International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 12 (2017) pp. 3329-3336

Design Development and Modelling of Linear Permanent Magnet Generator Topologies for Wave Energy Conversion

Taib bin Ibraahim[1], Aamir Hussain[2], Perumal Nallagowden[3], Farzanaa Rauf Abrro[4]

[1,2,3]Electrical and Electronic Engineering Department, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Malaysia.
[4]Department of Electronic Engineering, Mehran University of Engineering & Technology, Jamshoro, 76062, Sindh, Pakistan.

Abstract

This paper presents the design development and mathematical modeling of linear permanent magnet (PM) generator topologies for wave energy conversion. Three different topologies are proposed and developed using different design configuration and are compared with conventional topology for validation purpose. Mathematical model is developed for each topology based on its geometry. All the topologies are compared by using their corresponding mathematical models and taking into account constrained parameters of linear PM generator. Finite Element Analysis (FEA) is carried out in order to determine electromagnetic characteristics and analyze all the topologies by using their resultant data and dimensions obtained after model comparison. The main results; induced-EMF and flux-linkage for all proposed topologies are presented, which shows that Topology No.1 (Trgr-coil) has leading performance as compared to other topologies.

Keywords: Linear generator, wave energy, finite elemt analysis, mathematical modelling, compartive analysis

INTRODUCTION

The devastating greenhouse gases, which emit due to fossil fuel consumption, cause climate variations, fierce weather conditions, global warming and natural disasters, have led the present energy sector towards the sustainable development and renewable energy sources. In particular, ocean energy has gained a remarkable attention worldwide as compared to other renewable energy sources and among all its types wave energy is more dominant, leading and contains enormous power in waves with global exploitable power potential estimated above 2 TW [1,2]. The time-averaged power-flow intensity of wind and solar energy is 0.1-0.2 kW/m^2 and 0.4-0.6 kW/m^2, respectively; however, wave energy provides 2-3 kW/m^2, which is more spatially concentrated than both [3]. Furthermore, in perspective of power generation wave energy extraction devices (WEED) also lead in comparison to solar and wind extraction devices, which provide 20-30 % power only as compared to WEED which generate up to 90 % power [3-5].

The extraction of wave power into electrical is achieved through a chain of conversion-flow cycle known as wave-to-wire model as shown in Figure 1 [5]. The primary conversion encompasses wave energy converter (WEC), which converts available mechanical energy of incoming marine waves into the form required by subsequent device such as; aerodynamic energy. The secondary conversion is based on power take-off (PTO) mechanism, which provides electrical energy and has mainly two types; conventional and direct-drive machines. In tertiary conversion, the obtained electrical signal is converted into a signal based on the grid supply demand.

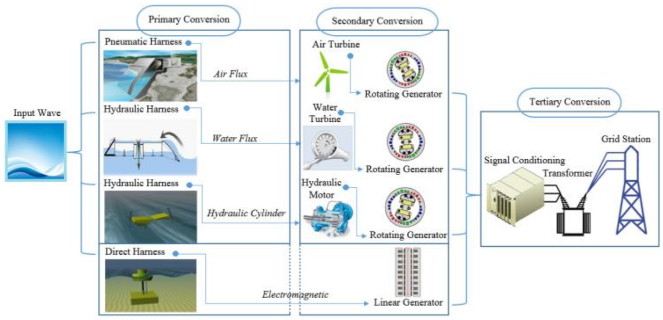

Figure 1. Wave to electrical conversion

At the dawn of marine conversion systems, the conventional rotating generators have remained a common option for electrical energy. Owing to high speed operation of rotating generators, they need mechanical interface such as; gearbox, hydraulic pump and turbines, which not only lengthen the overall system size but incur various mechanical losses, require high maintenance and reduce reliability [5,6]. Alternatively, to overcome these issues, wave energy conversion systems diversified towards direct-drive technology which is simple, robust and do not require any intermediate conversion. The term “direct-drive” is defined as a system in which the conversion of wave energy into electric power takes place directly without involving any intermediate mechanical conversion [6]. Figure 2 shows the basic illustration of direct-drive wave energy extraction system, which is based on a point absorber WEC connected directly with linear generator, based on two parts like rotational generator known as translator and stator.

