Permanent Magnet Tubular Generator with Quasi-Halbach Array for Free-Piston Generator System

Behrooz Rezaeealam
Departement of Electrical Engineering, Lorestan University

Article Info

Article history:

Received Sep 1, 2017
Revised Sep 22, 2017
Accepted Nov 3, 2017

Keyword:

PM linear generator
Finite element method
Imperialist competitive algorithm

ABSTRACT

In this paper, the performance of a free-piston generator system with tubular single-phase stator winding is investigated for three different configurations of permanent magnet arrays on the mover: radial, rectangular quasi-Halbach and trapezoidal quasi-Halbach arrays. The optimal shape of the rectangular quasi-Halbach magnetization is obtained by employing an optimization technique called Imperialist Competitive Algorithm (ICA), and the results are compared with the previously developed permanent magnet linear generator (PMLG) with magnets of radial magnetization. Then, the resultant design of rectangular quasi-Halbach array, is changed to trapezoidal quasi-Halbach array and its performance is compared with other types of magnet arrays. The employed ICA is based on the analytical model of the magnetic flux distribution in air-gap, and is further verified by a nonlinear transient finite element (FE) model. The FE model has been developed to study the performance of the reciprocating PMLG. The accuracy of the proposed FE model is exemplified by comparing the calculated results with the experimental ones regarding the PMLG with radial magnetization.

Corresponding Author:

Behrooz Rezaeealam,
Departement of Electrical Engineering,
Lorestan University, Khorramabad, Lorestan, Postal code: 68137-17133, IRAN.
Email: rezaee.bh@lu.ac.ir

1. INTRODUCTION

High oil prices have put the environmental friendly cars in the spotlight. Now, many car manufacturers are developing some alternative solutions to the conventional car. A free-piston generator is employed for energy conversion in which an internal combustion engine and a linear electric generator are integrated into a single unit [1,2]. Hence, the crankshaft and the connecting rod are omitted. As the moving parts of the engine are minimized, the flexibility and efficiency of the generator are improved. The free-piston generator is a proper choice for the series hybrid electric vehicles, because the fuel consumption is lower, and thereby, the environmental pollution may decrease. Also, the interesting feature of the free-piston generator is the multi-fuel functioning capability [3].

As the efficiency and power density of PMLG are higher than the ones of induction-type and switched reluctance generators [4,5,6,7], in recent years, several types of PMLG have been developed for free-piston generator system. The PMLG with transverse flux topology has high magnetic flux density, however, it suffers from high leakage flux [6]. The PMLG with radial magnetization that has been employed for free piston generator system [1,2], has a detent force due to the interaction of the mover permanent magnets with the stator core. Generally, the intense detent force adds to the thrust ripple of the PMLG.

The PMLG with quasi-Halbach topology has a self-shielding property and higher flux density than the one with radial topology [8,9]. Furthermore, by replacing the rectangular shaped magnets of quasi-Halbach array with trapezoidal shaped magnets, the average flux density in air gap of tubular actuators is elevated [10]. In literature, optimal design of quasi-Halbach topology has so far been presented based on different modeling techniques including magnetic equivalent circuit with lumped elements, analytical method using Maxwell equations, and finite-element method [11,12].

In this paper, in order to increase the thrust force and output power of the free piston generator system, the optimized PMLG with quasi-Halbach magnetization is employed. At first, optimization of the PMLG is performed using ICA, that is based on the analytical model of the PMLG, and an effective objective function is suggested, regarding the thrust force and the flux density distribution in air gap. Next, the performance of the optimized PMLG with quasi-Halbach magnetization, is investigated using FE method. For this purpose, a 2-D nonlinear transient FE model is developed to consider the reciprocating motion of the mover, by moving mesh techniques. Finally, it is shown that further improvement in the performance of the generator can be achieved by replacing the rectangular magnets of the quasi-Halbach topology with the trapezoidal magnets.

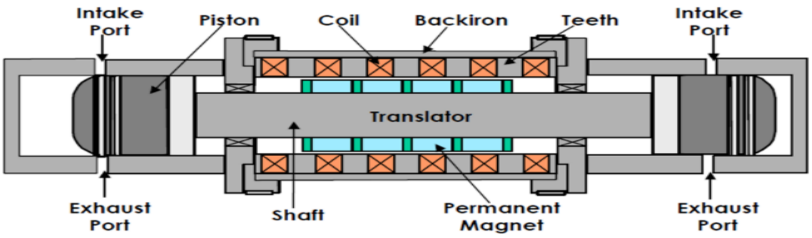


Figure 1. Free piston generator system with a PMLG [1].

