International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 11, No. 3, September 2020, pp. 1415~1422
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v11.i3.pp1415-1422

Designing of a generator for wave energy conversion for outdoor activities

Noor Syazana Abd Ghani, Taib Ibrahim, Nursyarizal Mohd Nor
Department of Electrical and Electronic Engineering, Universiti Teknologi PETRONAS, Malaysia

Article Info

Article history:

Received Jan 7, 2020
Revised Feb 22, 2020
Accepted Apr 6, 2020

Keywords:

Flux linkage
Induced-EMF
Linear generator
Permanent magnet
Wave energy conversion

ABSTRACT

Wave energy is one of the renewable resources with high availability area of the wave across the world. However, the wave power density in Malaysia is smaller compared to other countries with progressive development in Wave Energy Converter (WEC), which leads to wave energy utilization to produce pico-scale power generation for the benefit of outdoor activities. Thus, this paper is presenting the modeling of a tubular longitudinal permanent magnet linear generator for wave energy conversion for outdoor activities. This research aims to design a pico-scale linear generator with 100 W output power utilizing wave energy. The design is also intended to be a portable design with a weight that less than 20 kg, which compatible with outdoor activities. The generator is proposed by designing the different shapes of permanent magnets with slotless configuration. The designs are simulated using the Finite Element Analysis (FEA) to obtain the performance of flux distribution, flux linkage, and back EMF performance.

Corresponding Author:

Taib Ibrahim,
Department of Electrical and Electronic Engineering,
Universiti Teknologi PETRONAS,
Seri Iskandar, 32610, Perak, Malaysia.
Email: taibib@utp.edu.my

1. INTRODUCTION

As the world nowadays emerging into more advance with technological advances, more things consumption is needed, especially energy [1]. The use of energy in Malaysia is explicitly increasing by 1.8 % annually [2]. Hence, more generated energy power is required to satisfy the demand by increasing the scale of energy generation using renewable energy resources [3]. The studies on improving the performance and system on capturing the renewable resource and converting to electrical energy had conducted [1, 4]. The renewable resource comes from various type of forms, as one of them is from the ocean waves. Ocean wave has a high availability area across the world [5], and Malaysia is one of the countries that are surrounded by the sea with the available potential area for wave energy utilization. The sea Strait of Malacca surrounds West Peninsular Malaysia, while East Peninsular Malaysia surrounded by the South China Sea [5]. Based on the recorded wave availability, the wave power density in Malaysia is smaller [3, 6] compared to other regions such as southern Africa, Australia, and the northwestern coast of the United States with the available wave power to be around 10-40 kW/m. Nonetheless, the low density of wave energy at the coastline of Malaysia can be used to produce a pico-scale power generation system with output power below 5kW [7] for the benefit of outdoor activities. Furthermore, the Malaysia government introduced the Small Renewable Energy Power (SREP) scheme in 2001 that supports the development of small scale power generation from renewable energy [2, 8].

Wave energy can be harnessed through several stages before convert into electrical energy. The primary stage devices called Wave Energy Converter (WEC) [9]. Wave Energy Conversion (WEC) is a system that can be categorized based on its operating theory as Oscillating Water Column (OWC), Overtopping Devices (OTD), and Wave Activated Bodies (WAB) [3, 9, 10]. Oscillating water column (OWC) is the device that utilizes a partially submerged hollow air chamber. This device is working as a pneumatic converter to obtain high-speed airflow through the air turbine, which gives a robust and straightforward design. However, this device generates noise pollution and give to the high cost of production and maintenance together lifetime problem. Overtopping (OTD) device called the terminator is the system that uses a concept of the water reservoir and releasing through a turbine. OTD has few moving parts that can reduce the need for maintenance due to tearing problems and leads to a stable system due to the large size of the device. Next, wave activated bodies (WAB) which is oscillating bodies. Consists of the floaters that move parallel to the wave's motion and capture the energy. The point absorber device is also one of the devices that utilize the WAB principle. It has the advantage which gives minimal ecological impact and versatility as a floating device due to small size. Even though the size is small, but this device very complex to be installed and complicated mooring due to underwater power cable required [9–12]. Thus, based on the classification of the working principle, WAB is the most suitable device principle due to the small size and simple design of WAB. The device, according to this principle, precisely, point absorber, has the potential to be developed as portable pico-scale electricity [13, 14]. Point absorber is a floating structure device that has fixed buoy inside a cylinder that rises and falls with the differences in wave height [15] and has horizontal dimensions that are smaller than the wavelength of the wave. The secondary stage involves the electrical machine, called Power Take-Off (PTO), which converts mechanical force from wave energy into electrical energy [16, 17]. PTO for WEC consists of three main methods, which are a turbine system with the rotary generator, hydraulics transfer with the rotary generator, and direct drive linear generator [18].

