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Design Optimization of a Pico Linear Permanent Magnet Generator with Novel Shaped Magnet for Wave Energy Conversion using Finite Element Analysis

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Abstract
This paper presents the design optimization of a pico linear permanent magnet (PM) generator with novel shaped magnet for wave energy conversion. The finite element analysis (FEA) using time-stepping finite element method has been carried out where the electromagnetic characteristics such as open-circuit magnetic field distribution, magnetic flux density, induced-EMF, and flux linkage are presented. The optimization has been carried out based on the leading dimensions; angle "β", T_{mr}/T_p, and R_m/R_e, which have significant influence on the performance of linear PM generator. The optimum values for T_{mr}/T_p, PM angle β and R_m/R_e are 0.7, 80^o and 0.72 are achieved respectively, which yields maximum efficiency.

Keywords: Wave energy, linear generator, finite element analysis, efficiency, copper loss, core loss, optimization, dimensional ratio.

Introduction
Wave energy has a high seasonal availability and is fuel free, predictable and environment friendly. It is estimated that the potential worldwide wave power resource is 2 TW [1]. Since past decades, various efforts have been accomplished in the field of wind and solar energy generation. Alternatively, wave energy is still on initial stage but offers high potential energy. Marine wave energy is abundant and much consistent than solar and wind energy [2]. Wave energy is also called "blue energy" and has several potential benefits as compared to "brown energy", which is the form of energy achieved from fossil fuels and "green energy" which includes renewable energy sources such as; solar and wind energy [3]. Wave energy has 2-3 kW/m^2 power density as compared to wind and solar that has 0.4-0.6 kW/m^2 and 0.1-0.2 kW/m^2 respectively, while, in terms of power generation, wave energy converters generate maximum 90 % of power as compared to wind and solar that generates maximum 20-30 %, respectively [4]. The wave to mechanical energy conversion encompasses a full cycle as shown in Fig. 1. The primary stage involves conversion of available pneumatic energy of waves into mechanical energy, the secondary stage include an electrical machine which converts mechanical input to electric output, and the tertiary stage is based on signal conditioning which transform the signal into the form required by the grid. Conventional electrical machines are based on rotating generators that include mechanical section i.e. turbine part, gearbox and hydraulic pump [5-6]. Alternatively, direct-drive linear generator technology is proven efficient in wave energy conversion owing to absence of mechanical interface [7-9].

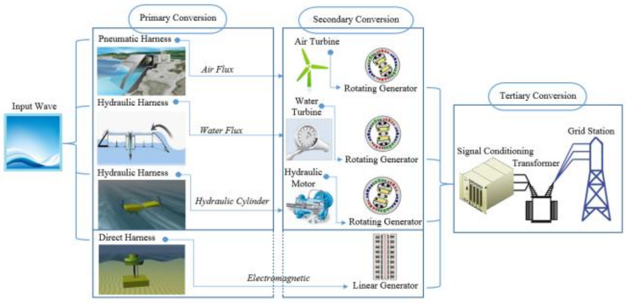


Fig. 1. Wave to electrical conversion cycle

In direct-drive system the moving part i.e. translator relative to stationary part (stator) is directly driven by the wave energy converter (WEC), which simplifies the overall system as shown in Fig. 2. The conventional synchronous generators use electromagnets to obtain magnetic field in the winding that further requires direct current and slip-ring assembly in order to achieve excitation. On the other hand, PM generators do not need a DC supply as an excitation circuit, slip rings and brush assembly [10-12]. PM are solid hard magnetic materials with an extremely large (wide) hysteresis cycle and a recoil permeability of 1.05-1.3 [13].
Variable Reluctance PM (VRPM) machines are recognized as high force density machines [10-11]. The type of these machines is Transverse Flux PM (TFPM) machine and Vernier Hybrid PM (VHPM) machine but unfortunately, difficult construction and low power factor are considerable disadvantages of these machines [14]. The development based on the longitudinal flux PM (LFPM) linear generators are very attractive owing to efficient electromagnetic performance but suffers from unwanted issues such as; high magnetic attraction forces and cogging force [15], [16-18]. Alternatively, air-cored linear PM generators are very attractive in terms of simplicity, lightweight [7-8] and unavailability of unwanted magnetic attraction forces and cogging force [10-11] but have limitations in electromagnetic performance. In past, various developments on air-cored machines [7], [10], [14], [19-20] have been carried out; these developments are based on high rating [7], [10-11], [19],