2. FREE-PISTON GENERATOR SYSTEM

The employed combustion engine in the system, is a linear, crankless, two stroke engine, as shown in Figure 1 in which two horizontally opposed pistons are fixed on a common connecting rod that oscillates between the two end-mounted cylinders. Ignition happens alternately in each cylinder, driving the piston back and forth. The bore of the engine is 36.5 mm and the maximum stroke length is 50 mm.

The profile of the reciprocating motion of the mover is numerically modeled using the following force balance equation [1]:

$$A_B P_1 \left(\frac{2r}{r+1}\right)^n \left[\left(1+\frac{x}{x_m}\right)^{-n} - \left(1+\frac{x}{x_m}\right)^{-n}\right] = m\ddot{x} \tag{1}$$

where A_B , P_1 , r, x, x_m, n and m are bore area, intake pressure, compression ratio, mover position maximum half stroke, ratio of specific heat and mass of the mover, respectively. The mass of the mover includes the mass of the moving parts of the PMLG.

The PMLG consists of two main parts, a stator and a mover. The stator consists of the armature core and the single-phase windings, and the mover is made up of the PM's with radial magnetization and the shaft on which they are mounted as shown in Figure 1. When the engine is running, the mover of the PMLG reciprocates relative to the stator windings, thereby the distribution of the magnetic field in air gap changes, leading to voltage induction in the stator winding. Thus, the output power could be extracted from the PMLG as the load is connected to the stator windings. The geometric parameters of the PMLG with radial magnetization, are listed in Table 1.

3. PMLG WITH QUASI-HALBACH MAGNETIZATION

Figure 2 shows the PMLG with quasi-Halbach magnetization, besides the one with radial magnetization. In this paper, the radial topology is replaced with the quasi-Halbach topology for reciprocating free-piston generator system.

The distribution of the radial component of the flux density B_r in the air gap along the axial distance z for PMLG with quasi-Halbach magnetization can be expressed as [9,13]:

$$B_r = \sum_{n=1,2,\ldots}^{\infty} \left(a_{In} BI_1(m_n r) + b_{In} BK_1(m_n r)\right) \sin(m_n z) \tag{2}$$

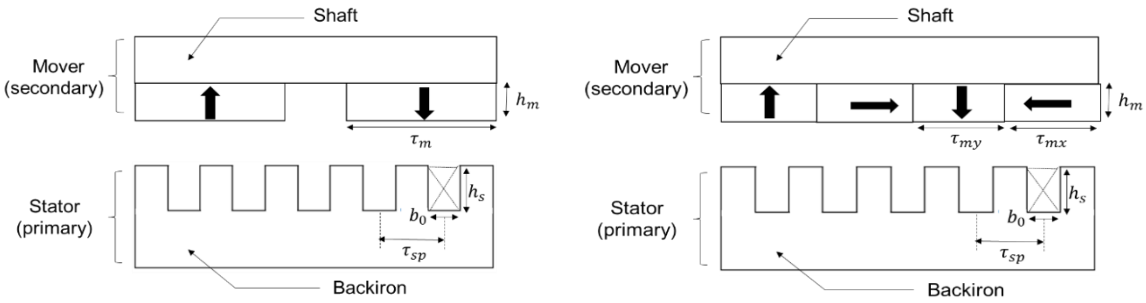
where, $m_n = (2n-1)\pi/\tau_p$ and τ_p is the magnet pole pitch, BI_1 is the modified Bessel function of the first kind of order 1 and BK_1 is the modified Bessel function of the second kind of order 1. a_{In}, b_{In}, a_{IIn}, and b_{IIn} have been described in [13] that also depend on the geometry of the PMLG.