Rotary generator in the study of [18] is suitable for the environment, efficiency, and cost-effective application of WEC. The major disadvantage of the rotary generator is its high maintenance requirements and complex structure. Even though the rotary generator is mostly used for power generation mainly due to its mature technology, however, advancement in direct drive linear machine design is a linear generator. Until now, the research regarding portable linear generator is still under the study [13, 19, 20]. The basic concept of the linear generator requires a translator with the magnet, which reacts like a rotor [21]. The translator is attached to the heaving buoy with the winding stator, mounted in a structure that is fairly presented in [14]. When the heaving buoy oscillates, the stator induces an electric current. Linear generator expected to be more efficient and robust for specific wave energy conversion applications due to the absence of the transmission system for linear movement, simple structure and requires less maintenance since it has minimal moving components despite being a portable generator. Thus, the linear generator is more promising due to its high efficiency and simple design that will be advantageous for the development of a pico-scale generator [21–24].

Therefore, in this paper, the linear generator is proposed via designing the different shapes of the permanent magnet, with the slotless configuration in return to generate a pico-scale linear generator with 100W output power utilizing wave energy. The back electromotive force (back-EMF) influences the characteristics of the permanent magnet linear generator (PMLG) that can be observed by simulation. Back-EMF is a typical electromagnetic calculation process that is known as the flux density waveform in the permanent magnet and can be determined by the shape parameters of the magnet. Therefore, the different shape of the magnet is one of the key problems of the permanent magnet design to determine the optimum design of varying shape in return to produce higher performance. The output from the generator is targeted to be used for outdoor activities application. Thus, the design is also aimed to be a portable design with a weightless than 20 kg.

2. RESEARCH METHOD

This research comes out with five designs based on the suitable linear generator configuration for outdoor activities application. Thus, the design of permanent magnet, material use, and topology selection need to consider as dictate the overall efficiency of the generator in terms of power loss, output voltage, and weight of the generator. The designs are simulated using the Finite Element Analysis (FEA) to obtain the performance of flux distribution, flux linkage, and back EMF performance.

2.1. Proposed design topologies

Proposed design will be tubular structure concept with slotless stator due to better excogitation as it offers a constant air gap and higher flux density. The slotless stator is required for the proposed design because of a light system and can minimize cogging force. Cogging force can be prevented from occurring as it can damage the magnet and ensure the piston motion in stable and smooth [25]. Compared to the slotted stator where many research states that slotted stators produce higher power density, which is good, but slotted stator can cause cogging. Cogging generally occurs at the magnet border and affects the motion of the piston to become unsmooth and unstable motion. In that case, the air gap effected. This instability will cause fluctuation in the output [26]. Furthermore, the design will come up with a combination of axial and radial to form the Halbach magnetization. The process of the Halbach magnetization will be implemented by moving magnet with a longitudinal flux path because moving magnet has a small working magnetic air gap [14] that yields to the higher forces via a higher magnetic field. It also has higher efficiency as requiring less amount of permanent magnet compare to moving coil, which needs more coil for the same output [27]. Thus, the proposed design will come out with the features of the tubular longitudinal slotless stator, and Halbach magnetization.