large-scale [20] and complicated design [10-11]. This research aims to propose and design a linear permanent magnet generator [12] which is simple, with low power rating 100 W and portable i.e. lightweight. This paper presents the modeling and design optimization of simple and lightweight linear PM generator based on trapezoid-shaped permanent magnet for wave energy conversion using finite element software ANSYS "Maxwell".

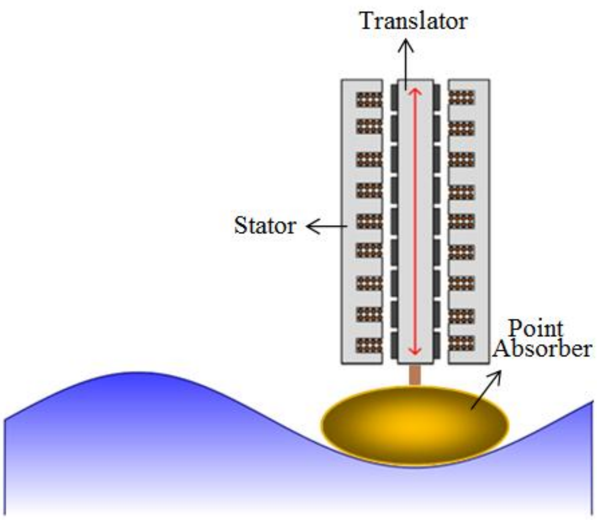


Fig. 2. Direct-drive wave energy conversion system

Linear Permanent Magnet Generator

The three-dimensional view of proposed linear generator is shown in Fig. 3.The translator is equipped with series of trapezoid-shaped permanent magnets. Neodymium-iron-boron (NdFeB) permanent magnet with the magnetic remanence of 1.14 T is used and quasi-halbach magnetization is employed on account of sinusoidal air-gap distribution [21]. The stator uses full-pitch winding with slot-less configuration which reduces the mass and in turn gives a simple and lightweight design [22].

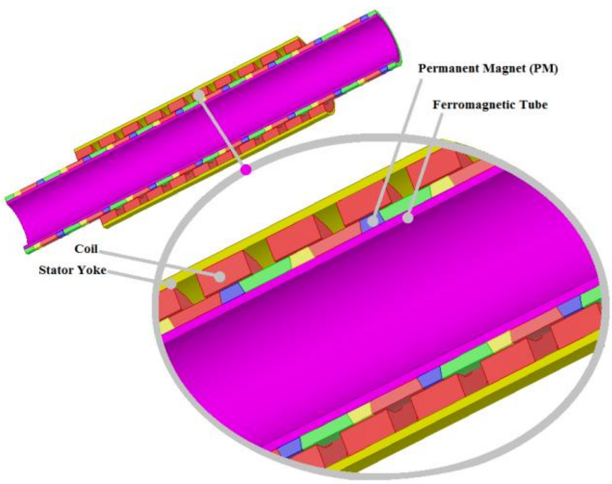


Fig. 3. Three-dimensional view of proposed Linear PM generator

Finite Element Analysis

FEA has been carried out on conventional linear PM generator with rectangular-shaped magnet. It validates with proposed design and identify that the proposed linear generator produces superior and higher electromagnetic performance as compared to conventional linear generator [23-27]. The axi-symmetrical cylindrical coordinate system is adopted. The boundary conditions are applied to all regions and the magnetization has been assigned to all permanent magnets [28]. Fig. 4. presents the comparison of induced-EMF and flux linkage for conventional [27] and proposed linear generator. It will be seen that, the proposed linear generator has higher performance as compared to conventional linear generator [27].

