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Research Article

Electromagnetic Characteristics Prediction and Efficiency Analysis of Linear Permanent Magnet Generator for Marine Wave Energy Conversion using Finite Element Method

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Abstract: This paper aims to present electromagnetic analysis and evaluation of efficiency of linear generator for marine wave energy conversion using Finite Element Method (FEM). A Linear Generator (LG) with a novel shape of magnet is proposed which has superior characteristics and improves the efficiency as compared to conventional magnet. Finite Element Analysis (FEA) has been carried out for proposed LG and compared with conventional, which validates the results and identifies that proposed magnet enhances the performance and efficiency as compared to existing conventional magnet. Two modes are analyzed; stationary and dynamic and their results such as mesh plot, no-load open-circuit magnetic flux distribution, magnetic flux density, flux-linkage and induced-voltage are presented. The main parts of efficiency such as; copper loss and iron loss are analyzed on various magnitudes of excitation currents and frequency ranges, respectively. The efficiency has been evaluated on various coil length variation by keeping electric power to a constant rating, which also provides higher characteristics as compared to conventional.

Keywords: Efficiency, electromagnetic characteristics, linear generator, permanent magnet, wave energy

INTRODUCTION

Nowadays new ways of producing energy are being explored to satisfy the growing needs of world. 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 (Astariz and Iglesias, 2015). Since past decades, various efforts have been accomplished in the field of wind and solar energy generation (Blažauskas *et al*., 2015; López *et al*., 2013). According to resources 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 generator maximum 20-30% (Lopez *et al.*, 2013; Drew *et al*., 2009). Conventional electrical machines are based on rotating generators that include mechanical section i.e. turbine technology, gearbox and hydraulic pump. Alternatively, direct-drive linear generator technology is proved efficient in wave energy conversion due to eliminated mechanical interface (Mueller and Baker, 2005). The available mechanical energy of waves can be harnessed into electrical energy via various stages (Blažauskas *et al*., 2015); the flow chain including main parts is presented in Fig. 1. This primary stage involves the conversion of wave motion in a body movement, an air-flow or water-flow through pneumatic, hydraulic or mechanical systems. The second stage is based on electrical generator that can be either conventional or direct-drive. The tertiary conversion is signal conditioning part, which is required before the signal is supplied to the grid.

In direct-drive system as shown in Fig. 2 the moving part i.e., translator relative to stationary part (stator) is directly driven by the Wave Energy Converter (WEC), thus simplifies the overall system. The conventional synchronous generators use electromagnets to have a magnetic field in the winding that further requires direct current and slip-ring assembly in order to have excitation (Cullity and Graham, 2008). On the other hand, permanent magnet generators do not need a DC supply as an excitation circuit, slip rings and brush assembly (Chau *et al*., 2012). Permanent magnets are solid hard magnetic materials with an extremely large (wide) hysteresis cycle and a recoil permeability of 1.05-1.3.

LITERATURE REVIEW

In literature, Variable Reluctance PM (VRPM) machines are recognized as high force density machines (Vermaak and Kamper, 2012a). The kinds of these

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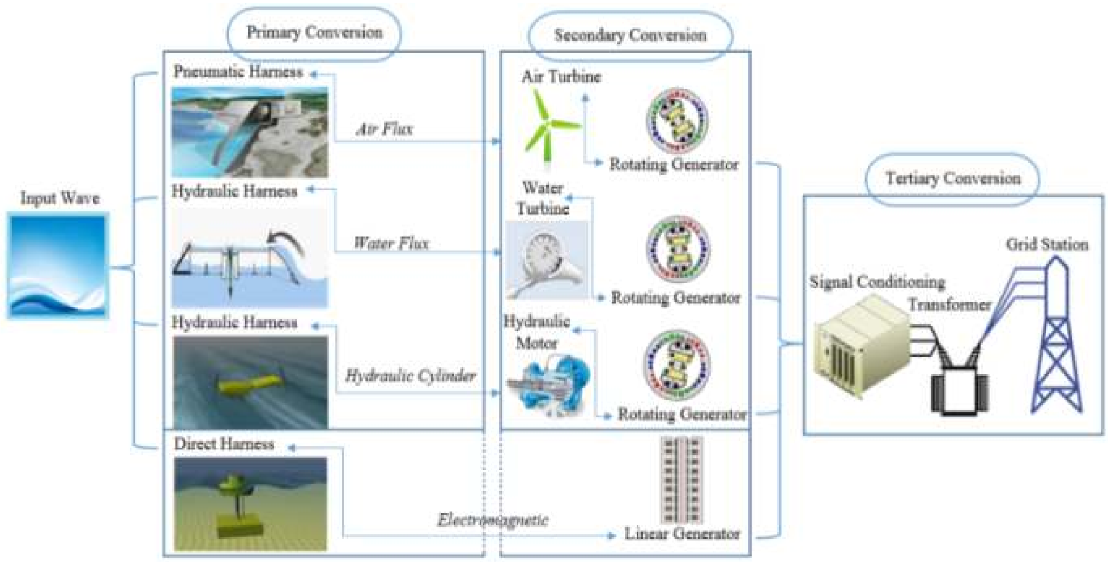