2.2 The proposed design with dimensions

Five designs were proposed. The manipulating aspect of these designs can be analyzed in the shape of a permanent magnet, which is different in the shape of the permanent magnet**.** The dimensions have been tabulated in Table 1. The designs are compared with conventional rectangular designs, as in Figure 1 and trapezoid designs, Figure 2.

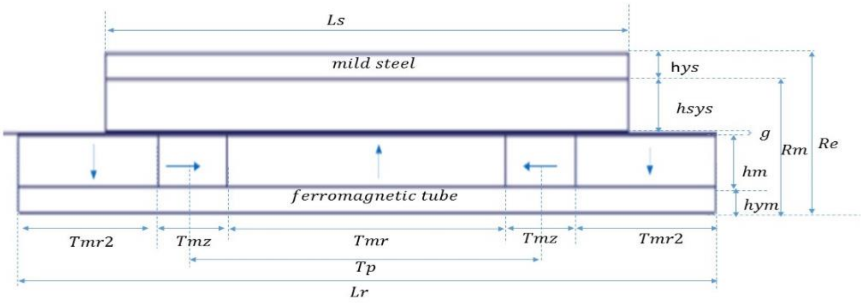


Figure 1. Rectangle design

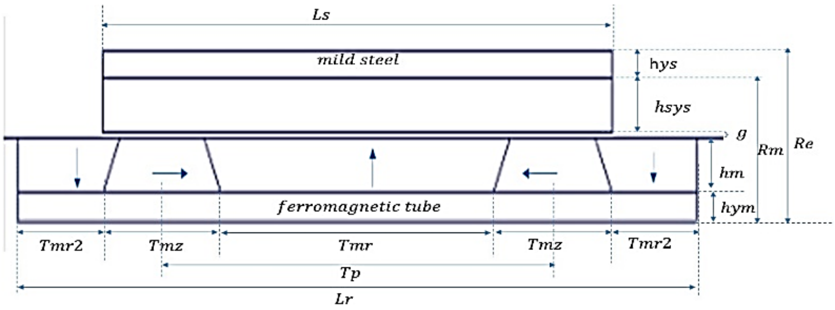


Figure 2. Trapezoid design

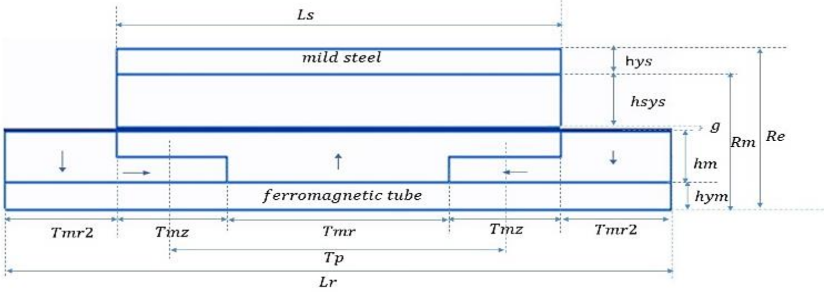


Figure 3. LT shape design.

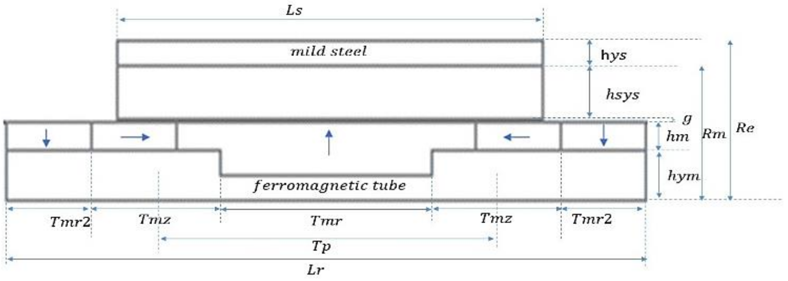


Figure 4. T-shape design.

