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Optimization of Linear Permanent Magnet (PM) Generator with Triangular-Shaped Magnet for Wave Energy Conversion using Finite Element Method

This paper presents the design optimization of linear permanent magnet (PM) generator for wave energy conversion using finite element method (FEM). A linear PM generator with triangular-shaped magnet is proposed, which has higher electromagnetic characteristics, superior performance and low weight as compared to conventional linear PM generator with rectangular-shaped magnet. The Individual Parameter (IP) optimization technique is employed in order to optimize and achieve optimum performance of linear PM generator. The objective function, optimization variables; magnet angle, $\mathcal{M}_{\theta(\Delta)}(\theta)$, the pole-width ratio, $\mathcal{P}_{w\_}ratio\,(\tau_p/\tau_{mz})$, and split ratio between translator and stator, $\mathcal{S}_{a\_}ratio\,(R_m/R_e)$, and constraints are defined. The efficiency and its main parts; copper and iron loss are computed using time-stepping FEM. The optimal values after optimization are presented which yields highest efficiency.

Keywords: Linear generator, Individual Parameter (IP) optimization technique, Permanent magnet, Finite element analysis, efficiency.

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1. Introduction

New ways of producing electrical energy remains continue in the exploration to satisfy world's growing appetite for electricity. Today's energy challenges require us to explore an alternative which is clean, environment friendly, renewable and prove a replacement for carbon fuels. The ocean wave energy has the potential to make an important contribution to the existing supply of energy [1]. The global estimated theoretical potential for wave power is 30,000000 TW/yr [2, 3]. The power density of wave energy is 2-3 kW/m^2, however, other existing energy such as; solar and wind energy provides 0.1-0.2 kW/m^2 and 0.4-0.6 kW/m^2, respectively [4, 5]. It has also been reported that wave energy converters produce power generation up to 90%, which is considerably higher than solar and wind energy, which produce maximum 20-30 % [4]. The conversion of available wave power into electrical power can be obtained by several ways.

Within this whole conversion flow cycle of wave to electrical conversion, direct-drive linear generator forms simple and non-complicated conversion chain as compared to conventional rotational generators which not only make the overall conversion chain complicated owing to mechanical unit like turbine machinery, gearbox, and hydraulics pump but increases maintenance too [6]. Direct-drive linear generator is the simplest and robust wave energy conversion system, it has mainly two parts akin to rotational generator; translator, which is a reciprocating part which moves with respect to the motion of waves and stator which remains static with respect to reciprocating part [7]. Direct-drive linear generator has several types but permanent magnet type has gained considerable attention on account of eliminated field winding and DC supply requirement which are main requirement in rest of the types [8].

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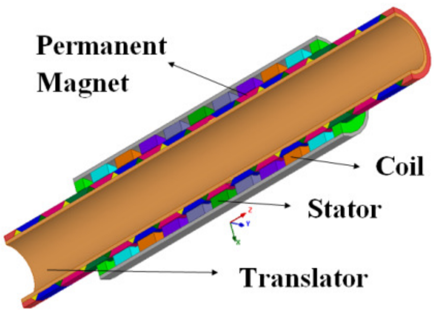
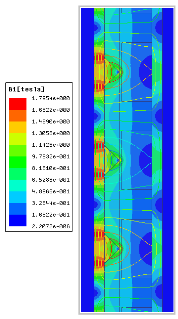
Direct-drive technology owing to its simple and efficient configuration has gone through the scale which is from small scale to the commercial level. The first development comes from Linear Variable Reluctance Permanent Magnet (VRPM) machines which further are classified into linear Transverse- Flux and Vernier Hybrid permanent magnet machines, the key advantage of these machines is high force density but low power factor and complicated design structure of these machines shifted the direct-drive technology towards synchronous PM machines [9]. The development based on iron-cored PM linear generators are an eye-catching preference in wave energy conversion owing to their desirable electromagnetic characteristics and slotted stator which uninterruptedly forms the flux linkage between stator and translator [10] but cogging force and magnetic attraction forces leaves them a thinkable choice. The cogging force is a type of force which resists the translating part to move smoothly [11] and magnetic attraction force is a normal force which causes obstruction in the operational motion characteristics [12, 13]. The developed analytical methods report that iron-cored machines require 60% structural mass in order to withstand these undesired forces [14]. Alternatively, linear air-cored PM generators are proved an appropriate choice due to absence of these undesired forces and are adopted widely from simple non-magnetic core to patented technology C-Gen [6, 7], however, their electromagnetic performance lacks strong electromagnetic characteristics but research has proved that this aspect can be compensated by inclusion of PM material, which still results the overall mass less than conventional iron-cored linear generators [11, 12].