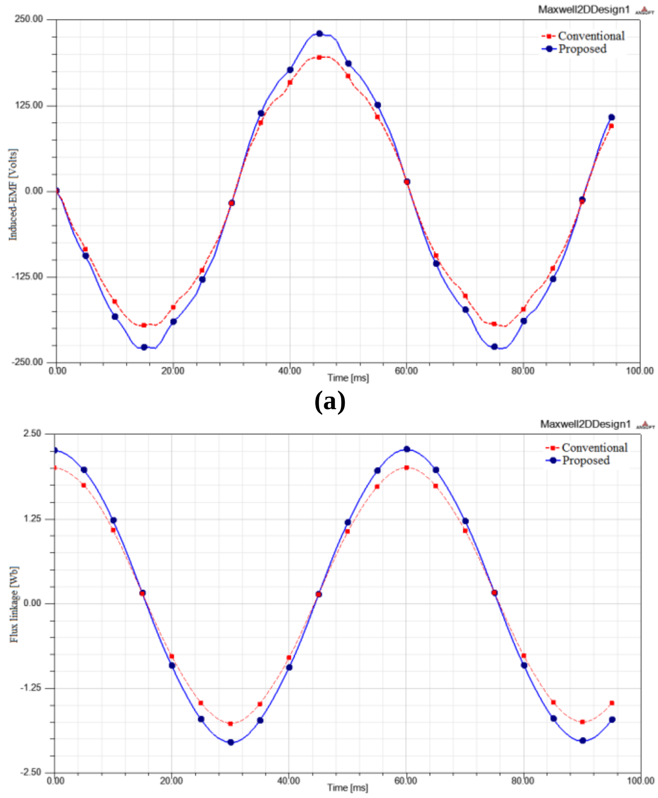
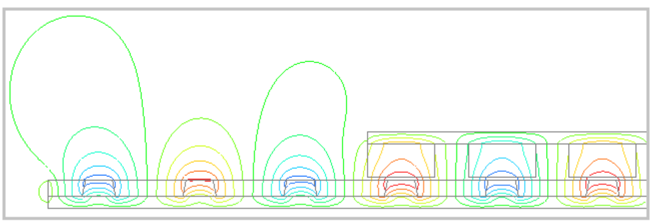
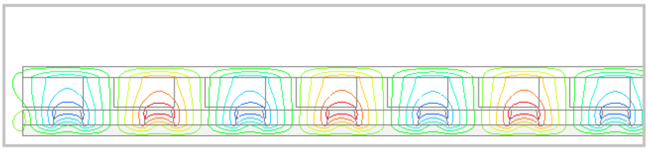


Fig. 4. Comparison of conventional and proposed design (a) Induced-EMF (b) Flux linkage

The finite element predicted open-circuit flux distribution at zero and maximum displacement Z_d (Z_d=0) are shown in Fig. 5. It will be seen that flux distribution is uniform and forms smooth linkage between translator and stator.



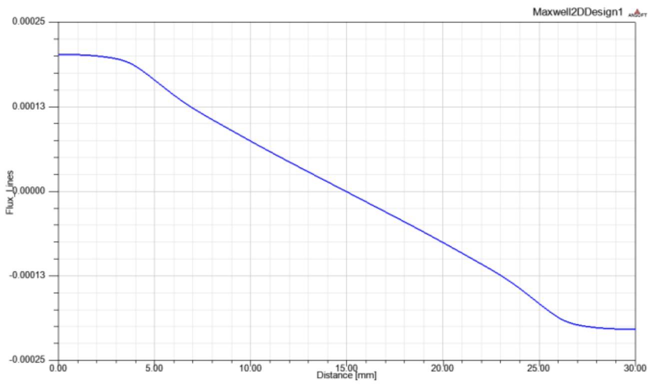
(a)