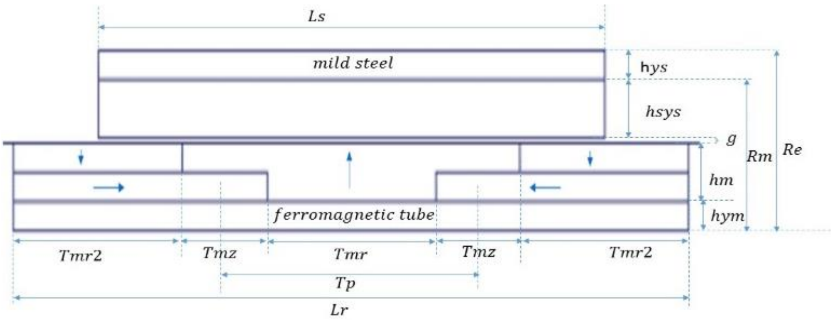


Figure 5. LT separated design.

Table 1. Design parameter details

	Description	Value (mm)
Ls	Length of stator	90
hys	Height of mild steel	5
hsys	Height of winding coil	10
g	Air gap	1
Rm	Outer radius of magnet	25
Re	Outer radius of the stator core	41
hm	Radial thickness of magnets	10
hym	Radial thickness of supporting tube	5
Tmr	Axial length of the radical magnetized magnet at the center	50
Tmz	Axial length of axially magnetized magnets	10
Tp	Pole pitch	70
Lr	Length of translator	150
	Number of turns	1000 turns
	Resistivity of copper	$1.7x10^{-5}$
	Steel material	Iron
	Magnet material	NdFeb

The rectangle design shape of the PMLG is the conventional design that easy to construct and simple design, as illustrated in Figure 1. According to the [28], the magnetic flux density will be higher due to the constant surface area and volume facing the armature. The trapezoid design, as in Figure 2, is part of the conventional design by [29] that has compared with three proposed designs. The radial magnet array has a large surface area and volume, which produce more flux density while the axial array of magnet has a smaller surface. Thus, the lower magnetic flux density will occur. The first proposed design is LT shape design as in Figure 3. The axial and radial array magnet of Tmz is combined in return to be active in magnetization. The surface area of the magnet at the center, Tmr, is the more significant dimension that directly facing the armature stator and expected to produce high flux density and induce a voltage. Next, the T-shape design in Figure 3 illustrated that the thickness of the back iron thicker than the other design but still has the same dimension of all design. The axial and radial array of magnetization is exposed to the armature, which is expected to produce high induced voltage. The third design, the LT separated magnet design, is proposed, as shown in Figure 5. Analyze that; the axial magnet array does not expose to the air gap and armature, which led to a lower magnetic flux. However, the surface area of the radial array is high, which expected to produce more flux to the armature, and more voltage is induced. Furthermore, all designs of the permanent magnet are employed with different shapes of the permanent magnet that would produce the better of electromagnetic characteristics in such flux density.

3. RESULTS AND DISCUSSION

3.1. Open circuit flux distribution

The simulation of the open circuit flux distribution was conducted to analyze the design excogitation performance in such as flux linkage, induced back EMF, and cogging force. The distribution of flux lines at no-load operation is shown for all designs in Figure 6 until Figure 10.