Fig. 1: Process of wave to electrical energy conversion (López *et al*., 2013)

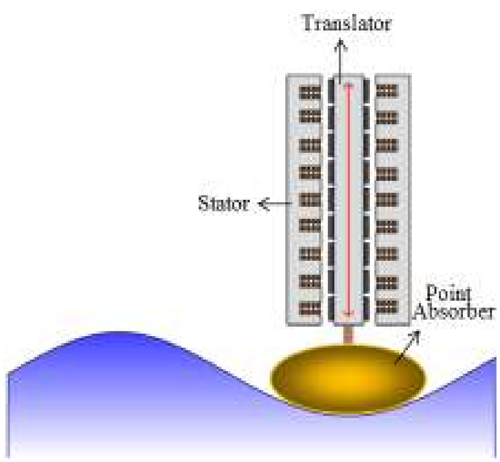
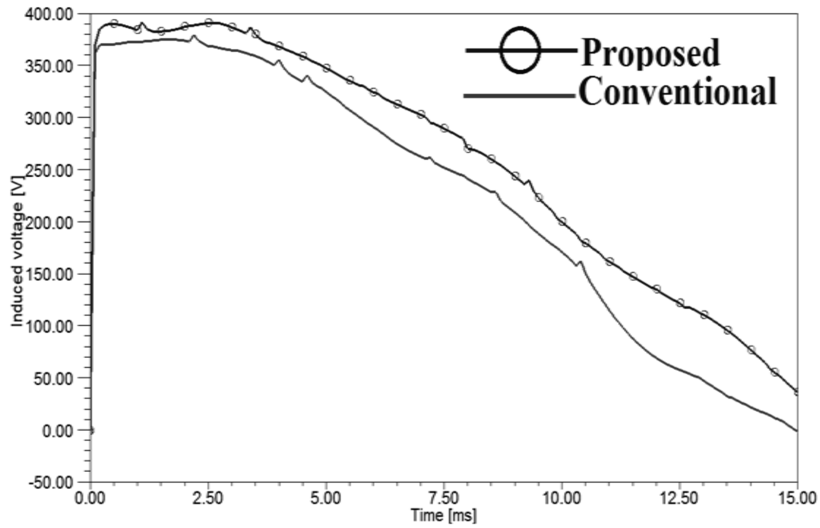


Fig. 2: Direct-drive wave energy conversion system

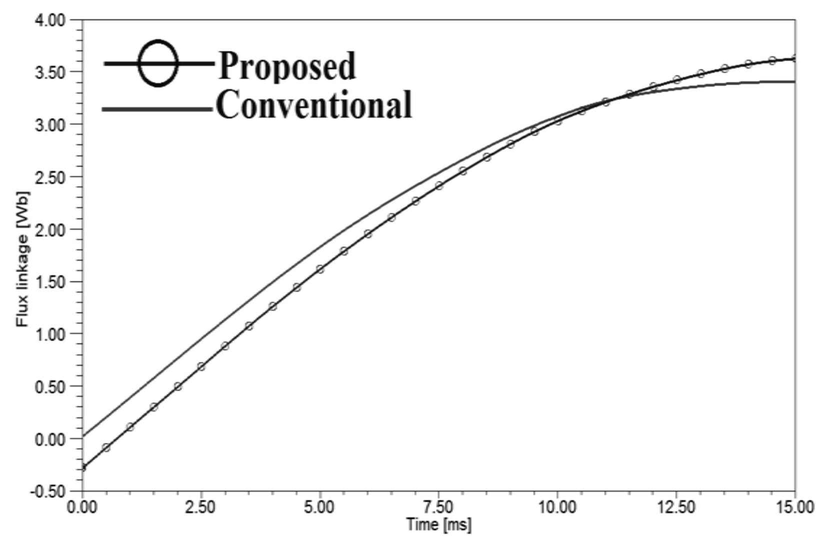
machines are Transverse Flux PM (TFPM) machine and variable reluctance PM (VRPM) machine but unfortunately, difficult construction and low power factor are considerable disadvantages of these machines (Mueller *et al*., 2005). The developments based on the longitudinal flux PM (LFPM) linear generators are very attractive owing to efficient electromagnetic performance but suffers from unwanted issues such as; high magnetic attraction forces and cogging force (Danielsson *et al*., 2006, 2005; Polinder *et al*., 2004; Prudell *et al*., 2010). The cogging force arises as a result of the mutual attraction between magnets and ferromagnetic core of translator (Hodgins *et al*., 2012; Gargov and Zobaa, 2012); it manifests itself by the tendency of the translator to align in a number of preferred positions regardless of excitation states. Number of techniques has been used to reduce it but almost all the techniques used against to cogging force also reduce the actual electromagnetic performance (Kakosimos *et al*., 2012). Moreover, pertaining to magnetic attraction force the analytical methods have been developed, that reveal that 60 % structural mass is required to overcome these forces (Nilsson *et al*., 2006). Alternatively, air-cored linear PM generators are very attractive in terms of simplicity, lightweight and unavailability of unwanted magnetic attraction forces (Chau *et al*., 2012) but have limitations in electromagnetic performance (Vermaak and Kamper, 2012b; Hodgins *et al*., 2010; Nie *et al*., 2013; Gargov *et al*., 2014). In past, various developments on air-cored machines have been carried out but are based on large scale (well-structured WEC), high rating (Hodgins *et al*., 2012) and embody complicated design (Vermaak and Kamper, 2012a; Hodgins *et al*., 2012). This research work presents electromagnetic analysis using stationary and dynamic modes of linear generator with permanent magnet which produces 80 W electric power using Finite Element Analysis (FEA) software. A novel shape of magnet "skewed" is proposed for linear generator which has superior and higher electromagnetic characteristics and performance as compared to the magnet.