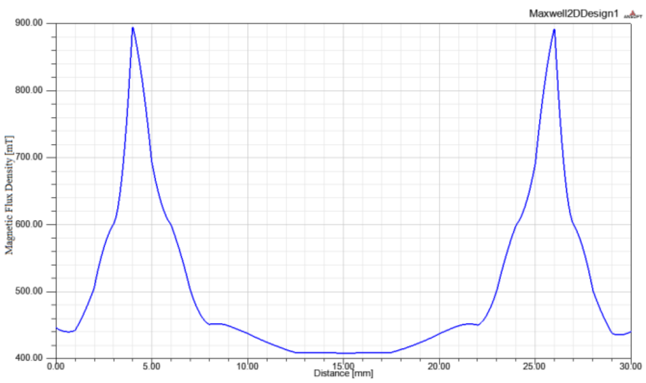
(b)

Fig. 5. Open-circuit flux distribution between translator and stator at (a) (Z_d *at zero displacement)* (b) (Z_d *at maximum displacement)*

The air-gap is the mechanical clearance between translator and stator, the magnetic flux density and flux line for one pole-pitch at zero displacement are shown in Fig. 6.



(a)



(b)

Fig. 6. Magnetic flux density (a) magnetic flux lines (b) in air-gap between translator and stator

Transient mode is a time-varying analysis and it is also called "on-motion" analysis. The translator is fixed on the center with respect to stator and is reciprocated with the velocity of 1 m/s. The stop time and time step is 30 ms and 1 ms, respectively with the step size of 5 ms. The RMS Induced-EMF generated in stator winding [29] can be written as;

$$E = \frac{2\pi}{\sqrt{2}} f N_{ph} \phi_m \qquad (1)$$

where E is the induced-EMF, f is electrical frequency, N_{ph} is the number of coil turns per phase and ϕ_m flux linked by winding.
The induced-EMF and flux linkage in the winding of stator is shown in Fig. 7. It will be seen that, the resultant waveform is sinusoidal [29] which in turn reduces the requirement of signal conditioning portion.

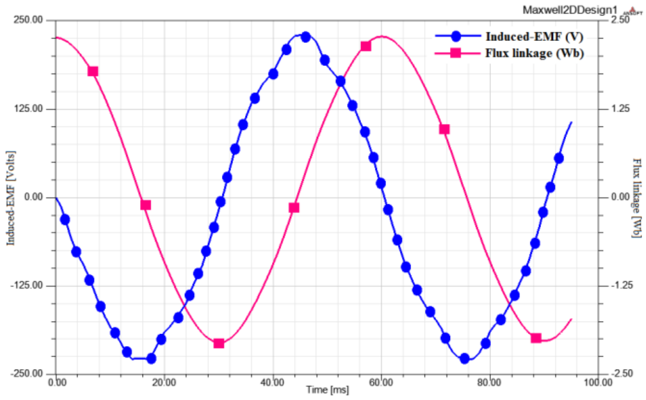


Fig. 7. Induced-EMF and flux linkage in coil of stator's winding

Efficiency Analysis

The efficiency of the electrical machine is the essential part that is to be taken into account under the design optimization [30]. The efficiency has been analysed as follows [31];

$$\eta = \frac{P_{out}}{P_{out}+P_{cu}+P_{fe}} \qquad (2)$$

where P_{out}, P_{cu}, and P_{fe} is output power, copper loss and iron loss, respectively.
Copper loss can be determined as follows [32];

$$P_{cu} = I^2 R \qquad (3)$$

where I and R is rms current and winding resistance, respectively.
The core loss or iron loss of the linear permanent magnet generator is composed of three different components [33]; hysteresis loss, classical eddy current loss, and excessive loss. Collectively, the total core loss [34] can be expressed as;