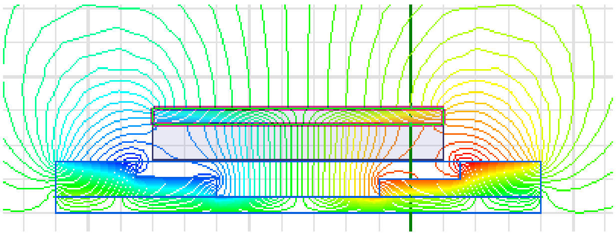


Figure 6. Flux line of LT shape design

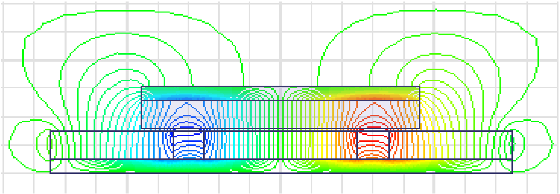
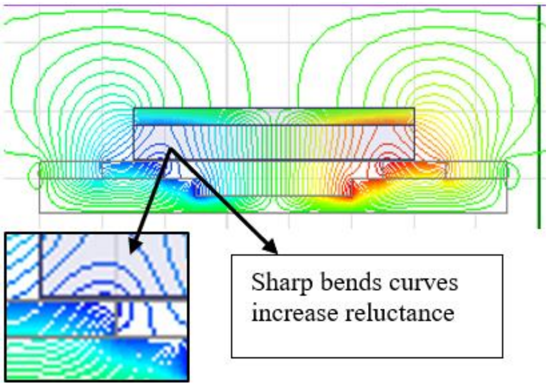
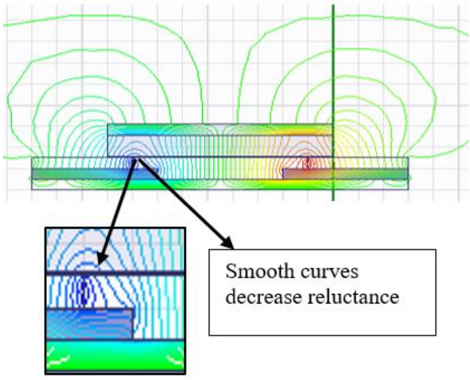


Figure 7. Flux line of rectangle design



Sharp bends curves increase reluctance

Figure 8. Flux line of T -shape design



Smooth curves decrease reluctance

Figure 9. Flux line of LT separated magnet design

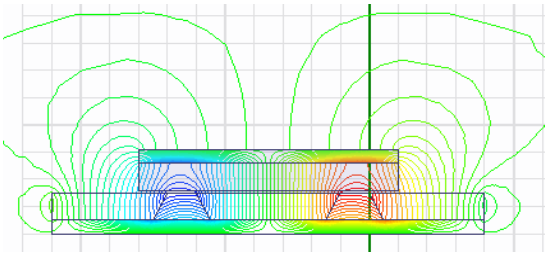


Figure 10. Flux Line of Trapezoid Desig

The flux line of PMLG is simulated under 2D models. Observe that in Figure 6 until Figure 10, the magnetization of Halbach equally distributed in the space of PMLG. The flux line for LT shape design spread evenly, but at the shape of magnet T, the flux line has a sharp curve, which increases the reluctance of the core, so less flux flow, similar to other designs which T-shape design. However, the smooth curve that occurs will decrease the reluctance of magnetic flux, and more flux distribution can lead to more flux linkage to in such of Rectangle, LT separated magnet and trapezoid. Thus, the flux linkage contributes to the higher induced voltage of the proposed design.

3.2. Air gap flux density.

Figure 11 shows how the air gap distribution compares the flux density. The density of flux increases at a distance of 50 mm, and around 100 mm, which is at the center of the stator due to flux flow to the adjacent magnet. In contrast, the higher peak value of flux density is by LT separated magnet, with an average of 420.40mT followed by Rectangle, Trapezoid, T-shape, and LT shape. Thus, the simulation's mean air gap flux density is recorded in Table 2.