MATERIALS AND METHODS

FEA has been carried out for both conventional and proposed linear generator for validation purpose. The axi-symmetrical cylindrical coordinate system is used. The boundary conditions are applied to all regions and the magnetization has been assigned to all magnets. The FEA identifies that the proposed LG produces prominent and higher electromagnetic characteristics as compared to conventional magnet (Hodgins *et al*., 2012). Figure 3 presents the comparison of induced-voltage and flux linkage for conventional and proposed



(a)



(b)

Fig. 3: Comparison of conventional and proposed design; (a): Induced-EMF; (b): Flux linkage

Table 1: Induced-EMF and flux-linkage for conventional and proposed linear PM generator

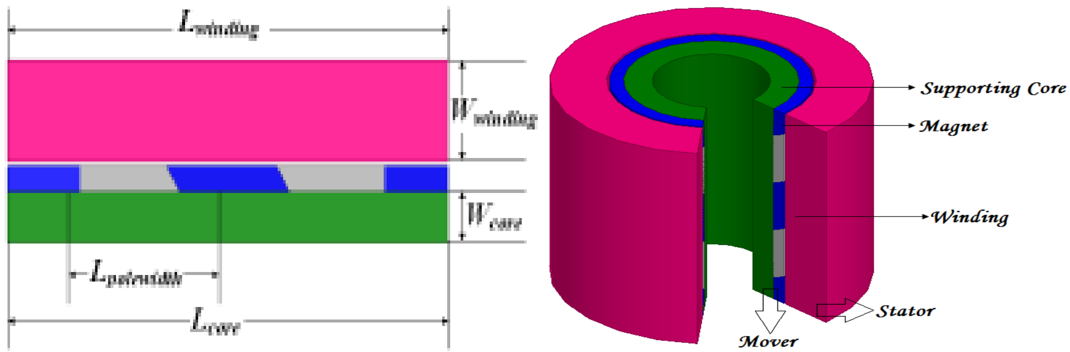
Electromagnetic parameter	Proposed LG	Conventional LG
Induced-voltage	277.186 V	268.701 V
Flux linkage	2.560Wb	2.404Wb

LG. The RMS value of proposed and conventional LG for induced-voltage and flux linkage is given in Table 1. It can be observed that, the proposed LG has foremost performance as compared to conventional linear generator (Hodgins *et al*., 2010).

The two-dimensional schematic and 3D finite element model of proposed linear generator is shown in Fig. 4. Translator consist Neoddyymium_iron_boronn (NdFeB) magnet with skewed shape (Danielsson *et al*., 2003, 2005). The main design parameters are tabulatedin Table 2. The

