td>Coil slot pitch, ( \tau_s )</td>
<td>40°</td>
</tr>
<tr>
<td>Number of turns per slot ( \tau_s )</td>
<td>440°</td>
<td>Slot pitch, ( \tau_s )</td>
<td>80°</td>
</tr>
</tbody>
</table>

\(^{1}\text{Value for Full Slot Winding Design} \quad ^{2}\text{Value for Alternate Slot Winding Design} \)

Figure 6 shows the 3D design of the proposed design. There are two proposed designs which are Design A (Full slot winding) and Design B (Alternate slot winding). The differences of the designs can be observed in 2D quarter-symmetry images shown in Figure 7 and Figure 8. This quarter symmetry is also used during simulation using Ansys Maxwell software. Design A is the basic design of slotted machine while Design B utilized alternate slot winding design. Design B is introduced as it is expected that alternate slot winding arrangement will have higher output induced back EMF than full slot winding design with other dimensions to be kept constant.

V. RESULTS AND DISCUSSION

Both designs are simulated using the finite element analysis, Ansys Maxwell software. In this section the preliminary results on flux distributions, air gap flux density, flux linkage and induced back EMF will be discussed.

A. Flux Distribution

Figure 9 and Figure 10 show the flux distribution of full slot winding design and alternate slot winding design respectively. As observed in Figure 9 and Figure 10, both designs have the same flux distribution. This is because flux distribution in static condition is not affected by the configuration of the winding. Thus, even though Design B has alternate slot winding, it does not affect the flux distribution of the machine as the magnetic properties of both designs are the same.

From the flux distribution results, it can also be observed that the flux distribution along the stator is not constant. This is due to the value of pole pitch which is bigger than slot pitch that in return causes certain slots or teeth to be located at weakest magnetic flux point such as at the centre of the magnet. This uneven flux distribution of the stator will result in flux linkage waveform that is not smooth and in consequence resulted in unstable induced back EMF waveform.

B. Air gap Flux Density

Figure 11 shows the air gap flux density result from the simulation. The average value for air gap flux density of both designs is around 0.7 Tesla which satisfies the desired air gap flux density. The flux density for both designs shows minor difference with at most location, graph of both designs overlapped each other as the magnetic properties of the translator for both designs are the same.

From Figure 11, it is observed that the flux density increases at stator tooth’s location as the tooth serves as good
magnetic conductor compared to air. However, flux density reduces when it is located between the stator teeth or the slot opening as there is lesser conduction path for the magnet.

Lastly, no flux density is recorded at the spacer location as aluminium is not a good magnetic conductor. It is also observed that the air gap value is slightly higher at the center of the stator as the magnetic flux is concentrated there whereas for the magnet at both ends of the stator, the flux flow to the adjacent magnets located outside the stator’s length.

![Figure 11. Air gap Flux Density of the Proposed Designs](image)

C. Flux Linkage and Induced Back EMF

The translator of the designs is set to have a velocity of 0.4 m/s and maximum translation of 0.4 m (half of wave height). The simulation is conducted under open circuit condition. The output induced back EMF and flux linkage of this simulation is from one stroke of the translation onto the stator coil winding.

Figure 12 shows the flux linkage of both design while Table 3 shows the maximum flux linkage value. As predicted in flux distribution result, the waveform of the flux linkage for both designs is not smooth due to the uneven flux distribution on the stator. The flux linkage of a machine is basically the product of number of turns, the coil surface area and the magnetic density. Even though the total number of turn of both designs is the same, the difference in number of turn per slot influences the flux linkage value. At each instantaneous time of translation, both designs have specific value of magnetic density passing onto different number of turn per slot, and thus resulting in slight different of flux linkage of the coil. From the values in Table 3, even though the flux linkage in Full Slot Winding Design is higher than Alternate Slot Winding Design, the difference is not significant with only 3.82 Wb difference.

The result of induced back EMF of both designs is as shown in Figure 13. Peak and average induced back EMF of the designs is tabulated in Table 4.

![Figure 12. Graph of Proposed Designs’ Flux Linkage](image)

![Figure 13. Graph of Proposed Designs’ Induced Back EMF](image)

### Table 3. Maximum Flux Linkage

<table>
<thead>
<tr>
<th>Design</th>
<th>Flux Linkage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Slot Winding</td>
<td>36.66 Wb</td>
</tr>
<tr>
<td>Alternate Slot Winding</td>
<td>32.84 Wb</td>
</tr>
</tbody>
</table>

### Table 4. Peak and Average Back EMF Value

<table>
<thead>
<tr>
<th>Design</th>
<th>Peak Back EMF</th>
<th>Average Back EMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Slot Winding</td>
<td>549.85 V</td>
<td>208.44 V</td>
</tr>
<tr>
<td>Alternate Slot Winding</td>
<td>573.94 V</td>
<td>186.05 V</td>
</tr>
</tbody>
</table>

As induced back EMF is defined as rate of change of flux linkage, the higher value of maximum flux linkage in Full Slot Winding Design does not indicate the same trend to be observed in induced back EMF value. At certain point, the rate of change of flux linkage in Alternate Slot Winding Design is steeper that resulted in higher value of peak back EMF induced.

However, as the average of both induced back EMF result is calculated, it is found out that Design A - full slot winding design has higher average value than Design B—alternate slot winding by 10%. This is because, even though Design B has higher peak induced back EMF value, the induced back EMF...
and flux linkage waveform of Design A is smoother. The difference in winding arrangement of the designs influences the output of induced back EMF. In addition, due to the winding arrangement of alternate slot winding which made the winding of each slot unequal, the rate of change of flux linkage across the winding is less stable which in return resulted in unstable waveform of induced back EMF.

As being indicated in Table 4, the average induced back EMF of both designs is not up to the desired rated voltage which is 240 V. Based on (1), the factors that affect the induced back EMF value are the velocity of the translator, air gap flux density and length of coil. As the velocity of the translator is constant based on the wave data calculation, only air gap flux density and length of coil could be optimized. The desired flux density of 0.7 T is already achieved, thus the optimization to improve the induced back EMF is to be done on the length of coil of the design. To increase the length of coil, two methods could be used which is either to increase the radius of the design, Re or to increase the number of coil turn. This optimization process will be conducted as the future work of the research.

VI. CONCLUSION AND FUTURE WORKS

Two generator designs have been proposed for WEC application in Malaysia. From the results, it is found out that by having different winding arrangements implemented onto designs with the same dimensions, the design’s flux linkage and induced back EMF will be affected. It can also be concluded that full slot winding or normal winding arrangement produces better open-circuit simulation result in term of induced back EMF compared to alternate slot winding design. Thus, the initial prediction of higher back EMF value in alternate slot winding design is not supported.

Further optimization and analysis will be done to both designs to improve the efficiency of the machine. Optimization of the proposed designs will be conducted in term of total number of turns to produce the desired output voltage, split ratio (Rm/Re) and pitch ratio (tm/ tp). The best design will then be chosen and fabricated for validation process and comparative study.

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REFERENCES


