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Portable Pico Linear Generator Design with Different Magnet Shapes for Wave Energy Conversion System

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ABSTRACT

There are abundant of wave energy converter technologies available to convert wave energy into useable energy. However, most of them are huge and suitable for large application. Thus, this paper aimed to propose portable pico generator designs for small scale application. Investigation on the performance of designs with varying halbach magnet shapes was mainly focused and discussed. Two designs of different magnet shape i.e. triangular and trapezoid were proposed. Open-circuit simulation and optimization results were obtained using Finite Element Method. From the results, it was found out that Trapezoid Magnet Design produced better performance and lower material cost compared to another proposed design, Triangular Magnet as well as conventional Rectangular Magnet shape.

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1. INTRODUCTION

Discussion on ocean wave energy conversion into useable energy started centuries ago. The first patent for the conversion techniques was introduced in year 1799 [1]. At present, several countries have started to develop and implement wave energy power plant in generating electricity. Up to date, high numbers of technologies for wave energy converter (WEC) are available [2],[3]. Generally, WEC system consists of several subsystems; primary interface, secondary interface, generation and control system. Primary interface is responsible to capture the moving ocean wave and it can be categorized as oscillating water column (OWC), overtopping devices and floating body [3]. Next, the captured mechanical energy will be transferred by secondary interface or transmission system to generation part of the system. There are several types of secondary interface for WEC which are hydraulic, turbine and direct drive [4]. The mechanical energy will then be converted into electricity by generator which can be either conventional rotary generator or linear generator.

Among the notable WEC designs is Pelamis WEC which was founded in year 1998 and the first installation was done in wave test site in year 2010 [5]. The technology is a floating device and it uses hydraulic transmission system [4]. Second generation Pelamis WEC, P2 was designed to give output power of 750 kW and the device is 180 m long with weight approximately 1350 tonnes [5]. Another established WEC technology is Oyster WEC that was developed by Aquamarine Power [4]. First generation Osyter has rated output power of 315 kW and weighted 200 tonnees [6]. The device was deployed and installed in year 2009 and bigger second generation Osyter is currently being developed [7]. There are many other WEC devices that have been developed and some was installed on site such as OWC based Wavegen Limpet [8] and OPT Power Buoy [9]. However, the available technologies are mostly designed for big scale application and thus the size of the structure is also huge.

Wave energy can also be targeted for small scale application for example fishing activities or near shore activities. For these types of usage, the system must have smaller output power with reduced size and lesser weight. Therefore, WEC system that suits these criteria was targeted to be developed. This research was mainly focus on generator part of the system that plays role in energy conversion into electricity. The proposed generator designs was targeted to weight around 25 kg with the output power of 100 W. The objectives of the research are;

a. To propose generator designs that is portable and small in size
b. To conduct simulation and optimization on the proposed designs using finite element method
c. To perform comparison on the designs' performance and choose the best design

2. RESEARCH METHOD

Two proposed designs were introduced based on suitable linear generator topology. The proposed designs were simulated and optimized using Finite Element Method. Instead of just comparing the proposed designs with each other, the proposed designs were also being compared with conventional design to observe for any improvement.

2.1. WEC Technology and Proposed Design

Floating body technology was chosen to be used in this research because it can be used in small scale application and simpler power take-off (PTO) can be implemented with this technology which is direct drive [4]. Direct drive linear generator has lesser mechanical part than conventional rotary generator and thus reduce the construction and maintenance cost [10]. Figure 1 shows the general concept of floating body technology with linear generator.

Topology of linear electrical machine can be categorized into several group which are; 1) tubular or planar structure, 2) slotted or slotless stator, and 3) iron-cored or air-cored. Oprea et al. studied the structures of permanent magnet linear generator which are tubular and planar four-sided structures. The performance for both structures were the same when considering the induced voltage and coil magnetic flux. However, the construction of tubular is more difficult compared to the four-sided structure. In contrast, the weight of the four-sided structure is heavier for the same dimensions and specifications as the tubular structure and thus causes larger loss [11]. Tubular topolgy using permanent magnet is implemented for this research as it will maximize power density, magnetic flux density and efficiency as well as able to minimize power loss compared to the four-sided structure [12].