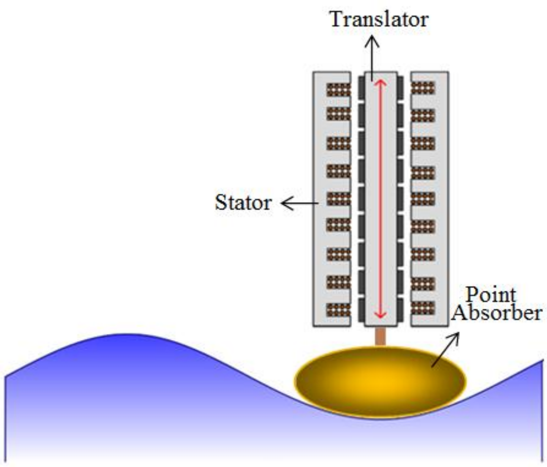

Figure 2. Direct drive wave energy conversion system

RELATED WORK

The development of linear generators for direct-drive wave energy extraction systems is based on several operating principles similar to conventional rotating generators and includes various design configurations, which range from small scale to commercial level. In early developments, Linear Variable Reluctance Permanent Magnet (VRPM) Machines [7] with its two main types; Transverse Flux and Machines [7] and Vernier Hybrid machines were ideally preferred due to high shear-stress or force density perfectly suitable for wave power [8]. However, the inherent low power factor, high leakage inductance and complexity of design structure were their main drawbacks, which imposed the requirement of capacitors, control devices and power electronics [9]. The induction generators were ruled out at very early stage owing to their asynchronous mode of operation, which is highly unfavorable for slow motion of waves [10]. Alternatively, due to good efficiency at low speeds and high force density, synchronous PM generators have gained a considerable attention in direct-drive wave energy extraction systems [11]. Besides, the unavailability of field winding system and DC supply makes synchronous PM generators more favorable choice [12]. At present, majority of developments are based on iron-cored synchronous PM generator due to its outstanding features such as; enviable electromagnetic characteristics and synchronous mode of operation [13-18]. This class of synchronous machine is more preferable due to its attractive electromagnetic performance but unfortunately the existence of normal and cogging forces is its major drawback, which eventually degrades the overall system efficiency [19]. The normal force is a magnetic attraction force, which acts perpendicular to the direction of motion and cogging force is caused due to interaction between slotted tooth and magnet [20,21]. The analytical developed tools have reported that iron cored machines demand 60% structural mass to overcome these undesired forces [22].

On the other hand, air-cored synchronous PM generators are identified as promising alternative due to absence of normal and cogging forces [23-26]. However, owing to ironless core, electromagnetic performance is limited but inclusion of active part such as; permanent magnet in translating part can balance the overall performance within the same margin of volume of iron-cored machines [24]. This work presents the design development, analysis and comparison of linear PM generator topologies proposed for wave energy conversion by using mathematical modeling and finite element analysis software ANSOFT Maxwell 14.0.

TOPOLOGIES OF PROPOSED LINEAR PERMANENT MAGNET GENERATOR

The geometry plays very important role in the design development of linear generator, its variation affects the overall performance and efficiency substantially. The linear PM generator is proposed with three different topologies, each topology is based on stator which houses windings and translator with embedded magnets as reciprocating part. Since, each geometric shape owns a different form and structure; therefore it is necessary to develop its mathematical model. This work proposes three different topologies for linear PM generator; Trgr-coil, Sqre-coil, and Trgr-mgnt. The main design specifications of proposed linear PM generator are listed in TABLE I.

Table 1: Main Design Specifications of Proposed Linear Pm Generator

Item	symbol	value	unit
Rated power	$\mathcal{P}_o$	100	Watts
Rated velocity	v	1.0	m/s
Stroke length	z_d	0.09	m
No. of phases			1

A. Topology No.1 (Trgr-coil)

Triangular topology (Trgr-coil) is based on inner stator and outer translator. The stator contains hollow type triangular prism yoke with winding wound on it. The translator contains triangular prism supporting tube with corners and magnets embedded on every side internally. The top view (TV) and section view (SV) is shown in Fig. 3 and Fig. 4, respectively. The round corners are cylinder and are adopted in order to provide smooth flux linkage.