Furthermore, the thrust force resulting from the interaction between the winding current and the permanent magnet field, is given by:

$$F_w = \sum_{n=1,2,\ldots}^{\infty} F_n \sin m_n z \tag{3}$$

Table 1. PMLG parameters

Number of active rotor poles	P	4	Poles
Pole pitch	τ	41.91	mm
Diameter	D	62.865	mm
Number of windings	N_s	296	turns
Magnet Thickness	h_m	18.415	mm
Magnet width	l_w	41.0718	mm
Magnet Gap	w_{mg}	0.4191	mm
Tooth Width	w_t	20.955	mm
Slot Width	w_s	20.955	mm
Back Iron Thickness	h_{bi}	14.7066	mm
Air Gap	g	1.651	mm
Magnet Inner Diameter	ID_m	26.035	mm
Magnet outer Diameter	OD_m	62.865	mm



(a) (b)

Figure 2. PMLG topologies. (a) Radial array. (b) quasi-Halbach array.

where, the harmonic components F_n have been described in [13], and the effective force is defined as:

$$F_{n_{rms}} = \sqrt{\sum_{n=1} F_n^2} \tag{4}$$

4. OPTIMIZATION OF THE PMLG WITH QUASI-HALBACH MAGNETIZATION USING ICA

The PMLG with radial magnetization in [1,2] is considered as the basis for the design of the PMLG with quasi-Halbach magnetization. As depicted in Figure 2, the design variables are the height of magnet (h_m), the width of the magnets (τ_{mx}, τ_{my}), the stator slot pitch (τ_{sp}), width and height of the stator slot (b_0, h_s), and the number of series turns in one slot (N_{sp}) in the PMLG with quasi-Halbach magnetization. The fixed variables are pole pitch τ_p, pole pairs, air gap length, and also, the length and the outer diameter of the generator due to the mechanical constraints in the mover. The pole pitch is considered fixed, because it is set equal to the stroke length of the engine to reduce the harmonic content of the output waveforms, and then:

$$\tau_{my} = \tau_p - \tau_{mx} \tag{5}$$

Now, the optimization technique of ICA is employed to obtain the optimal shape of the PMLG with quasi-Halbach magnetization, by maximizing the flux density in the air gap and also the effective thrust force. For this purpose, the fitness function is defined as follows [14]:

$$FF = \left(\alpha_1 . F_{n_{rms}} + \alpha_2 . B_{rI}\right)_{(x_1,\dots,x_n)} \tag{6}$$

where $x_1, \dots, x_n$ are design variables, and $\alpha_1 + \alpha_2 = 1$, that the index weights of 0.6 and 0.4 are considered for α_1 and α_2, respectively.

The ICA is employed to search for the maximum value of *FF*. The ICA provides a random search method to get the overall optimal solution in a complex multi-dimensional search space. In this algorithm, the number of population is equal to the number of countries. Every country has an array of variables that is defined as follows:

$$country = [h_m, \tau_{mx}, \tau_{sp}, b_0, h_s, N_{sp}] \tag{7}$$

In order to start the algorithm, some of this population should be created. Thus the total population matrix is created randomly. The total population matrix is defined as follows:

$$COUNTRY = \begin{bmatrix} country_1 \\ country_2 \\ . \\ . \\ . \\ country_{N_{country}} \end{bmatrix} = \begin{bmatrix} h_{m_1} & \tau_{mx_1} & \tau_{sp_1} & b_{0_1} & h_{s_1} & N_{sp_1} \\ h_{m_2} & \tau_{mx_2} & \tau_{sp_2} & b_{0_2} & h_{s_2} & N_{sp_2} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ h_{m_{N_{country}}} & \tau_{mx_{N_{country}}} & \tau_{sp_{N_{country}}} & b_{0_{N_{country}}} & h_{s_{N_{country}}} & N_{sp_{N_{country}}} \end{bmatrix} \tag{8}$$

The costs of the countries are defined as follows:

$$cost_i = f(country_i) = f(h_m, \tau_{mx}, \tau_{sp}, b_0, h_s, N_{sp}) \tag{9}$$

The objective function is defined as (6) for increasing the thrust force and the flux density. As illustrated in Figure 3, the ICA with parameters listed in Table 2, is employed to search for the optimal design. The optimal design is described by the resultant values for the parameters listed in Table 3.

Table 2. ICA parameters.

symbol	Quantity	value
n_{pop}	Number of countries	500
n_{imp}	Number of imperials	10
n_{var}	Number of unknown variables	4
n_{dec}	Number of decades	500

Table 3. Specification of optimal designed generator.

parameter	optimal
h_m	18.415 [mm]
τ_{mx}	16.428 [mm]
τ_{my}	24.64 [mm]
h_s	14.706 [mm]
b_0	20.955 [mm]
τ_{sp}	41.91 [mm]
N_{sp}	39 [turns]

5. TRANSIENT FINITE ELEMENT MODELING

In this section, the PMLG with radial array described in [1,2] and also, the one with quasi-Halbach array structure are simulated using time-stepping transient FEM. The Multiphysics finite element package COMSOL considers the relative movement between the translator and the stator using moving mesh techniques [15]. The stator mesh remains fixed and is connected to the moving translator mesh. The shapes of the generator changes during the solving process and the new mesh is obtained according to the new shape of the generator. Figure 4 shows the triangular mesh for initial position of the translator and also at the moment when the translator reaches its end position.