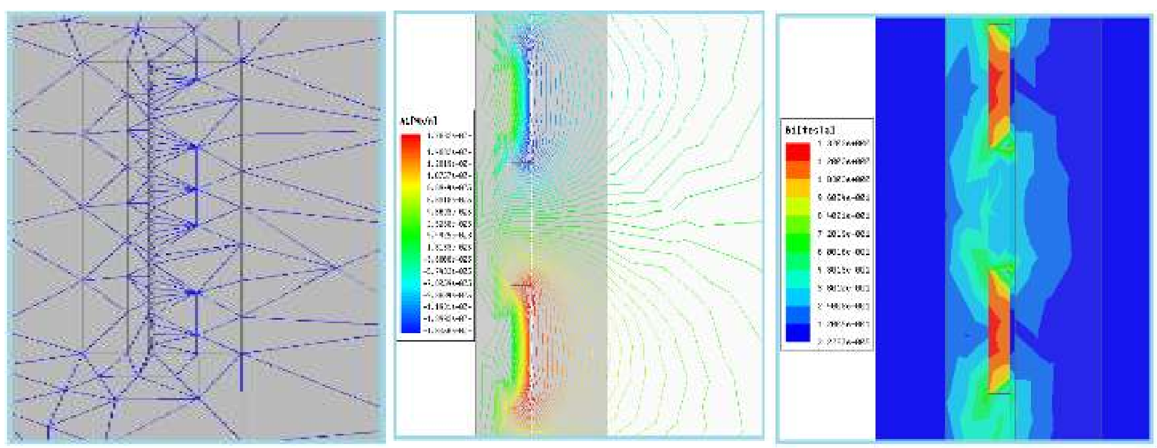
Table 2: Design parameters

Parameter	Value
Power rating	80 W
Length of magnet	0.025 m
Length of spacer	0.005 m
Magnet width	0.0048 m
Pole width	0.040 m
Radius of winding	0.0495 m
Height of supporting core	0.005 m
Yoke thickness	0.005 m
Maximum displacement	0.015 m
velocity	1.00 m/s
Air-gap width	0.001 m



(a) (b)

Fig. 4: Linear PM generator; (a): 2D view; (b): 3D view



(a) (b) (c)

Fig. 5: Pre-refined electromagnetic characterics; (a): mesh plot; (b): no-load magnetic flux lines; (c): flux desnity

electromagnetic analysis is carried out using FiniteElement Analysis (FEA) software Ansoft Maxwell V.16.0. It comprises two modes:

- Stationary Analysis
- Dynamic Analysis

RESULTS AND DISCUSSION

Two different modes are analyzed which determines the in-depth electromagnetic characteristics of LG geometry.

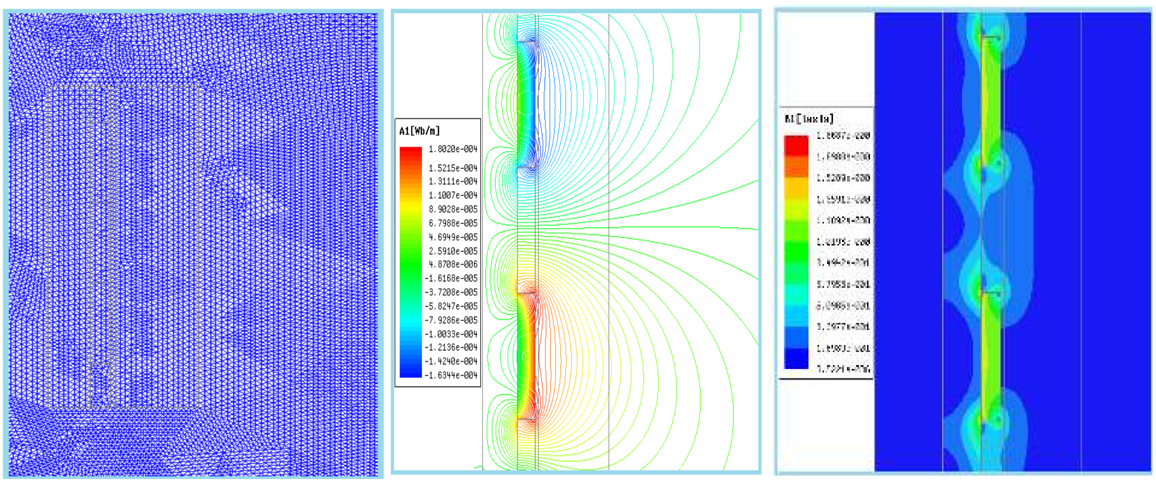
Stationary analysis: This analysis is carried out when the translator is static with stator or displacement is zero (z=0 m). It includes the inspection of mesh plot, field overlays such as; open-circuit no-load magnetic flux distribution and flux density and air-gap performance evaluation by flux line and flux density. The key to achieve the required and accurate solution to given problem is relied on mesh. It is the combination of small elements on which the analysis is carried out or in other words this is the analysis procedure called "Finite Element Analysis" (FEA) (Gieras *et al*., 2008; Gupta *et al*., 1990; Rhinefrank *et al*., 2008; Pelc and Fujita, 2002; Cullity and Graham, 2008). Firstly, default or pre-refined characteristics are taken into account in order to inspect the electromagnetic behavior within geometry of machine. Figure 5 shows the mesh plot, open-circuit magnetic flux distribution and flux density. It can be observed that mesh is entirely rough, jagged, uneven and wide throughout all the parts. Similar characteristics are experienced by open-circuit magnetic flux distribution and flux density. It can be observed that magnetic flux lines are significantly scattered, forms unsmooth linkage between translator and stator and magnetic flux density also exhibits non-uniform distribution and is unbalanced inclusively.