This work presents design optimization of single-phase, 100 W, linear PM generator with triangular-shaped magnet using Individual Parameter (IP) optimization technique. The time-stepping finite element method (FEM) is used to analyse the linear PM generator by using finite element analysis software ANSOFT Maxwell 14.0.

2. Proposed Design& Finite Element Analysis

The finite element three-dimensional view of proposed linear PM generator is shown in Fig. 1 (a).The translator resides series of PM with quasi-halbach magnetization, which produces sinusoidal flux distribution in air-gap [15]. The static part “stator” has single-phase distributed winding configuration which minimizes the heat losses [6, 7].





(a) (b)

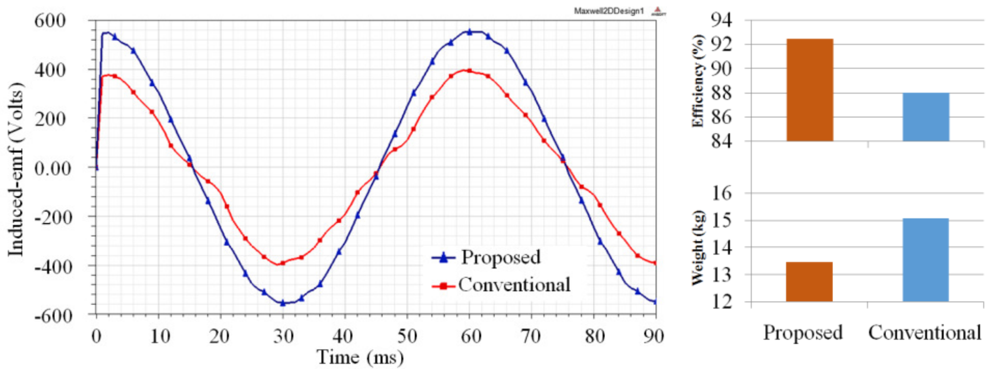
Fig. 1. (a) Three-dimensional view of proposed linear PM generator (b) Open-circuit magnetic flux distribution and magnetic flux density

In order to determine electromagnetic characteristics finite element analysis has been carried out. The axi-symmetrical cylindrical coordinate system is adopted, the boundary conditions are applied to all regions and the magnetization is assigned to all permanent magnets. The finite element predicted open-circuit flux distribution and magnetic flux density at zero displacement Z_d ($Z_d=0$)is shown in Fig. 1 (b). It will be seen that flux distribution is uniform and forms smooth linkage between translator and stator. In order to illustrate the benefit of proposed linear PM generator and validate, a conventional linear PM generator equipped with rectangular-shaped magnet has been analysed in terms of electromagnetic characteristics, weight and optimization against same design specification [16, 17]. The time-varying performance using transient mode is analysed as shown in Fig. 2 (a) The RMS Induced-emf generated in stator winding [7] can be written as;

$$E = \frac{2\pi}{\sqrt{2}} f N_{ph} \phi_m \tag{1}$$

where $E$is the induced-EMF, f is frequency, N_{ph} is the no. of turns in winding and $\phi_m$flux linkage.

Fig. 2 (a) and Table 1 shows the comparison of induced-EMF produced in stator winding and Fig. 2 (b) shows the comparison of finite element evaluated efficiency and total machine weight for conventional and proposed linear PM generator, respectively. It will be seen that, the proposed linear generator achieves higher electromagnetic performance and results lower weight for overall machine within same design specifications as compared to conventional linear generator [16, 17]



(a) (b)

Fig. 2. (a) Induced-emf produced in stator winding (b) efficiency and weight comparison for conventional and proposed linear PM generator

Table 1:Induced-EMF and Flux-linkage in winding

Design type	Induced-EMF (V)	Flux-linkage (Wb)
Proposed design	351.6278	3.3602
Conventional design	225.2489	2.2536

3. Efficiency Analysis

The efficiency is the worthwhile part in the design analysis of linear generator [18]. It computes existing losses and subsequently determines the net resultant performance. It can be computed as;

$$\eta = \frac{P_{out}}{P_{out}+P_{cu}+P_{fe}} \tag{2}$$

where P_{out}, P_{fe}, and P_{cu} are output-electric power, core loss and heat loss, respectively.