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 12 (2017) pp. 3329-3336

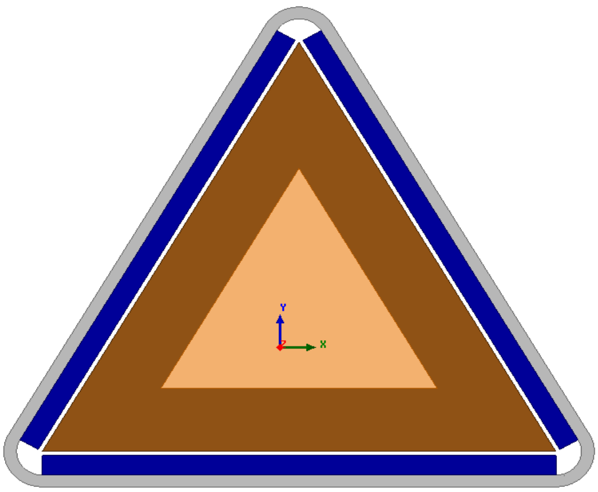

Figure 3: Top View (TV) of Topology No.1 (Trgr-coil)

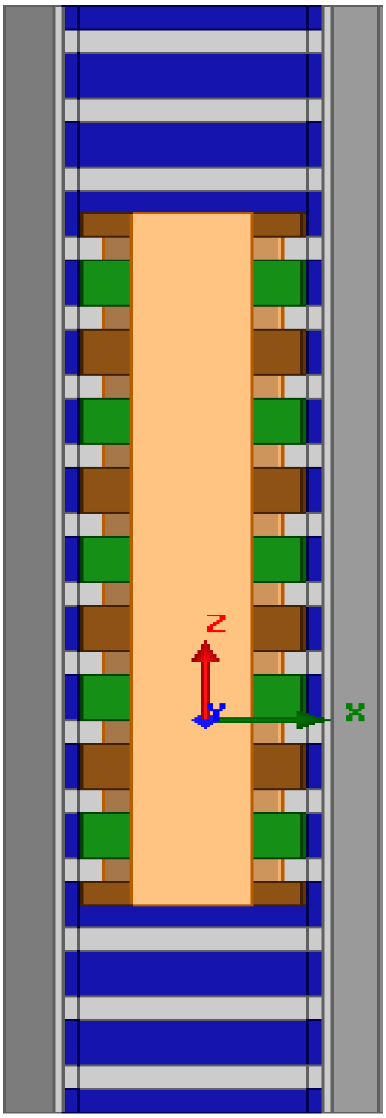

Figure 4: Section View (SV) of Topology No.1 (Trgr-coil)

1) Mathematical model

The mathematical model is developed by using standard laws, identities and geometry formulations.

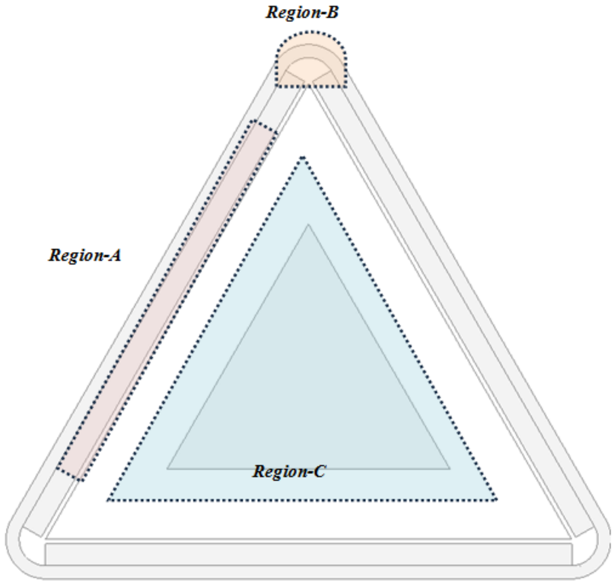

Figure 5: Mathematical model of Topology No.1 (Trgr-coil)

Region-A

$$V = \sum_{i=1}^{3} \mathcal{L} w h \quad (1)$$

Where V is the total volume, $\mathcal{L}$ is the vertical length of machine w is the thickness of translator and stator h is the longitudinal length

Region-B

$$V = \sum_{i=1}^{3} \pi(ab - cd) \times \mathcal{H} \quad (2)$$

Where ab and cd are major and minor axis of elleiptical cylinder and $\mathcal{H}$ is the longitudinal length