Bizzozero et al. proposed two topologies of tubular linear generator for sea wave energy production which are the slotted and slotless permanent magnet generators [13]. They concluded that the usage of the slotted configuration will give rise to more construction difficulties and by extension, the cost. In addition, when comparing in term of the force acting on the coil, the magnitude of force for slotless is lower than the magnitude of slotted generator due to high cogging and end effects. Moreover, slotted generator generates more reactive power but less active power compared to slotless generator. Nevertheless, slotted topology produces high flux densities and sheer stress compared to the slotless one [13],[14]. Thus, slotless stator was chosen to be used in order to obtain minimum cogging force. This will prolong the lifespan of the permanent magnet because the motion of piston is even and constant [15].

The design utilizes halbach magnet configuration instead of axial and radial configuration because it is expected to produce higher force with equal volume of magnet. Halbach configuration will eliminate one side of the magnetic flux while the other side will be increased by √2 [16]. The usual halbach magnet configuration has rectangular magnet shape as shown in Figure 2.

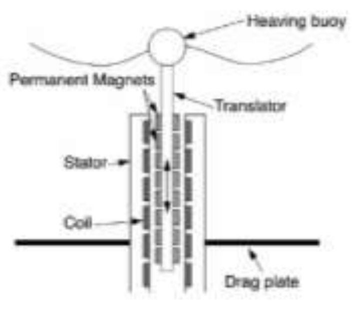

Figure 1. Floating Body Technology with Linear Generator [3]

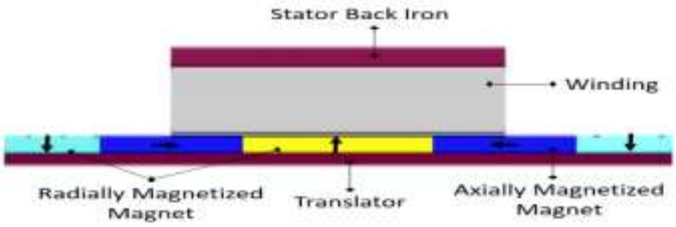

Figure 2. Conventional Rectangular Halbach Magnet Configuration

Based on the selection, the proposed designs will be tubular slotless linear generator with halbach magnet configuration. Two designs were proposed in which the manipulating aspect of these designs is the shape of the magnet. Instead of utilizing conventional rectangular magnet shape, different magnet shapes which are triangular and trapezoid shape were implemented in the proposed designs. The dimensions of the proposed designs are as shown in Table 1 while the proposed designs are illustrated in Figure 3. It is expected that different magnet shapes will produce better output as the number of horizontal edges of the proposed magnet shapes is more than the usual shape. This is because as flux density is mostly concentrated at the edges of magnet, more edges present in the design will increase the amount of flux linkage.

Table 1. Dimension of the Proposed Designs

Dimension	Value	Dimension	Value
Length of stator, l_s	200 mm	Total turns of coil winding	1000 turns
Height of back iron, h_{bi}	5 mm	Air gap diameter, g	0.8 mm
Length of winding, w_{wd}	200 mm	Length of magnet assembly, l_m	400 mm
Height of winding, h_{wd}	18 mm	Height of magnet, h_m	5 mm
Outer radius of stator, r_e	100 mm	Number of magnetic pole	1
Outer radius of magnet, r_m	76.2 mm		

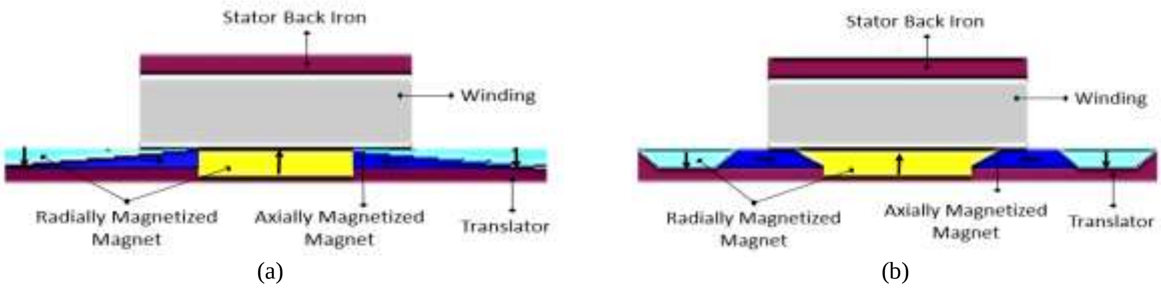

Figure 3. 2D Image of Proposed Designs (a) Triangular Magnet Shape Design and (b) Trapezoid Magnet Shape Design