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

where P_{hi}, P_{ci} and P_{ei} is hysteresis loss, classical eddy current loss and excessive loss, respectively. Using flux density waveform [33-34], these components can be written as;

$$P_{hi} = \kappa_h f B_m^{\alpha} \qquad (5)$$

$$P_{ci} = \frac{2\pi\sigma d^2 f^2}{12\delta} \int_{2\pi} \left(\frac{dB}{d\theta_e}\right)^2 d\theta_e \qquad (6)$$

$$P_{ei} = \sqrt{2\pi}\kappa_e f^{\frac{3}{2}} \int_{2\pi} \left|\frac{dB}{d\theta_e}\right|^{\frac{3}{2}} d\theta_e \qquad (7)$$

where f, B_m^{α} and θ_e are the frequency, peak flux density and electrical degree, respectively, and σ, δ and d are the electrical conductivity, mass density and lamination thickness, respectively. The coefficients κ_h, α and κ_e associated with hysteresis and excess loss component can be determined from manufacturer's data sheet.

Design Optimization

The objective of optimization is to maximize efficiency and minimize the total losses [35]. In order to achieve maximum value of efficiency, the leading design parameters which have significant influence on the performance of linear PM generator are optimized. The main leading design parameters are; permanent magnet angle "β", ratio of T_{mr}/T_p and ratio of R_m/R_e. The optimization of design parameters is set to constant output power when varying "β",, T_{mr}/T_p, and R_m/R_e. This is due to give equal or fair process of optimization [36]. The schematic diagram of linear PM generator with geometric parameters is presented in Fig. 8. and their dimension is listed in Table I;

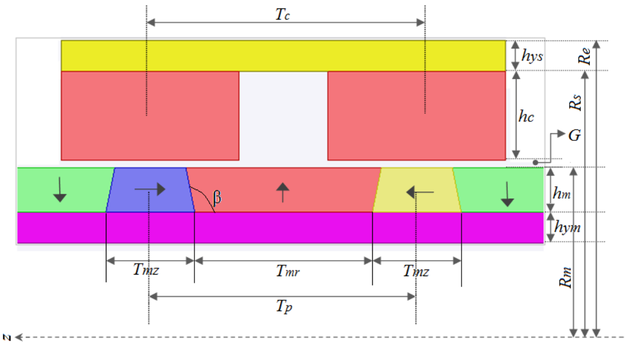


Fig. 8. Schematic diagram of linear PM generator

TABLE I. Dimension of design parameters

Parameter	Value
Rated Power, P_{out}	100 W
Length of radially magnetized magnet, T_{mr}	20 mm
Length of axially magnetized magnet, T_{mz}	10 mm
Magnet height, h_m	5 mm
Pole-pitch, T_p	30 mm
Outer radius of stator core, R_e	52.8 mm
Radial thickness of ferromagnetic tube, h_{ym}	3.5 mm
Stator yoke height, h_s	3.5 mm
Reciprocating velocity, v	1 m/s
Air-gap length, G	0.8 mm
Magnetic Remanence, B	1.14 T

A. Influence of angle (β)

The translator of linear generator is equipped with trapezoid-shaped permanent magnet, which is highly influenced by the angle of permanent magnet (β). The variation of angle (β) is worthwhile because it gives rise to the flux-linkage and in turn increases induced-EMF but after optimal value it diminishes the performance owing to drop in flux-linkage. The output power is set constant when varying the angle as shown in Fig. 9. Fig. 10 shows the angle of permanent magnet is optimized for various degrees. It will be seen that, on 80° the maximum induced-EMF is achieved.