Region-C

$$V_t = 0.5(b_{se}\ell_{te}h_{ve} - b_{si}\ell_{ti}h_{vi}) \quad (3)$$

Where V_t is total volume, b_{se} is exterior base, ℓ_{te} is exterior length, h_{ve} is exterior height, b_{si} is interior base, ℓ_{ti} is interior length, and h_{vi} is interior height

B. Topology No.2 (Sqre-coil)

Square topology (Sqre-coil) is based on inner stator and outer translator. The stator contains hollow type square prism yoke with winding wound on it. The translator contains square shaped supporting tube with round corners and magnets embedded on all sides internally. The top view (TV) and section view (SV) is shown in Fig. 6 and Fig. 7, respectively.

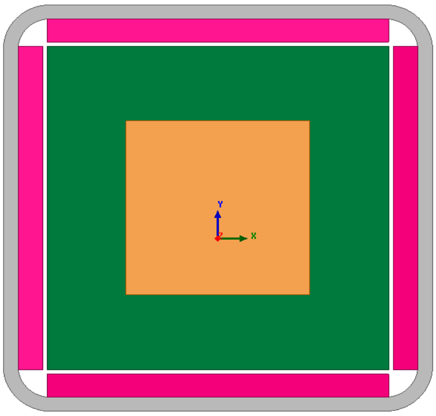

Figure 6: Top View (TV) of Topology No.2 (Sqre-coil)

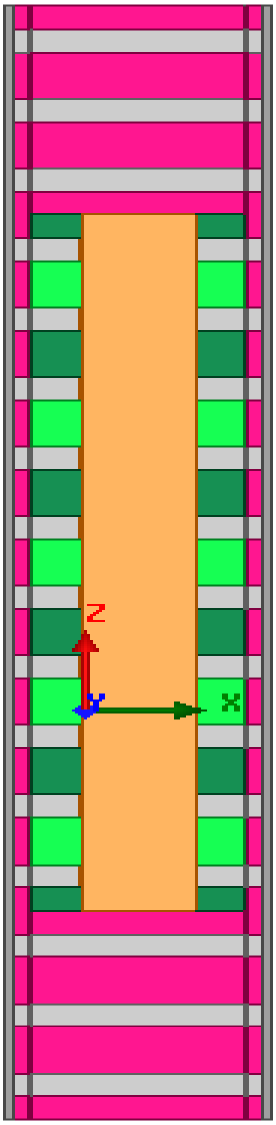

Figure 7: Section View (SV) of Topology No.2 (Sqre-coil)

1) Mathematical model

The mathematical model for Sqre-coil is shown in Fig. 8.

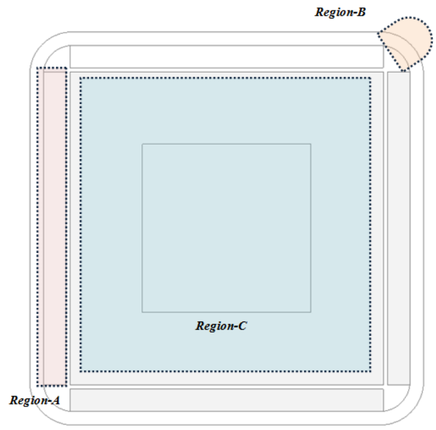

Figure 8: Mathematical model of Topology No.2 (Sqre-coil)

Region-A

$V = \mathcal{L}\mathcal{w}\mathcal{h}$
(4)

Where V is the total volume, $\mathcal{L}$ is the vertical length of machine $\mathcal{w}$ is the thickness of translator and stator $\mathcal{h}$ is the longitudinal length

Region-B

$$V = \pi(ab - cd) \times \mathcal{H} \quad (5)$$

Where ab and cd are major and minor axis of elleiptical cylinder and $\mathcal{H}$ is the longitudinal length

Region-C

$$V = \mathcal{L}_{ge}\mathcal{w}_{te}\mathcal{h}_{oe} - \mathcal{L}_{gi}\mathcal{w}_{ti}\mathcal{h}_{oi} \quad (6)$$

Where V is the total volume, $\mathcal{L}_{ge}$ is the exterior vertical length of machine $\mathcal{w}_{te}$ is the exterior thickness of translator and stator $\mathcal{h}_{oe}$ is the exterior longitudinal length$\mathcal{L}_{gi}$ is the interior vertical length of machine $\mathcal{w}_{ti}$ is the interior thickness of translator $\mathcal{h}_{oi}$ is the interior longitudinal length

C. Topology No.3 (Trgr-mgnt)

This topology (trgr-mgnt) contains inner translator and outer stator. The translator contains triangular shaped supporting tube with magnets buried on every side externally. The stator contains triangular shaped yoke with round corners and uses modular type coils. The top view (TV) and section view (SV) is shown in Fig. 9 and Fig. 10, respectively.