Figure 6 shows the modified or post-refined mesh plot, open-circuit magnetic flux distribution and flux density. It can be seen that now the accomplishment of mesh particles are very narrow and fine which leads the solution towards accuracy, as revealed by open-circuit magnetic flux distribution and flux density. Now, it can be observed that magnetic flux lines are uniform, forms smooth and straight linkage, moreover, the magnetic flux density also bounds the magnetic field strongly and equitably.

The air-gap is the space between translator and static part of linear generator (Baker *et al*., 2004), it provides the present nature of magnetic characteristics during off-motion and on-motion analysis such as magnetic flux density and flux line. Figure 7 shows magnetic flux density and flux line between the air-gap for one pole width at zero displacement.

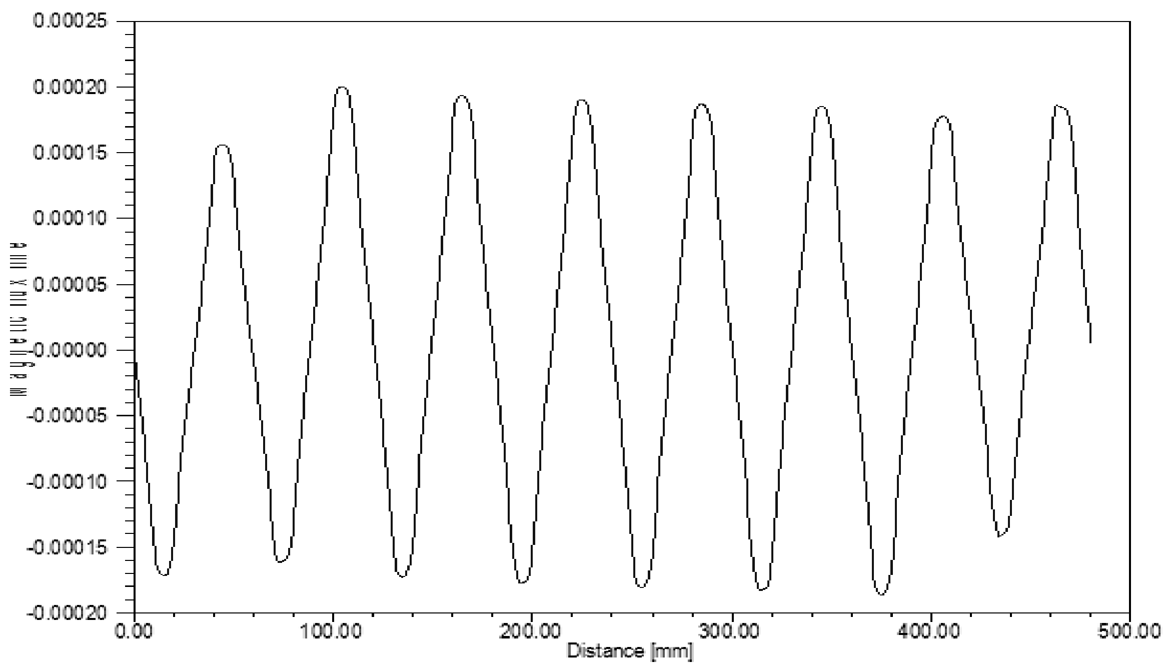
Dynamic analysis: Dynamic analysis or transient mode is a time-varying analysis and it is also called "on-motion" analysis (Prado *et al*., 2006; Leijion *et al*., 2005; Kakosimos *et al*., 2012). The translator reciprocates with respect to static unit "stator" with the speed of 1 m/s (Danielsson, 2006; Vermaak, 2013). The stop time and time step is 15 ms and 10 ms, respectively with the step size of 5 ms. The RMS Induced-EMF generated in stator winding (Vermaak, 2013) can be written as:

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



(a) (b) (c)

Fig. 6: Post-refined electromagnetic characterics; (a): mesh plot; (b): no-load magnetic flux lines; (c): flux desnity