2.2. Finite Element Analysis and Optimization

The proposed designs were simulated using Finite Element Analysis ANSYS Maxwell software. Conventional rectangular magnet shape was also simulated to serve as reference for comparison. Air gap flux density was being observed for static conditions. Open circuit test was conducted in dynamic simulation to obtain flux linkage and induced voltage produced by the generator designs. The parameters for open-circuit simulation are tabulated in Table 2.

Table 2. Parameters for open circuit test

Parameter	Value
Velocity	1 m/s
Moving distance	100 mm
Stop time	0.05 s
Step size	0.05 s

Optimization was conducted to increase the performance of the design. Two values were optimized which are pitch ratio, T_{mr} / T_p and split ratio, R_m/R_e. Pitch ratio optimization was executed by altering axial length of radically magnetized magnet while maintaing pole pitch. Induced voltage was observed during the process. For split ratio optimization, the radius of magnet was modified and at the same time the outer radius of stator core was kept constant. The result for split ratio was in term of efficiency of the designs.

3. RESULTS AND ANALYSIS

3.1. Air-gap Flux Density Results

Figure 4 shows the flux density along air gap of the three generator designs. From the graph, it can be observed that Triangular Magnet Shape design has the same density peaks as reference design. These peaks are formed at the edges of the magnets where most flux can be found. For Trapezoid Magnet Shape design, other than the peaks that are located at the same spots as other designs, it has additional four peaks. These additional peaks are due to the shape of trapezoid magnet which is not in 90^0 at the sides and thus having more edges that are at different horizontal spots than each other. The average and maxiumum flux density values are tabulated in Table 3. From the data, Triangular magnet shape has the highest value of flux density.

3.2. Flux Linkage and Induced Voltage Results

Figure 5 shows the result of flux linkage of the designs while the average and maximum values are tabulated in Table 3. From the tabulated data, Trapezoid Magnet Shape design has the highest maximum and average value of flux line, while the reference Rectangular Magnet Shape design has the lowest flux linkage value. This result was as expected in which proposed designs that have more horizontal magnet edges will produce better flux linkage. Flux linkage graph of the three designs are having the same pattern, however the gradient of the graphs differ. This difference will reflect in the induced voltage produced by the generator.

Induced voltage result of the designs is illustrated in Figure 6 and tabulated in Table 3. The result shows that Trapezoid Magnet Shape design produced highest maximum and average value of induced voltage. These induced voltage results are corresponding to flux linkage results in which design with high gradient of flux linkage graph is having high value of induced voltage. Based on flux linkage results, it can be observed that Trapezoid Magnet Shape design has steepest graph line compared to others. This high flux linkage and induced voltage of Trapezoid Magnet Shape design is due to the surface area of axial magnet which is larger compared to other two magnet shape designs. It can be concluded that from the induced voltage results, both proposed magnet shape designs which are triangular and trapezoid have higher induced voltage value compared to the reference design which is Rectangular Magnet Shape design.