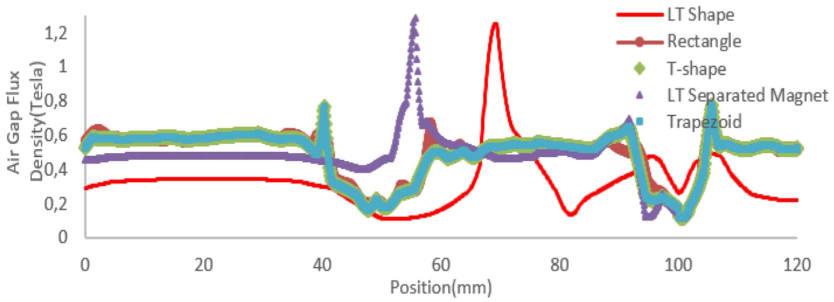


Figure. 11. Air gap flux density

3.3. Flux linkage and back-EMF

Figure 12 shows the design's flux linkage, while Figure 13 shows the back-induced EMF obtained from the dynamic state. The translation moves with a velocity of 1m/s along the Z-axis. Results from the two-stroke translation obtained in simulation. The simulation data from induced voltage and flux linkage reported in Table 2.

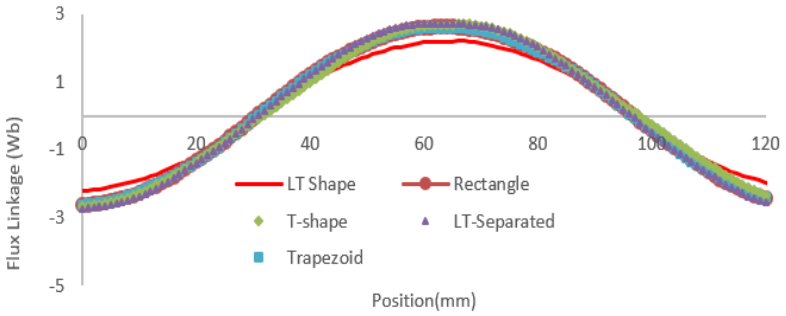


Figure 12. Flux linkage

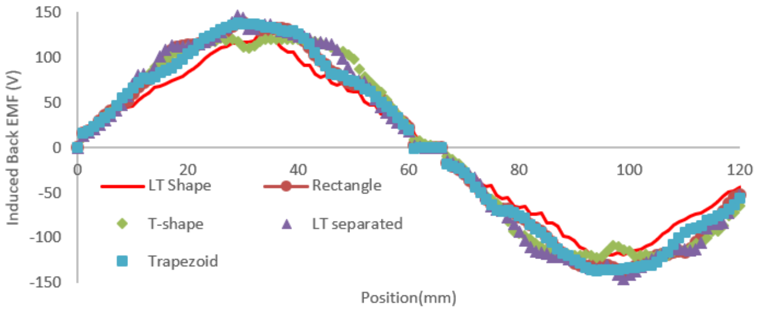


Figure 13. Induced back EMF.

Table 2. Average of induced back EMF and flux linkage.

Design	Air Gap Flux Density(mTesla)	Flux Linkage (Wb)	Induced Back EMF (V)
LT Shape	273.12	2.23	126.95
Rectangle	405.55	2.63	138.6
T-shape	344.95	2.73	121.28
LT Separated Magnet	420.40	2.74	145.62
Trapezoid	398.86	2.61	137.59

Table 2 shows the average air gap flux density, flux linkage, and induced back EMF for all proposed designs. Comparing with all designs, LT separated magnet design obtained the higher flux linkage and induced voltage. Nonetheless, the value of flux linkage of the designs is slightly different, which is around 0.1 to 0.5 Wb only. The flux linkage in Figure 12, the value is proportional to obtained for induced voltage value, as in Fig. 13, the induced voltage of all designs has exceeded the rated design voltage, which is 100 V when open circuit as well as to get the pico-scale generator output power.

3.4. Weight of the proposed design

Moreover, the total weight has measured based on the volume of the specific material by design proposed. The volume of proposed designs gained from the simulation of designs by FEA. The parameter of the designs influences the measured weight and the density of the material used. All designs provide almost the same weight based on the initial dimension of the design. All designs have the same volume of copper which is 319 cm^3, same volume of iron, 336 cm^3 and same volume of magnet that is 377 cm^3.Therefore, the total weight of all design of the proposed PMLG is 8.33kg as well as meet the requirement to be a portable design with weight less than 20kg.