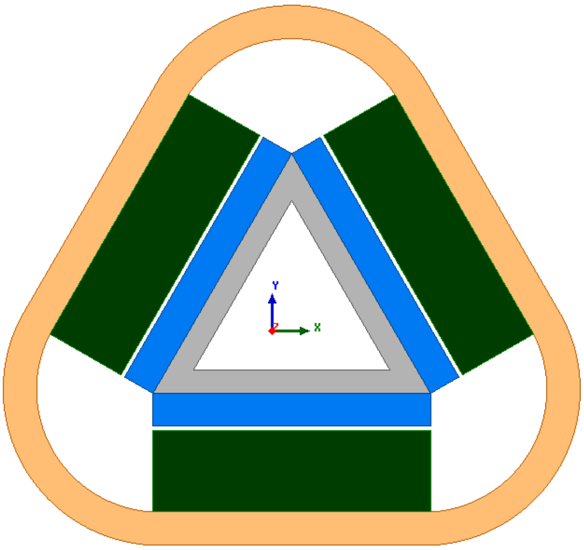

Figure 9: Top View (TV) of Topology No.3 (Trgr-mgnt)

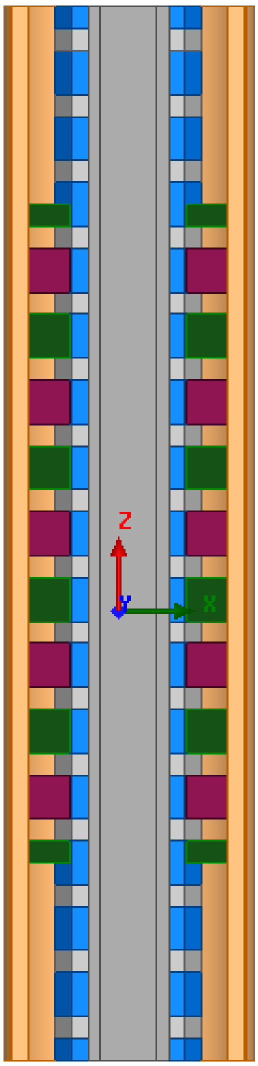

Figure 10: Section View (SV) of Topology No.3 (Trgr-mgnt)

1) Mathematical model

The mathematical model for trgr-extr coil is shown in Fig. 11.

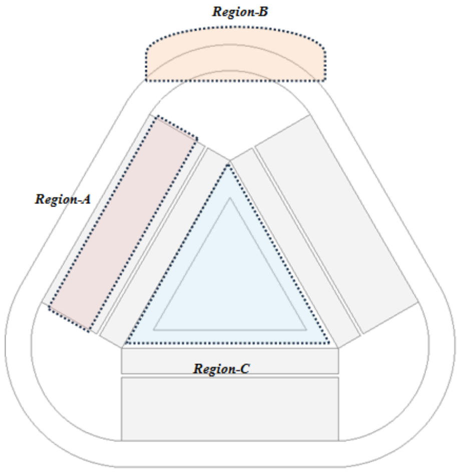

Figure 11: Mathematical model of Topology No.3 (Trgr-mgnt)

Region-A

$$V = \mathscr{L}\mathscr{w}\mathscr{h} \tag{7}$$

Where V is the total volume, $\mathscr{L}$ is the vertical length of machine $\mathscr{w}$ is the thickness of translator and stator $\mathscr{h}$ is the longitudinal length

Region-B

$$V = \pi(ab - cd) \times \mathcal{H} \tag{8}$$

Where ab and cd are major and minor axis of elleiptical cylinder and $\mathcal{H}$ is the longitudinal length

Region-C

$$V = 0.5h\ell\mathfrak{b} \tag{9}$$

Where V is total volume, $\mathfrak{b}$is exterior base, ℓ is exterior length, h is exterior height