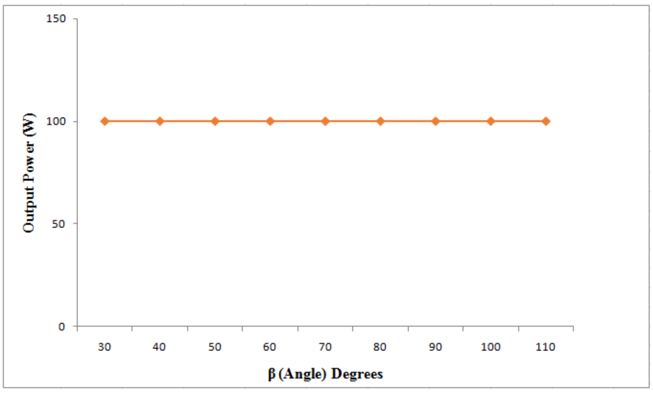


Fig. 9. The output power versus variation of angle β

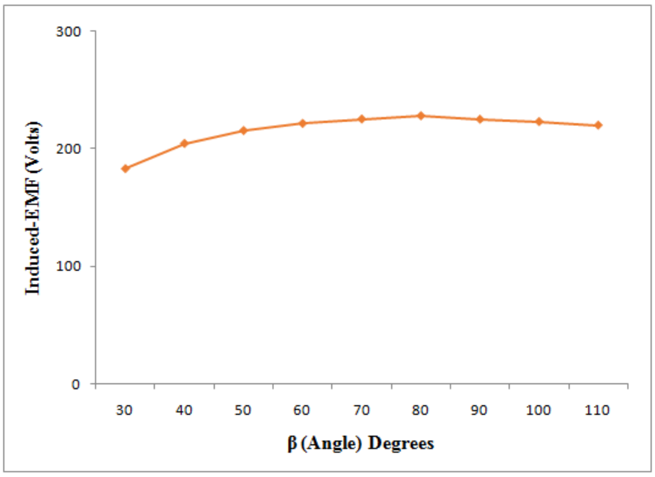


Fig. 10. Influence of angle β on induced-EMF

Similarly, the efficiency of linear generator is analyzed on various degrees of permanent magnet angle β, which exhibits higher value on 80° as shown in Fig. 11.

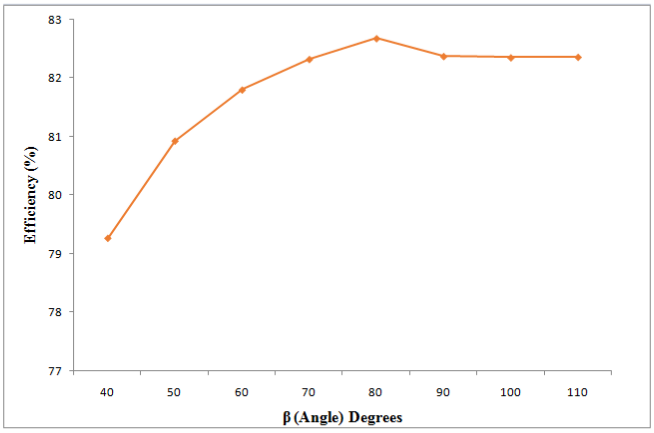


Fig. 11. Influence of angle β on efficiency

The same trend is analyzed for copper loss, the copper loss has minimum value on 80° (degrees) as shown in Fig. 12.

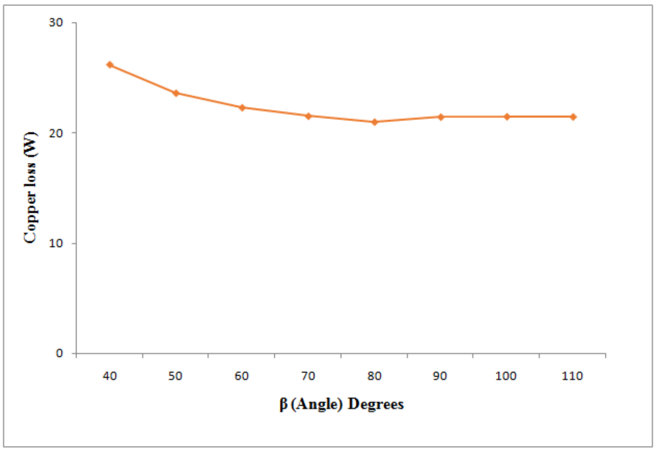


Fig. 12. Influence of angle β on copper loss

B. Influence of T_{mr}/T_p

The optimization is carried out by keeping output power to a constant value by adjusting the magnitude of current [17-18] as shown in Fig. 13. T_{mr}/T_p is the called "pole-width ratio" [37-38], it is very significant due to it affects the maximum flux-linkage between coil and PM. The thickness and pole-pitch for permanent magnet is kept constant during optimization.