4. CONCLUSION

The wave energy available in Malaysia was identified. The potential of low wave density in Malaysia can be utilized in the portable pico-scale generator to power-up small power appliances for outdoor activities. This research has proposed five designs, namely Rectangle, LT Separated magnet, LT Shape, T Shape, and Trapezoid, which differ in shape of permanent linear magnet and have been compared with the conventional design. The LT separated design has produced a better performance in terms of the electromagnetic characteristics based on the FEA compared to the other design. It can conclude that the different shapes of permanent magnet contribute to the performance of the linear generator for WEC. The parameters and dimensions of the proposed designs have shows that the designs can be a portable design for outdoor activities. However, the design needs to be optimized for further and details analysis in return to have the best performance for WEC application for outdoor activities.

ACKNOWLEDGEMENTS

The authors acknowledge the support from Universiti Teknologi PETRONAS for the award by graduate assistants and research facilities.

REFERENCES

[1] M. Faizal and Y. H. Tan, "Potential of wave power as source of electricity in Malaysia," *International Journal of Advanced Scientific Research and Management*, vol. 3, no. 5, pp. 50–59, 2018.

[2] B. K. Sovacool and I. M. Drupady, "Examining the small renewable energy power (SREP) program in Malaysia," *Energy Policy*, vol. 39, no. 11, pp. 7244–7256, 2011.

[3] N. A. M. Zamri, T. Ibrahim, and N. M. Nor, "Optimization of linear generator designs for wave energy converter (WEC) system in Malaysia," in *2016 6th International Conference on Intelligent and Advanced Systems (ICIAS)*, pp. 1–6, 2016.

[4] C. Wang and Z. Zhang, "Key technologies of wave energy power generation system," in *2017 IEEE International Conference on Mechatronics and Automation (ICMA)*, pp. 61–65, 2017.

[5] S. C. Loon and J. Koto, "Wave energy for electricity generation in Malaysia—Merang shore, Terengganu," *International Journal of Energy and Environment*, vol. 4, no. 1, pp. 8–18, 2016.

[6] A. Mirzaei, F. Tangang, and L. Juneng, "Wave energy potential along the east coast of Peninsular Malaysia," *Energy*, vol. 68, pp. 722–734, 2014.

[7] A. A. Nimje and G. Dhanjode, "Pico-hydro-plant for small scale power generation in remote villages," *IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)*, vol. 9, no. 1, pp. 59–67, 2015.

[8] H. Polinder and M. Scuotto, "Wave energy converters and their impact on power systems," in *2005 International Conference on Future Power Systems*, 2005.

[9] B. Drew, A. R. Plummer, and M. N. Sahinkaya, *A review of wave energy converter technology,* Sage Publications Sage UK: London, England, 2009.

[10] R. Ekström, B. Ekergard, and M. Leijon, "Electrical damping of linear generators for wave energy converters—A review," *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 116–128, 2015.

[11] S. S. Prakash *et al.*, "Wave energy converter: A review of wave energy conversion technology," in *2016 3rd Asia-Pacific World Congress on Computer Science and Engineering (APWC on CSE)*, pp. 71–77, 2016.

[12] O. Farrok and Md. M. Ali, "A new technique to improve the linear generator designed for oceanic wave energy conversion," in *8th International Conference on Electrical and Computer Engineering*, pp. 714–717, 2014.

[13] Aamir Hussain Memon, T. bin Ibrahim, and N. Perumal, "Portable and pico-scale linear generator for wave energy conversion," in *2014 5th International Conference on Intelligent and Advanced Systems (ICIAS)*, pp. 1–4, 2014.