METHODOLOGY

The main objective of this research is to design and develop a lightweight and pico-scale linear generator which weighs 10-15 kg mass and produces 100 W electric power, complying with this, three different topologies of linear generator are proposed and compared using geometric modeling and Finite Element Analysis (FEA) in order to achieve optimal candidate. Firstly, the mathematical model is developed for all proposed topologies by using their corresponding shape, structure and geometric form. In order to obtain optimal topology with aforementioned objectives and perform FEA, all the topologies are compared by using their respective mathematical models against the constrained parameters of linear PM generator. The description of constrained parameters is given in TABLE II.

Table II: Constant Values of Constrained Parameters

Section		Volume [mm^3]	Vertical length [mm]
Translator	PM	500390.40	600
	Supporting tube	305434.08	
Stator	Yoke	318160.50	200
	Winding	521240.00	100

In order to illustrate benefit of proposed topologies and provide benchmarking, conventional linear generator [6] is designed with its respective specifications and configuration in order to produce required rating.

In line with the targeted mass and power rating, few parameters have to be fixed or constant known as constrained parameters. These are fixed due to targeted load and wave elevation. Since, the low mass is the main objective of this research; therefore, size has to remain fixed for all topologies in order to provide uniform and transparent comparison. The wave elevation is associated with the fondle movement which highly influences the electromagnetic characteristics of linear generator, therefore, the vertical length "elevation" of each part also have to remain same in order to balance the required rating of linear generator. The resultant data and dimensions obtained after model comparison is given in TABLE III.

Table III: Resultant Data and Dimensions of all Topologies after Model Comparison

Topology	Section		Length [mm]	Width [mm]	Number of turns per coil	Model Depth [mm]
Trgr-coil	Translator	PM	92.00	3.77	982	138.00
		Supporting tube	114.50	2.30		
	Stator	Yoke	49.49	3.84		
		Winding	92.00	12.27		
Sqre-coil	Translator	PM	60.55	4.30	1120	121.10
		Supporting tube	75.12	2.62		
	Stator	Yoke	32.56	4.37		
		Winding	60.55	13.99		
Trgr-mgnt	Translator	PM	54.21	6.40	1282	81.31
		Supporting tube	54.21	3.91		
	Stator	Yoke	54.21	6.52		
		Winding	54.21	16.02		

FEA RESULTS AND DISCUSSION

All the topologies are modeled with their resultant dimensions and are analyzed using FEA in order to determine electromagnetic characteristics of linear PM generator [25]. The flux linkage of winding, comprising a number of series connected coils each displaced by coil pitch τ_c is given by

$$\psi_c = \sum \phi_{cn} sin m_n \left(\frac{z-\tau_c}{2}\right) \quad (10)$$

where

$$\phi_{cn} = \frac{-4\pi N_c K_{rn} K_{dpn}}{(R_s - R_i) m_n} \quad (11)$$

Where N_c is the number of series turns, R_i is the inner radius of winding and R_s is K_{dpn} is winding factor and K_{rn} is harmonic coefficient

$$e_c = \frac{-d\psi_c}{dt} = -v\sum \phi_{cn}\, m_n cos m_n\left(\frac{z-\tau_c}{2}\right) \qquad (12)$$

Where v is the velocity of translator

The induced-EMF and flux-linkage produced in the stator winding in the dynamic mode with 1m/s velocity is shown in Fig. 12 and Fig. 13. It will be seen in TABLE IV that, proposed topologies obtains highest performance as compared to conventional linear PM generator [6].