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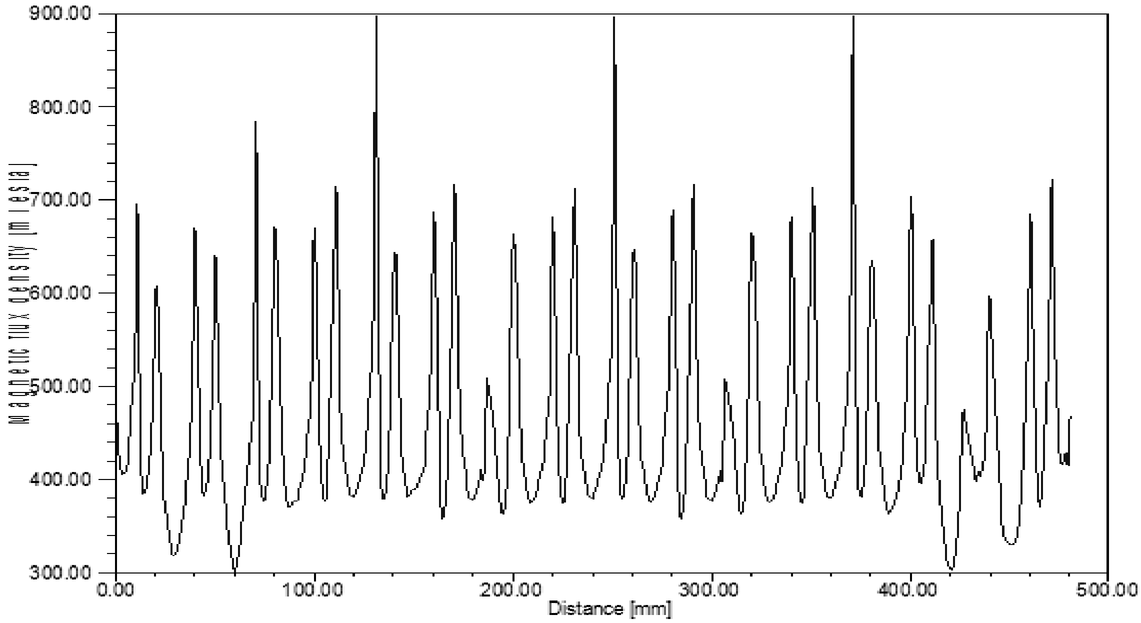


(b)

Fig. 7: Magnetic flux density; (a): magnetic flux lines; (b): in air-gap between translator and stator

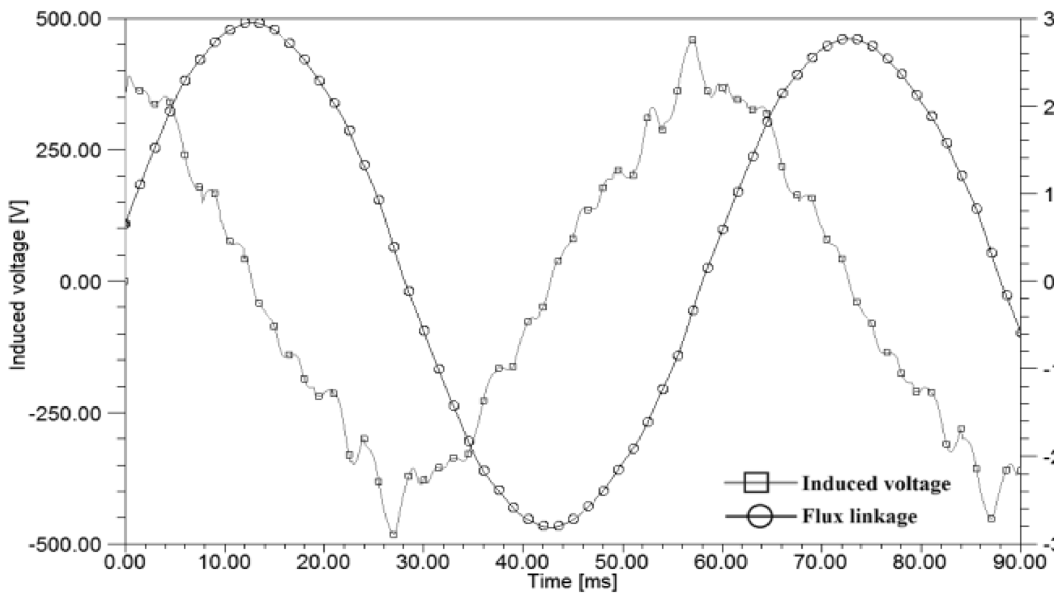


Fig. 8: Induced-EMF and flux linkage in coil of stator's winding

where,

E : The induced-voltage

f : Electrical frequency

N_{ph} : The no. of coil turns per phase and ϕ_m flux linked by winding.

The induced-voltage and flux linkage in the winding of stator is shown in Fig. 8. It can be observed that, the resultant waveforms are time-derivative of each other according to their fundamental electromagnetic relationship and exhibits sinusoidal shape, which eventually reduces the signal condition part substantially (Danielsson *et al*., 2003; Vermaak, 2013; Kakosimos *et al*., 2012; Leijion *et al*., 2005).