Copper or heat loss can be determined as follows [19];

$$P_{cu} = I^2 R \tag{3}$$

Where I and R areRMS magnitude of current and resistance of coil, respectively.

Coreloss of the linear generator is based on three diverse quantities; eddy-current, excessive and hysteresis loss [20]. The combined form can bewritten as;

$$P_{fe} = \Sigma(P_{hi} + P_{ci} + P_{ei}) \tag{4}$$

whereP_{ei}, P_{ci}, and P_{hi} are eddy-current, excessive and hysteresis loss, respectively.

4. Design Optimization

The objective function of optimization is efficiency maximization "η" under the constraints and constants values. The Individual Parameter (IP) optimization technique [21, 22] is employed, which is also known as linear optimization [23]. The IP optimization technique is a powerful tool in the design optimization of linear electrical machines, it assists to find the best optimal point amongst the entire defined space [24]. The original schematic of linear PM generator used for optimization is shown in Fig. 3.Amongst all design parameters some parameters have insignificant influence on the performance of linear PM generator such as; the height of ferromagnetic tube, h_{ym}, and stator supporting tube, h_{ys}, which are kept equal and minimum because they only assist to position and hold active parts such as magnets and winding. Therefore, the stator outer radius, R_e, is set to 50 mm. All the constant values used for optimization are listed in Table 2.

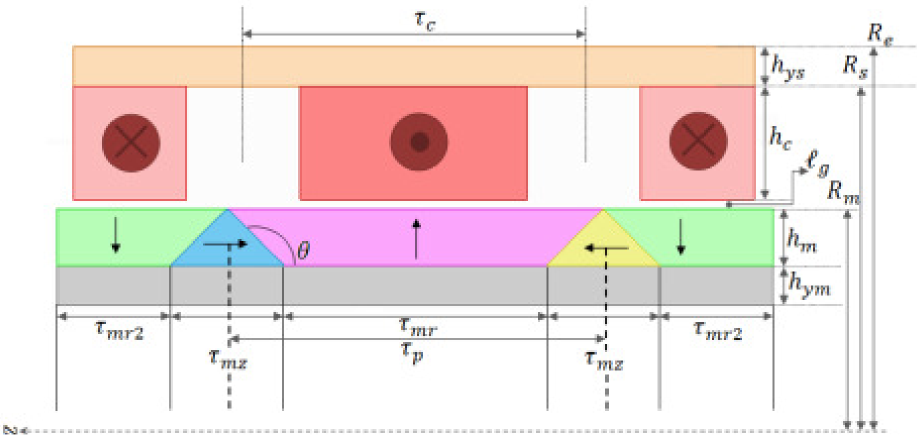


Fig. 3. Schematic diagram of linear PM generator for optimization

Table 2:Constant values for optimisation

Item	**symbol**	**value**	**unit**	**Item**	**symbol**	**value**	**unit**
Air-gap length	ℓ_g	0.8	mm	Coercive force	H_c	-864	KA/m
Magnet thickness	h_m	5	mm	Wire diameter	d	0.8	mm
Height of ferromagnetic tube	h_{ym}	3.5	mm	Machine length (Z-direction)	ℓ_z	480	mm
Height of stator	h_{ys}	3.5	mm	Steel material	Mildsteel		
Stator outer radius	R_e	50	mm	Magnet material	NdFeB (N35)		
Total height	h_{th}	50	mm	Number of phases	1		
Resistivity of copper	ρ	1.7×10^{-5}	Ω.mm				
Rated velocity	v	1.0	m/s				
Magnet remanence	B_r	1.14	T				
Relative permeability	μ_r	1.05	-				