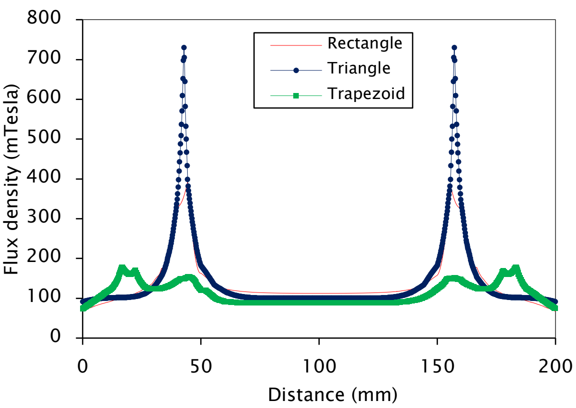

Figure 4. Air-gap Flux Density

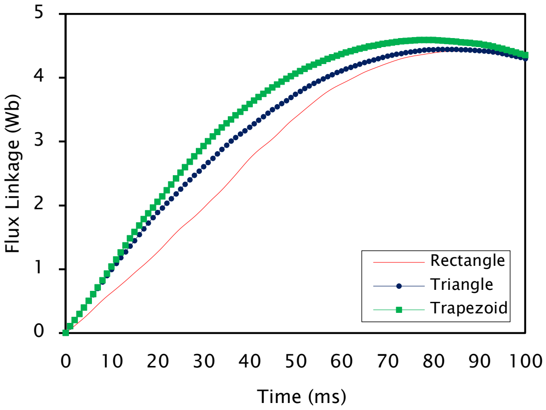

Figure 5. Flux Linkage of the Designs

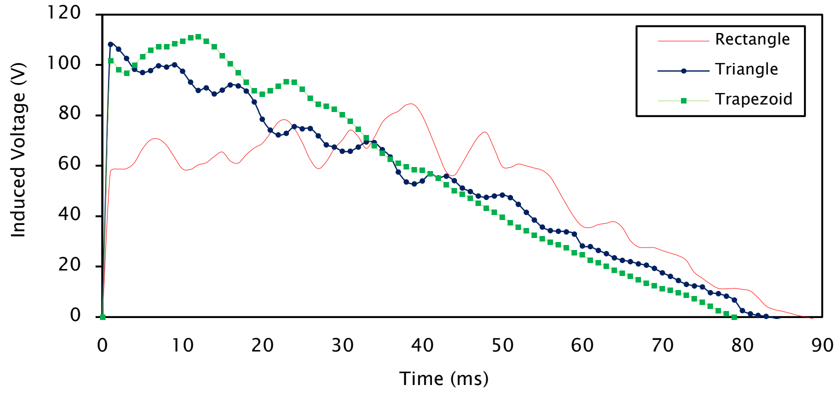

Figure 6. Induced Voltage of the Designs

Table 3. Average and Maximum Values of Flux Density, Flux Linkage and Induced Voltage

Design		Rectangular Magnet (Ref.)	Triangular Magnet	Trapezoid Magnet
Flux Density	Average Value (mT)	139.611	144.001	111.649
	Maximum Value (mT)	393.794	730.145	178.479
Flux Linkage	Average Value (wb)	2.903	3.192	3.387
	Maximum Value (wb)	4.420	4.446	4.591
Induced Voltage	Average Value (V)	45.03	45.54	47.77
	Maximum Value (V)	84.20	108.23	111.26

3.3. Optimization Results
3.3.1. Pitch Ratio Optimization
Induced voltage value is observed in pitch ratio optimization. The result for pitch ratio optimization is illustrated and tabulated in Figure 7 and Table 4 respectively. Based on the result, it is shown that the optimal pitch ratio in Rectangular, Triangular and Trapezoid Magnet Shape design are at different point. Trapezoid Magnet Shape design produced the highest optimal induced voltage with the increment of 2% from original value while reference design; Rectangular Magnet Shape recorded the lowest value.

3.3.2. Split Ratio Optimization
The result of split ratio optimization is as shown in Figure 8 and Table 4. As will be observed, the optimal split ratio value for Triangular and Trapezoid Magnet Shape design are the same at 0.742 while for reference design, the optimal value is slightly differ. Trapezoid Magnet Shape design produced highest efficiency for split ratio optimization followed by Rectangular and Traingular Magnet Shape designs. This dissimilar value of efficiency is due to copper loss for each design is different at different point of R_m/R_e.