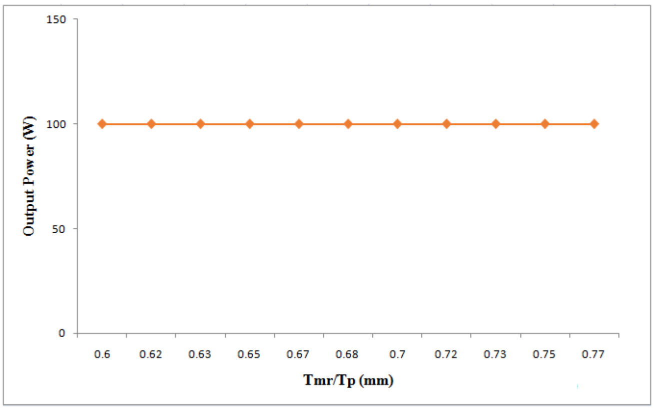


Fig. 13. The output power versus variation of T_{mr}/T_p

Fig. 14 shows the variation of the efficiency with T_{mr}/T_p at optimal value of $\beta = 80^o$. It will be seen that, the optimal ratio occurs at T_{mr}/T_p =0.70, which gives maximum efficiency and afterwards the flux linkage causes saturation which in turn diminish the efficiency.

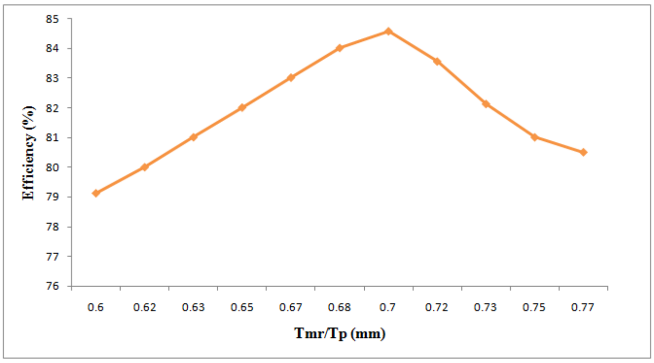


Fig. 14. Influence of T_{mr}/T_p on the efficiency of linear permanent magnet generator

Fig. 15 shows the influence of T_{mr}/T_p on the copper loss of the linear permanent magnet generator. It will be seen that, at 0.70 the copper loss has minimum value.

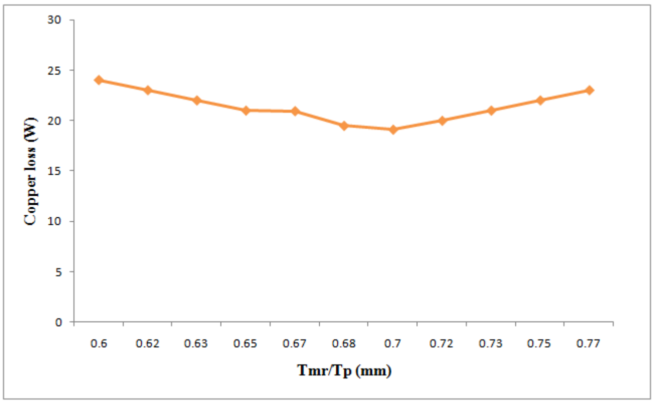


Fig. 15. Influence of T_{mr}/T_p ratio on copper loss

C. Influence of R_m/R_e

The R_m/R_e ratio is called "split ratio", it is an optimal balance between magnetic and electrical loading [39-40]. It is very significant part because its variation determines the maximum efficiency and minimum losses. Likewise, the output power is kept constant by adjusting the magnitude of current as shown in Fig. 16. The outer diameter of stator is kept constant when varying radius of outer diameter of translator.