Efficiency analysis: In order to analyze the complete characteristics it is worth determining the efficiency of LG (Danielsson, 2006; Crozier, 2014). It can be computed as:

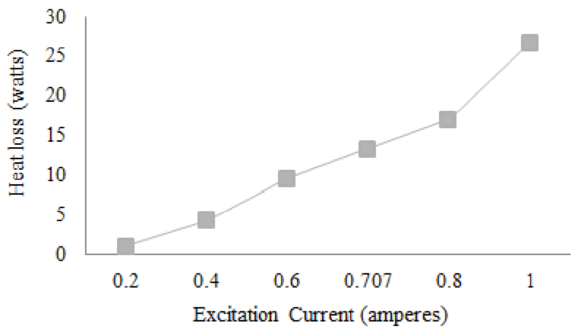
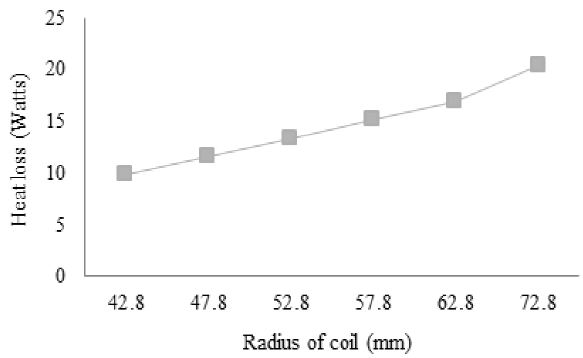


Fig. 9: Heat loss versus excitation current



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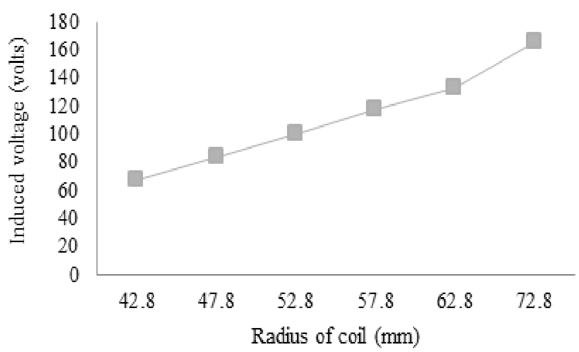


(b)

Fig. 10: Influence of external coil radius on; (a): induced-emf and; (b): heat losss

$$\eta = \frac{P_o}{P_o+P_h+P_i} \tag{2}$$

where, P_o, P_h, and P_i is rated power, heat loss and iron loss, respectively.

Copper or heat loss can be computed as follows (Vermaak, 2013):

$$P_h = I^2 R \tag{3}$$

where $I$and R is rms current and winding resistance, respectively.

To analyze the effect of heat loss, the excitation current is injected into stator winding, which eventually exhibits similar information according to heat loss and resistance relationship. In Fig. 9, it can be observed that as the current rises up, the heat losses increase simultaneously.

The coil is composed of conductors and its resistance is essential part in the computation of efficiency (Danielsson, 2006). It can be determined as:

$$R = \rho \frac{L}{A} \tag{4}$$

where,

R : The resistance of wire in ohms
ρ : The resistivity of copper
L : The length of wire in meters
A : The area of coil in meter squares

Figure 10a represnts the influence of induced-voltage with respect to the coil length variation and it can be observed that according to aforementioned coil-resistance relationship as length of conductor increases the induced-voltage also increases. Meanwhile, this practice increases heat losses (Fig. 10b).

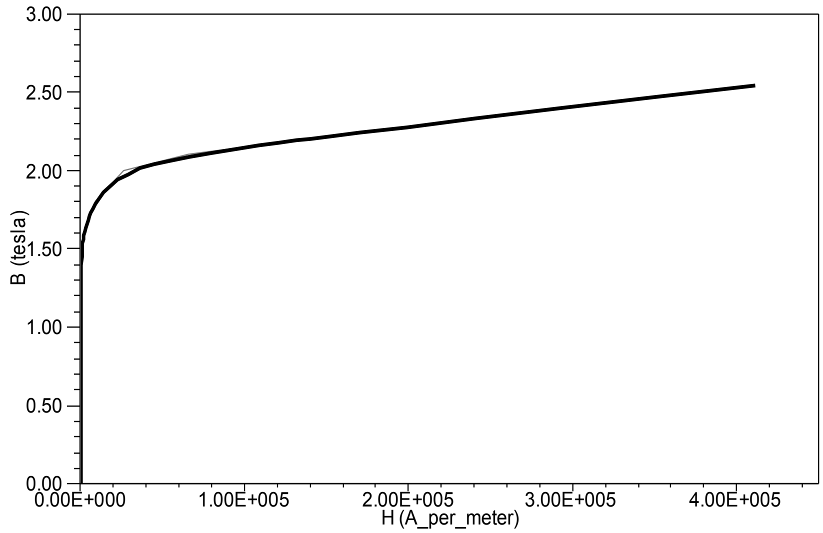
The core loss is based on three diverse parts; hysteresis loss, classical eddy current loss and excessive loss. Communally, the total iron loss (Crozier, 2014) can be described a:

$$P_i = \Sigma(P_{hy} + P_c + P_e)(5)$$

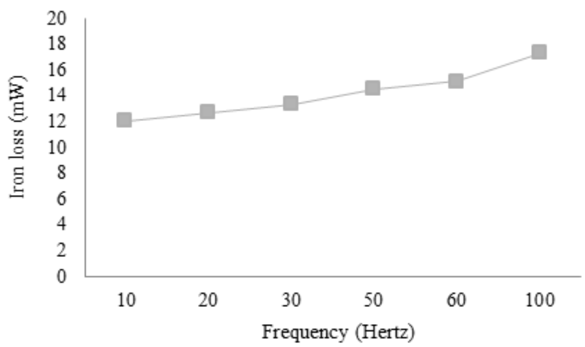
where, P_{hy}, P_c and P_e is hysteresis loss, classical eddy current loss and anomalous loss, respectively.

To diminish hysteresis loss, high grade magnetic material with low hysteresis area is chosen. The core of the stator and translator employs M-36 electrical steel material, which gives nearly the lowest core loss (Cullity and Graham, 2008). The magnetic curve of M-36 steel is shown in Fig. 11a. The iron loss is computed on various frequencies grounded on the manufacturer specific iron loss curves (Crozier, 2014). Figure 11b shows that as frequency is increased the iron loss also increases.

The efficiency has been analyzed for proposed and conventional with respect to the variation of coil width (variation 'V-1 to V-10'). This dimension is a dominant part in the performance evaluation of LG (Crozier, 2014) and efficiency is highly influenced by it. Throughout the variation, the rated power rating is normalized by keeping its original rated value, so that the variation process may not affect the rest of design characteristics as shown in Fig. 12. Consequently, it can be seen that the proposed LG has attained higher efficiency as compared to the conventional as shown in Fig. 13 on optimum variation point (V8).



(a)



(b)

Fig. 11: Magnetic B-H curve for M-36 Steel (Crozier, 2014) (a) and iron loss versus frequency magnitudes (b)

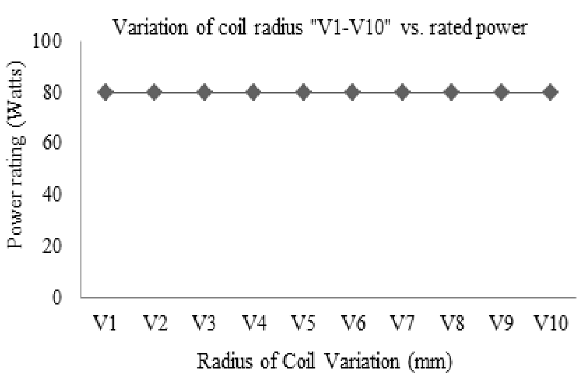


Fig. 12: Output power versus coil variation

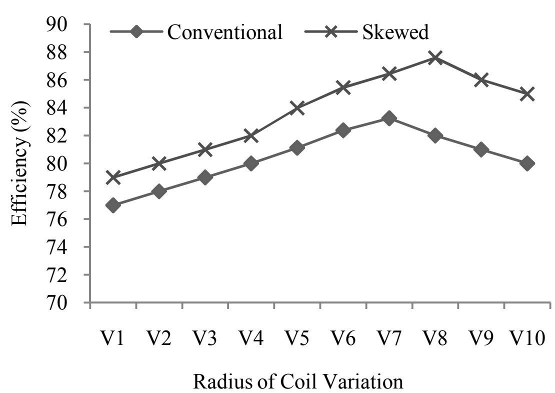


Fig. 13: Efficiency versus coil variation

CONCLUSION

The proposed LG with the novel shape of magnet is modeled and its electromagnetic characteristics are determined by FEA. Firstly, the comparative analysis with conventional shape has been carried out and there after the detailed electromagnetic characteristics with two different modes; stationary and dynamic analysis have been analyzed. The results such as; mesh plot, no-load open-circuit magnetic flux distribution, magnetic flux density, flux-linkage and induced-voltage are presented and explained. The total losses which are main parts of efficiency are examined; heat loss is analyzed on various excitation currents which prove the coil and resistance relationship. Furthermore, iron loss is determined on various frequencies provided by manufacturer data sheet which specifies the frequency and core loss relationship. The efficiency analysis is carried out and compared with conventional with respect to coil variation dimension which identifies that proposed design has higher performance as compared to conventional. The prime value where efficiency is maximum is given.

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