The total height of machine, h_{th}, is kept at 50mm and the length of translator and stator in Z-direction, ℓ_z,is kept at 480mm and 300mm owing to stroke limitations. The definitions of optimization variables and constraints are listed in Table 3, these are the leading design parameters which have significant influence on the machine performance and include, magnet angle, $\mathcal{M}_{\theta(\Delta)}$, the pole-width ratio, $\mathcal{P}_{w\_}ratio$, and split ratio between translator and stator, $\mathcal{S}_{a\_}ratio$, and are defined as follows;

$$\mathcal{M}_{\theta(\Delta)} = \theta \quad (5)$$
$$\mathcal{P}_{w\_}ratio = \tau_p/\tau_{mz} \quad (6)$$
$$\mathcal{S}_{a\_}ratio = R_m/R_e \quad (7)$$

The variables in Table 3 are individually optimized i.e. only one parameter varies while others are kept constant and the rated output power is always maintained fixed at 100 W by adjusting the magnitude of rated current [18, 19]. The initial value of pole-pitch, τ_p, and axial length of radially magnetized magnet, τ_{mr}, are assumed 20mm. The coil height, h_c, and coil-pitch, τ_c, are assumed to be equal to 20mm, as initial value.

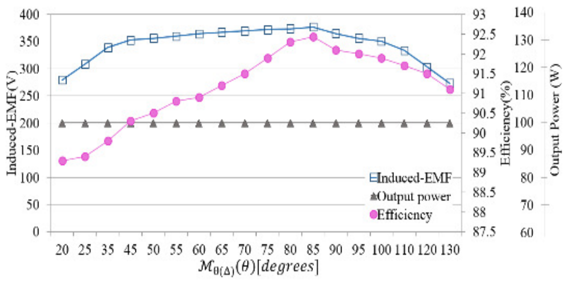
Table 3:Optimization variables and constraints

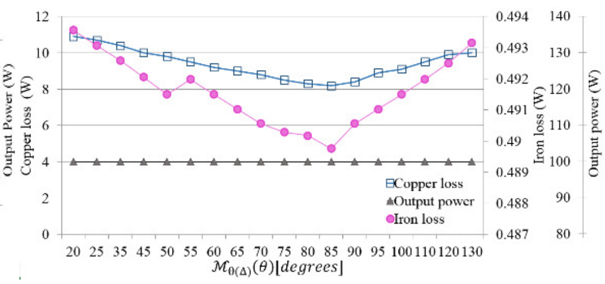
Optimization variable	**symbol**	**initial value**	**constraints**
magnet angle	$\mathcal{M}_{\theta(\Delta)}(\theta)$	50°	[20°,130°]
pole-width ratio	$\mathcal{P}_{w\_}ratio\ (\tau_p/\tau_{mz})$	6.0	[5.2,7]
split ratio	$\mathcal{S}_{a\_}ratio\ (R_m/R_e)$	0.70	[0.66,0.75]

Each individual optimization follows the optimizing sequence of magnet angle,$\mathcal{M}_{\theta(\Delta)}$, the pole-width ratio, $\mathcal{P}_{w\_}ratio$, and split ratio between translator and stator, $\mathcal{S}_{a\_}ratio$, like, when one individual parameter is optimized and will be used in subsequent individual parameter optimization.

4.1.Influence of $\mathcal{M}_{\theta(\Delta)}(\theta)$

The translator of linear generator is equipped with permanent magnet, however, magnet has angle θ as shown in Fig. 3. The variation of this angle yields a considerable impact on the characteristics and performance of linear generator and is of prime importance to analyze [21, 22] because their variation gives rise to the flux-linkage and in turn increases the induced-EMF.. The output power is set constant when varying the angle θ. Fig. 4 (a) shows the influence on induced-emf produced in winding, efficiecny and output power of linear PM generator with respect to variation in $\mathcal{M}_{\theta(\Delta)}$The effect on copperloss, ironloss and output power while varrying $\mathcal{M}_{\theta(\Delta)}$ is shown in Fig. 4 (b)