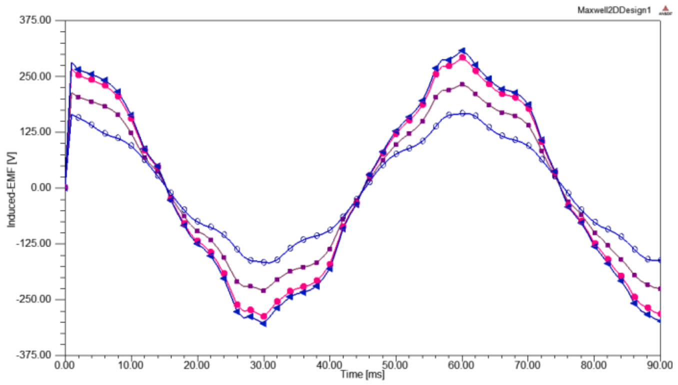

Figure 12: Induced-EMF produced in the winding of stator

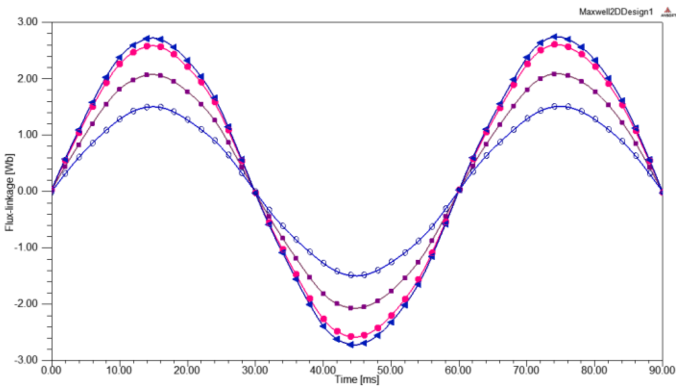

Figure 13: Flux-linkage produced in the winding of stator

Table IV: Induced-EMF and Flux-Linkage Produced in the Winding of Stator

Topology	Type	Induced-EMF (volts)	Flux-linkage (Wb)
Tplgy_No.1	Trgr-coil	199.01	1.92
Tplgy_No.2	Sqre-coil	188.95	1.82
Tplgy_No.3	Trgr-mgnt	151.56	1.46
Conventional		122.58	1.18

CONCLUSION

Three different topologies for linear PM generator; Trgr-coil, Sqre-coil, and Trgr-mgnt are proposed for wave enrgy conversion. The mathematical model is developed for each topology using its corresponding geometry. The comparative analysis has been carried out by using mathematical model of each topology along with their constrained parameters; size and elevation. The resultant data and dimensions are employed in order to model and analyze all topologies by using FEA. The main results induced-EMF and flux-linkage are presented. FEA shows that Trgr-coil provides highest electromagnetic characteristics as compared to Sqre-coil, and Trgr-mgnt topologies. The topology with highest performance will be fabricated and tested for validation purpose.

ACKNOWLEDGMENT

This research is supported by Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia.

REFERENCES

[1] S. Astariz and G. Iglesias, "Wave energy vs. other energy sources: A reassessment of the economics," *International Journal of Green Energy,* vol. 13, pp. 747-755, Feb. 2016.

[2] G. Emmanouil, G. Galanis, C. Kalogeri, G. Zodiatis, and G. Kallos, "10-year high resolution study of wind, sea waves and wave energy assessment in the Greek offshore areas," *Renewable Energy,* vol. 90, pp. 399-419, May 2016.

[3] I. López, J. Andreu, S. Ceballos, I. M. d. Alegría, and I. Kortabarria, "Review of wave energy technologies and the necessary power-equipment," *Renewable and Sustainable Energy Reviews,* vol. 27, pp. 413–434, Nov. 2013.

[4] A. Razavieh, A. Sedaghat, R. Ayodele, and A. Mostafaeipour, "Worldwide wind energy status and the characteristics of wind energy in Iran, case study: the province of Sistan and Baluchestan," *International Journal of Sustainable Energy,* vol. 36, pp. 103-123, Nov. 2014.

[5] M. Penalba and J. V. Ringwood, "A Review of Wave-to-Wire Models for Wave Energy Converters," *Energies,* vol. 9, pp. 1-45, Jun.2016.

[6] A. H. Memon, T. b. Ibrahim, and P. Nallagowden, "Portable and pico-scale linear generator for wave energy conversion," in proceedings 5th International Conference on Intelligent and Advanced Systems, Kuala Lumpur, 2014.

[7] K. V. Babu, B. L. Narasimharaju, and D. M. V. Kumar, "Switched reluctance machine for off-grid rural applications: a review," *IETE Technical Review,* vol. 33, pp. 428-440, Dec. 2016.

[8] H. Polinder, B. C. Mecrow, A. G. Jack, P. G. Dickinson, and M. A. Mueller, "Conventional and TFPM linear generators for direct-drive wave energy conversion," *IEEE Trans. Energy Conversion,* vol. 20, pp. 260-267, May 2005.