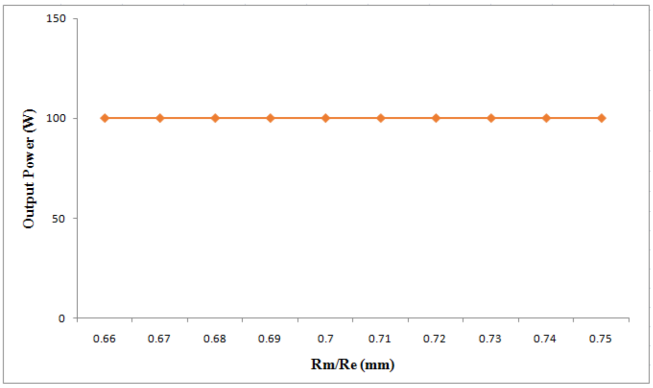


Fig. 16. The output power versus variation of R_m/R_e

Fig. 17 shows the variation of the efficiency as a function of R_m/R_e. It is seen that, the optimal ratio is R_m/R_e =0.72, which gives maximum efficiency.

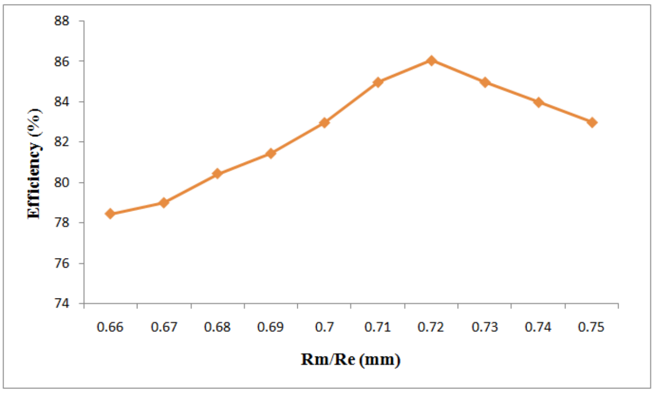


Fig. 17. Influence of R_m/R_e on the efficiency of linear permanent magnet generator

Fig. 18 shows the influence of R_m/R_e on the copper loss of the linear permanent magnet generator. It will be seen that, the minimum value on which copper loss is minimum occurs at 0.72.

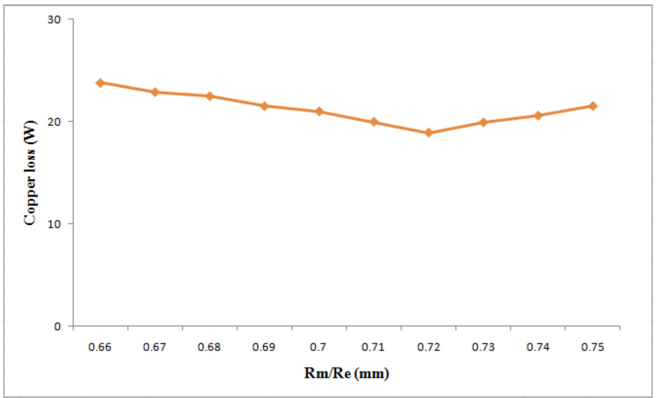


Fig. 18. Influence of R_m/R_e ratio on copper loss

Conclusion

The linear PM generator with trapezoid-shaped permanent magnet and its electromagnetic characteristics; open-circuit magnetic flux distribution, induced-EMF, and flux linkage are presented. The characteristics show that the linear PM with trapezoidal shape magnet has better performance than the linear PM generator with rectangular shape magnet. The optimization has been carried out for highest efficiency and the influence of leading dimensional parameters; permanent magnet angle β, ratio of T_{mr}/T_p and ratio of R_m/R_e are analyzed. The proposed design will be fabricated and tested in order to validate the results.

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