[14] N. Shahabudin, I. Taib, and N. A. M. Zamri, "Portable pico linear generator design with different magnet shapes for wave energy conversion system," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 8, no. 1, pp. 360-366, 2017.

[15] G. Bacelli, J. V. Ringwood, and J.-C. Gilloteaux, "A control system for a self-reacting point absorber wave energy converter subject to constraints," *IFAC Proceedings Volumes*, vol. 44, no. 1, pp. 11387–11392, 2011.

[16] E. Tedeschi and M. Molinas, "Impact of control strategies on the rating of electric power take off for wave energy conversion," in *2010 IEEE International Symposium on Industrial Electronics*, pp. 2406–2411, 2010.

[17] O. Farrok, Md. R. Islam, Md. R. Islam Sheikh, Y. Guo, J. Zhu, and G. Lei, "Oceanic wave energy conversion by a novel permanent magnet linear generator capable of preventing demagnetization," *IEEE Transactions on Industry Applications*, vol. 54, no. 6, pp. 6005–6014, 2018.

[18] İ. Ö. Erselcan and A. Kukner, "A review of power take-off systems employed in wave energy converters," *Journal of Naval Science and Engineering*, vol. 10, no. 1, pp. 32–44, 2014.

[19] H. Chen, Y. Zhan, H. Wang, and R. Nie, "A Tubular permanent magnet linear generator with novel structure," *IEEE Transactions on Plasma Science*, vol. 47, no. 6, pp. 2995–3001, 2019.

[20] J. Faiz and M. Ebrahimi-Salari, "Design and simulation of a 250 kW linear permanent magnet generator for wave energy to electric energy conversion in caspian sea," in *2009 International Conference on Sustainable Power Generation and Supply*, pp. 1–6, 2009.

[21] H. Polinder, M. A. Mueller, M. Scuotto, and M. Goden de Sousa Prado, "Linear generator systems for wave energy conversion," in *Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Sept.*, 2007.

[22] T. Shimono, S. Takano, and H. Asai, "Development of DC linear permanent magnet machine based on multi-layered core-less structure," in *2019 10th International Conference on Power Electronics and ECCE Asia (ICPE 2019-ECCE Asia)*, pp. 1976–1981, 2019.

[23] J. Zhang, H. Yu, and Z. Shi, "Design and experiment analysis of a direct-drive wave energy converter with a linear generator," *Energies*, vol. 11, no. 4, pp. 735, 2018.

[24] K. R. Rao, T. Sunderan, and M. R. Adiris, "Performance and design optimization of two model based wave energy permanent magnet linear generators," *Renewable energy*, vol. 101, pp. 196–203, 2017.

[25] M. F. Romlie and R. Kannan, "Comparison of tubular and planar design of a micro linear generator for vibration energy harvesting," in *2015 IEEE Conference on Energy Conversion (CENCON),* pp. 233–237, 2015.

[26] L. Huang, F. Yue, M. Chen, and M. Hu, "Research on a field-modulated linear permanent-magnet generator for wave energy conversion," in *2017 20th International Conference on Electrical Machines and Systems (ICEMS),* pp. 1–4, 2017.

[27] M. Seal and M. Sengupta, "Design, analysis and fabrication of a linear permanent magnet synchronous machine," *Sādhanā*, vol. 42, no. 8, pp. 1419–1429, 2017.

[28] M. A. F. M. Hamim, T. Ibrahim, and N. M. Nor, "Modeling of a tubular permanent magnet linear generator for wave energy conversion using finite element method," in *2014 5th International Conference on Intelligent and Advanced Systems (ICIAS)*, Kuala Lumpur, Malaysia, pp. 1–5, 2014.

[29] A. H. Memon, T. bin Ibrahim, and P. Nallagownden, "Modeling and analysis of linear permanent magnet generator for wave energy conversion using finite element method," in *Applied Mechanics and Materials*, vol. 785, pp. 258–262, 2015.