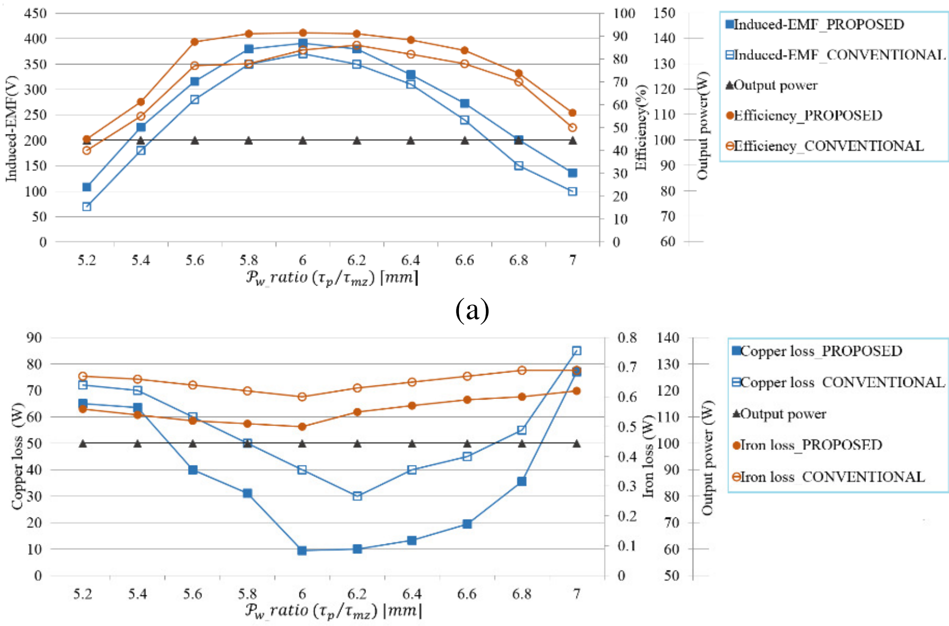


(a) (b)

Fig. 4. Influence on (a) induced-emf, efficiency and output power (b) copper loss, iron loss and output power with variation in $\mathcal{M}_{\theta(\Delta)}(\theta)$

4.2. Influence of $\mathcal{P}_{w}\_ratio\ (\tau_p/\tau_{mz})$

τ_p/τ_{mz} is called "pole width ratio", and defines the relationship between Magnet Magnetization and Magnet Pole-pitch (MM&MP) variation [22, 23]. This ratio also determines the maximum linkage of flux between stator winding and PM of translator. For MM&MP variation also optimization is carried out by keeping output power to a constant value by adjusting the magnitude of current [18, 19] Fig. 5 (a) shows the influence on induced-emf produced in winding, efficiecny and output power of linear PM generator with respect to variation in $\tau_p/\tau_{mz}$for conventional and propsoed linear PM generator. The effect on copper loss, iron loss and output power while varrying $\tau_p/\tau_{mz}$for conventional and propsoed linear PM generator is shown in Fig. 5 (b). It will be seen that the proposed design attains highest charcateritcs i.e. induced-emf and efficiency and lowest losses i.e. copper loss and iron loss as compared to conventional linear PM generator.



(b)

Fig. 5. Influence on (a) induced-emf, efficiency and output power (b) copper loss, iron loss and output power with variation in $\mathcal{P}_{w}\_ratio\ (\tau_p/\tau_{mz})$

4.3.Influence of $\mathcal{S}_{a}\_ratio\ (R_m/R_e)$

The R_m/R_e ratio is called "split ratio", it is an optimal balance between magnetic and electrical loading [18,19]. It is very essential part because its variation determines the maximum efficiency and minimum losses [18]. Likewise, the output electric power is retained to its fixed value by performing adjustment in the magnitude of rated current. The external diameter of static part is maintained constant when varying radius of outer diameter of translator.Fig. 6 (a) shows the effect on induced-emf, efficiecny and output power of linear PM generator with respect to variation in $R_m/R_e$for conventional and propsoedlinear PM generator. The influence on copper loss, iron loss and output power while varrying $R_m/R_e$for conventional and propsoed linear PM generator is shown in Fig. 6 (b). It will be seen that the proposed design obtains highest electromagnetic charcateritcs and lowest losses such as; copper loss and iron loss as compared to conventional linear PM generator.