[9] M. A. Mueller and N. J. Baker, "Direct drive power take-off for offshore marine energy converters," *in Proc. Inst. Mech. Eng. A, J. Power Energy,* vol. 219, pp. 223-234, May 2005.

[10] N. J. Baker, M. A. Mueller, L. Ran, P. J. Tavner, and S. McDonald, "Development of a linear test rig for electrical power take off from waves," *Journal of Marine Engineering & Technology* vol. 6, pp. 3-15, Jan. 2007.

[11] R. Dutta, L. Chong, and M. F. Rahman, "Review of the impact of parameter variation on the operating speed range of the interior permanent magnet synchronous machine," *Australian Journal of Electrical and Electronics Engineering,* vol. 11, pp. 22-32, Jan. 2015.

[12] O. Wallscheid, T. Huber, W. Peters, and J. Böcker, "A critical review of techniques to determine the magnet temperature of permanent magnet synchronous motors under real-time conditions," *European Power Electronics and Drives,* vol. 26, pp. 11-20, Jan. 2016.

[13] O. Danielsson, Eriksson, M. and Leijon, M., "Study of a longitudinal flux permanent magnet linear generator for wave energy converters," *Int. J. Energy Res,* vol. 30, pp. 1130–1145, Nov. 2006.

[14] J. Prudell, M. Stoddard, E. Amon, T. K. A. Brekken, and A. v. Jouanne, "A permanent-magnet tubular linear generator for ocean wave energy conversion," *IEEE Trans. Industry Applications,* vol. 46, pp. 2392 - 2400, Nov. 2010.

[15] C. Zhongxian, Y. Haitao, and H. Minqiang, "The research on direct-drive wave energy conversion system and performance optimization," *Acta Oceanologica Sinica,* vol. 33, pp. 178-183, Sep. 2014.

[16] A. M. Kassem, A. H. Besheer, and A. Y. Abdelaziz, "A linear quadratic gaussian approach for power transfer maximization of a point absorber wave energy converter," *Electric Power Components and Systems,* vol. 43, pp. 1173-1181, Jun.2015.

[17] E. Lejerskog, E. Strömstedt, A. Savin, C. Boström, and M. Leijon, "Study of the operation characteristics of a point absorbing direct driven permanent magnet linear generator deployed in the Baltic Sea," *IET Renewable Power Generation,* pp. 1-7, May 2016.

[18] C. Zhongxian, Y. Haitao, L. Chunyuan, and H. Liwei, "Design, construction and ocean testing of wave energy conversion system with permanent magnet tubular linear generator," *Transactions of Tianjin University,* vol. 22, pp. 72-76, Feb. 2016.

[19] S. Tounsi, R. Néji, and F. Sellami, "Design methodology of permanent magnet motors improving performances of electric vehicles," *International Journal of Modelling and Simulation,* vol. 29, pp. 96-103, Jan. 2015.

[20] K. Nilsson, O. Danielsson, and M. Leijon, "Electromagnetic forces in the air gap of a permanent magnet linear generator at no load," *Journal of Applied Physics,* vol. 99, p.034505, Feb. 2006.

[21] S. J. Arand and M. Ardebili, "Cogging torque reduction in axial-flux permanent magnet wind generators with yokeless and segmented armature by radially segmented and peripherally shifted magnet pieces," *Renewable Energy,* vol. 99, pp. 95–106, Dec. 2016.

[22] M. A. Mueller, A. S. McDonald, and D. E. Macpherson, "Structural analysis of low-speed axial-flux permanent-magnet machines," *IEE Proceedings on Electric Power Applications,* vol. 152, pp. 1417 - 1426, Nov. 2005.

[23] N. Hodgins, O. Keysan, A. McDonald, and M. Mueller, "Linear generator for direct drive wave energy applications," in *Proc. International Conference on Electrical Machines*, Rome, Itlay, 2010, pp. 1-6.

[24] R. Vermaak and M. J. Kamper, "Design aspects of a novel topology air-cored permanent magnet linear generator for direct drive wave energy converters," *IEEE Trans. Industrial Electronics,* vol. 59, pp. 2104-2115, May 2012.

[25] N. Bianchi, *Electrical machine analysis using finite elements*. USA: CRC Press, 2005, ch. 5.