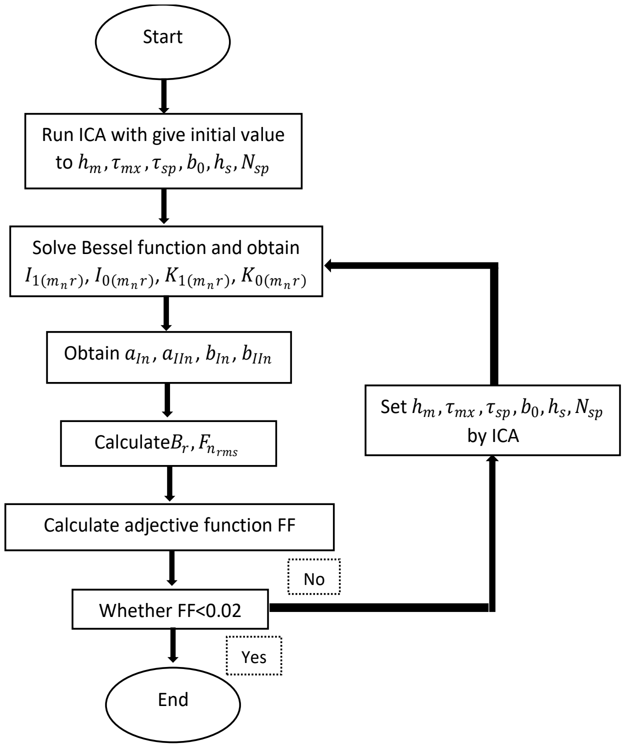
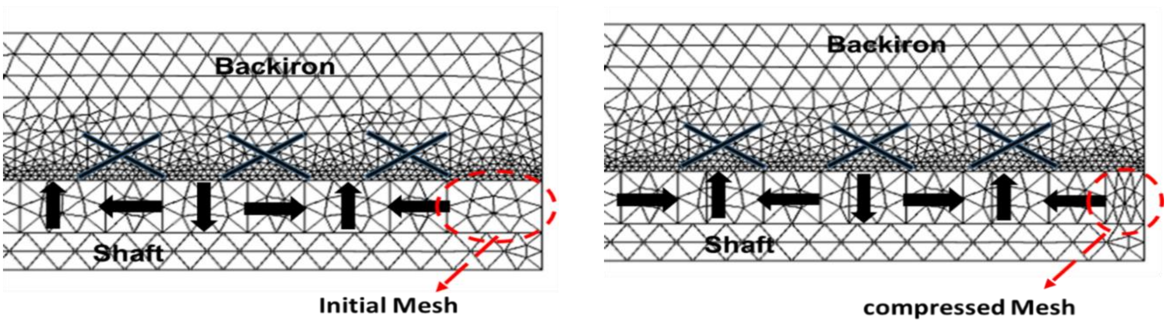


Figure 3. ICA flowchart.



(a) (b)

Figure 4. The triangular mesh: (a) initial position of the translator (b) the moment at which the translator reaches its end position

The finite element model of the optimized PMLG with quasi-Halbach array is shown in Figure 5 that illustrates the distribution of magnetic flux density inside the generator. The quasi-Halbach topology has a self-shielding property and higher flux density in the air-gap region in comparison to the radial topology as shown in Figure 6. Also, the distribution of magnetic flux density is more uniform inside the generator with quasi-Halbach topology.