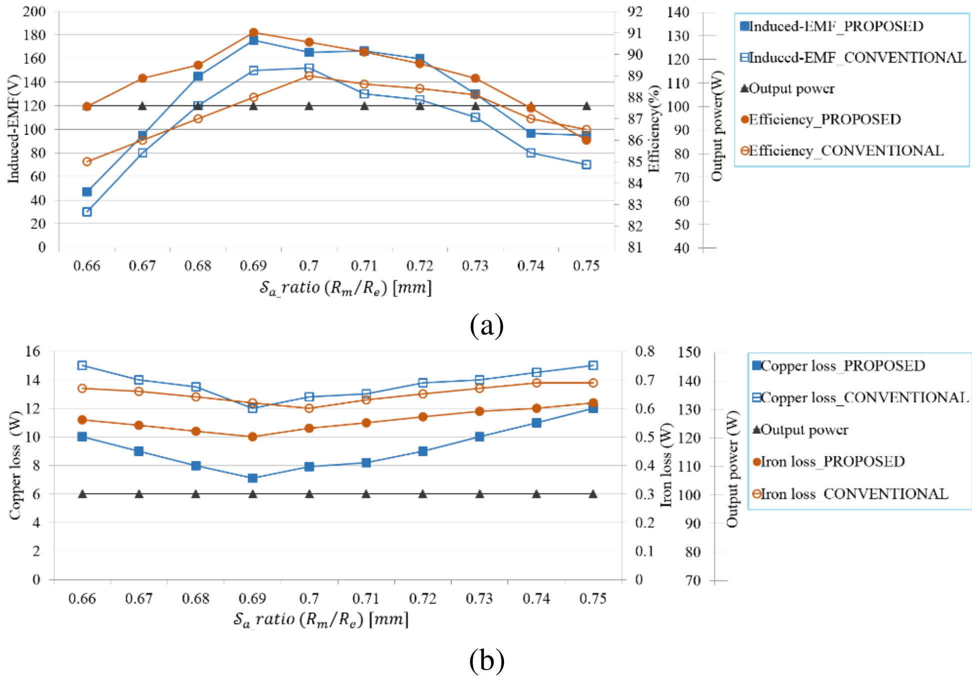


Fig. 6. Influence on (a) induced-emf, efficiency and output power (b) copper loss, iron loss and output power with variation in $\mathcal{S}_{a\_}ratio\ (R_m/R_e)$

The optimum value for magnet angle, $\mathcal{M}_{\theta(\Delta)}$, the pole-width ratio, $\mathcal{P}_{w\_}ratio$, and split ratio between translator and stator, $\mathcal{S}_{a\_}ratio$, which yields higher efficiency are listed in Table 4.

Table 4:Optimal values after optimization

Optimisation variable	symbol	Optimal value
magnet angle	$\mathcal{M}_{\theta(\Delta)}(\theta)$	85°
pole-width ratio	$\mathcal{P}_{w\_}ratio\ (\tau_p/\tau_{mz})$	6.0
split ratio	$\mathcal{S}_{a\_}ratio\ (R_m/R_e)$	0.69

5. Conclusion

The direct-drive linear generator is an energetic and robust technology which enhances the performance of wave energy conversion system dynamically. A linear PM generator is proposed with triangular-shaped magnet which has superior characteristics and lower mass as compared to conventional linear PM generator. The finite element analysis is carried out in order to determine the electromagnetic characteristics and to validate the proposed design. The Individual Parameter (IP) optimization technique is adopted in order to optimize and achieve highest performance of linear PM generator. The objective function is to maximize efficiency and optimization variable are magnet angle,$\mathcal{M}_{\theta(\Delta)}$, the pole-width ratio, $\mathcal{P}_{w\_}ratio$, and split ratio between translator and stator, $\mathcal{S}_{a\_}ratio$, which are optimized according to the nature of technique. The constraints along with their ranges and initial values are also provided. The optimal values for magnet angle,$\mathcal{M}_{\theta(\Delta)}$, the pole-width ratio, $\mathcal{P}_{w\_}ratio$, and split ratio between translator and stator, $\mathcal{S}_{a\_}ratio$, which results maximum electromagnetic characteristics and highest efficiency are given.

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