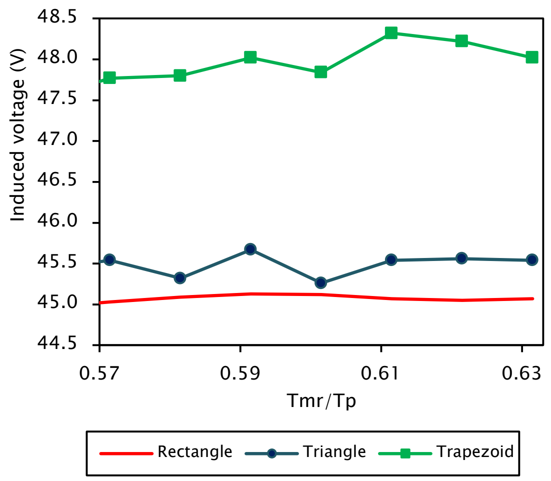

Figure 7. Pitch Ratio Optimization

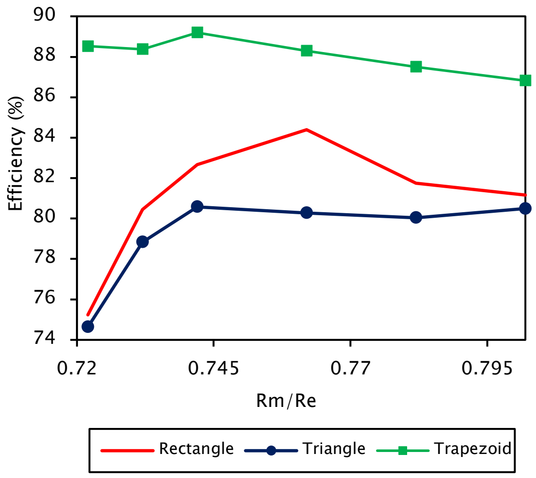

Figure 8. Split Ratio Optimization

Table 4. Induced Voltage and Efficiency of Optimal Pitch and Split Ratio Value

Design		Rectangular Magnet (Ref.)	Triangular Magnet	Trapezoid Magnet
Pitch Ratio	Optimal Pitch Ratio	0.5915	0.5915	0.6115
	Average Induced Voltage (V)	45.13	45.67	48.32
Split Ratio	Optimal Pitch Ratio	0.762	0.742	0.742
	Efficiency (%)	84.40	80.58	89.20

3.4. Material Cost Calculation

Total material cost is estimated based on the volume of a specific material required by the designs. Table 5 shows the total weight and material cost of each design.

Table 5. Designs' Total Weight and Material Cost

Design	Volume of material (cm^3)				Total Weight (kg)	Total Material Cost (RM)
	Copper	Steel	Magnet	Iron		
Rectangular Magnet (Ref.)	1950	611	926	613	32.58	2,391.48
Triangular Magnet	1950	595	890	613	32.19	2,331.94
Trapezoid Magnet	1950	596	890	613	32.19	2,331.94

As shown in Table 5, the price of three designs are almost the same. However, the proposed designs are slightly cheaper compared to the reference conventional design, Rectagular Magnet Shape. Nonetheless, the cost considered does not include the construction cost and it is only the cost of the materials for the generator. The total weight of the designs are heavier than the targeted weight by approximately 7 kg or 28 % in order to obtain the desired output power of 100 W.

From the optimization and material cost calculation, the best generator design is Trapezoid Magnet Shape design which has better efficiency than Triangular Magnet by 11 %. In addition, the design also improve the performance of conventional magnet shape design by 5 % and the material cost is also cheaper. Even though the weight of the design is slightly heavier than the targeted weight, the 7 kg difference is still in acceptable range.

4. CONCLUSION

Two generator designs which are Triangular and Trapezoid Magnet Shape design were proposed for the utilization with small scale wave energy conversion system. The designs differ in term of the shape of the permanent magnets while maintaining other dimensions. From the simulation and analysis, it shows that Trapezoid Magnet Shape design has the best performance. The induced voltage produced and efficiency of Trapezoid Magnet Shape design is the highest among the simulated designs. Furthermore, the material cost calculation for Trapezoid Magnet Shape design is slightly lower compared to conventional Rectangular Magnet Shape design. It can also be concluded that different magnet shape designs able to slightly improve the performance of the conventional shape. It is recommended that further study to be conducted in fabricating the design so that experimental testing can be done. From experimental results, the simulation data can then be validated.

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Naily Akmal Mohd Zamri was born in Selangor, Malaysia in 1992. She obtained her Bachelor degree in Electrical and Electronic Engineering from Universiti Teknologi PETRONAS, Malaysia in year 2015. She has published one international journal paper and 2 papers for international conference. She is currently an MSc student in Universiti Teknologi PETRONAS. Her interest areas include linear electrical machine design, renewable energy (wave) and power electronics.