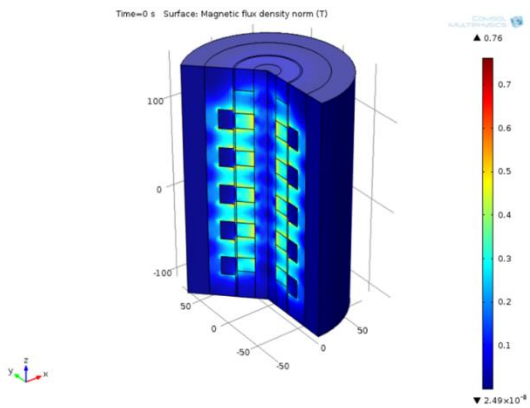
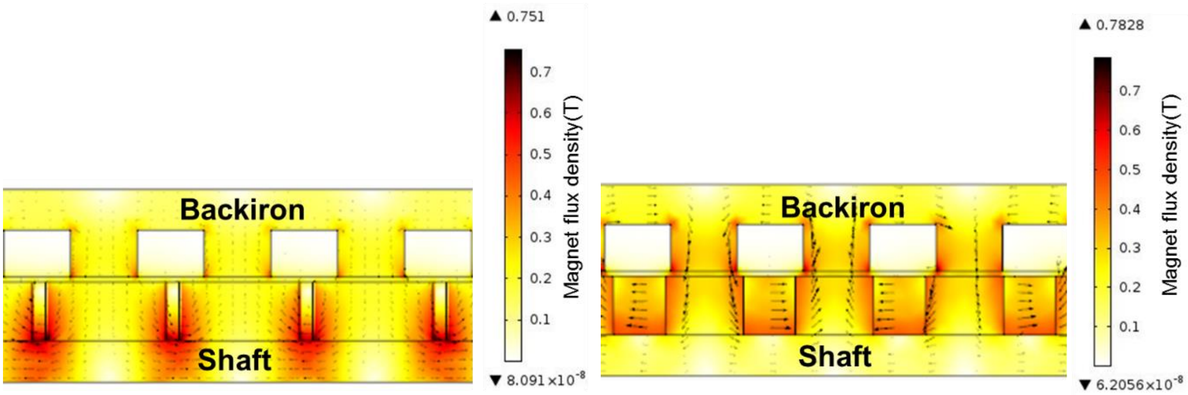


Figure 5. 3D view of the magnetic flux density distribution in PMLG



(a) (b)

Figure 6. Flux density distribution in the generators: (a) Radial array. (b) quasi-Halbach array.

The design optimization in this work was carried out based on the analytical model of the machine presented in Section 4. As the validity of the design optimization greatly depends on the accuracy of the model, therefore, for the purpose of comparison, the magnetic flux density distribution as a function of position along the air-gap is depicted in Figure 7 for the PMLG with quasi-Halbach array, that has been calculated using analytical equation of (2) and also using the finite element model of the generator, which demonstrates good agreement between them.

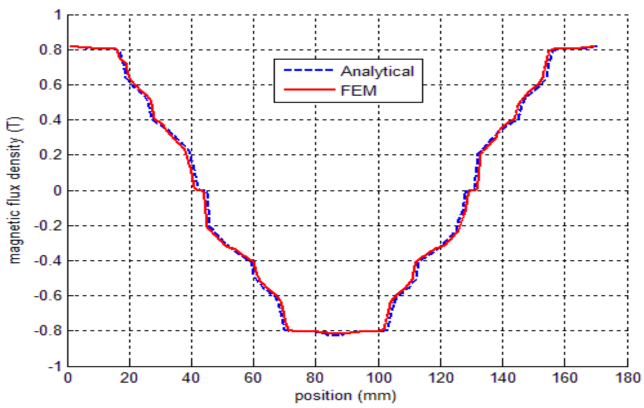


Figure 7. Comparison between analytically predicted and FEM calculated distributions of the flux density in air gap of the optimized PMLG with quasi-Halbach array.

Figure 8 shows the analytical results for the magnetic flux density distribution as a function of position along the air-gap for both generators. Higher magnetic flux density is seen inside the air-gap of the generator with quasi-Halbach array than with radial array. Figure 9 shows the thrust force for radial array and quasi-Halbach array topologies and it is seen that trust force increases effectively in a PMLG with quasi-Halbach array. Figure 10 shows the output power of the generators. For the case of PMLG with radial array, the derived output power from the simulation, matches roughly with the experimental one [1,2], justifying the suitability of the developed transient finite element model. The engine-generator system was capable of supplying a peak power of 315W for radial array [1,2] and, over the same range of load, the PMLG with quasi-Halbach array provides the peak power of 336 W as shown in Figure 10.

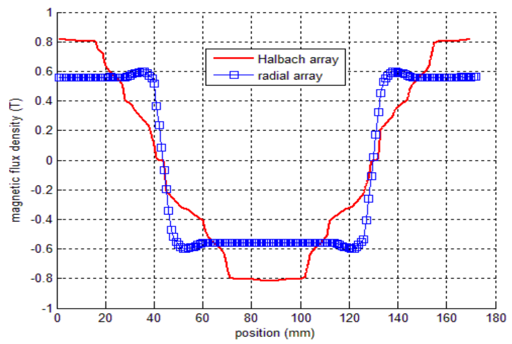


Figure 8. Magnetic flux density distribution in air gap of the PMLG with quasi-Halbach and radial array topologies

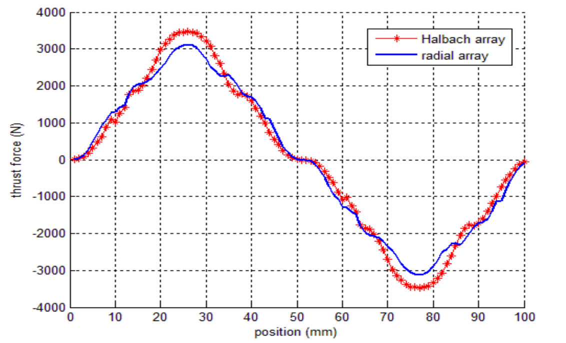


Figure 9. Thrust force waveforms of the radial array and the quasi-Halbach array topologies

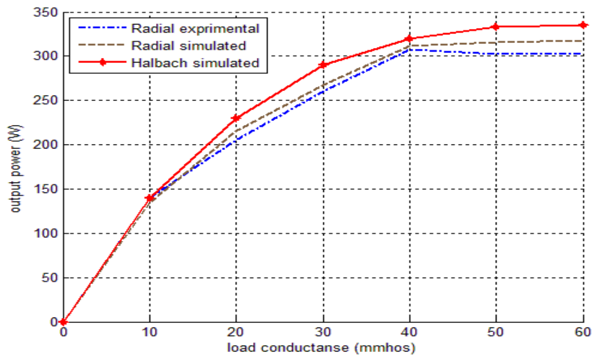


Figure 10. Output power of the PMLG with radial and quasi-Halbach arrays versus load conductance

6. TRAPEZOIDAL MAGNETS

In the previous section, an analytical model was employed to optimize the design of the quasi-Halbach topology with rectangular magnets and also, a finite element model was developed to examine the performance of the generator in more detail. In this section, the finite element model is extended to be able to investigate the influence of the angle α_m of the trapezoidal magnet on the performance of the PMLG, as shown in Figure 11.

The flux density distribution in air gap is calculated for several values of the parameter α_m as indicated in Figure 12. It is found that the maximum amplitude of flux density inside the air-gap is obtained at $\alpha_m = 110^{\circ}$, however, the highest average value of the flux density is achieved at $\alpha_m = 100^{\circ}$. Furthermore, Figure 13 shows the output power of PMLG with trapezoidal magnets for different values of α_m and, it is noticed that the maximum output power of 359 W is attained with, $\alpha_m = 100^{\circ}$.

As the mover of the PMLG reciprocates, the distribution of the magnetic field varies along the axial direction and therefore the linkage flux of the stator winding varies, leading to the induced back-EMF in the stator winding. Based on the developed finite element model, the back-EMF waveforms of the PMLG are shown in Figure 14, for the three cases of radial, rectangular quasi-Halbach and trapezoidal quasi-Halbach ($\alpha_m = 100^{\circ}$). The results show the performance improvement with trapezoidal magnets.

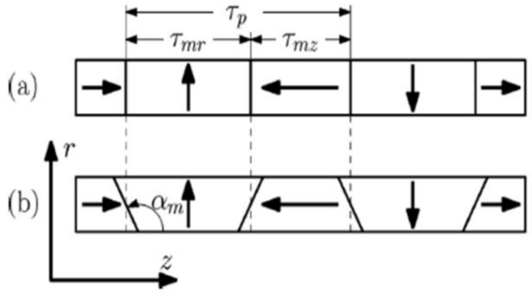


Figure 11. Quasi-Halbach magnetization patterns: (a) Rectangular shaped PM's. (b) Trapezoidal shaped PM's

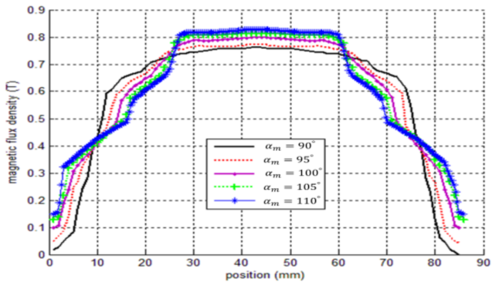


Figure 12. The effect of α_m on the waveform of the radial component of the flux density in air gap

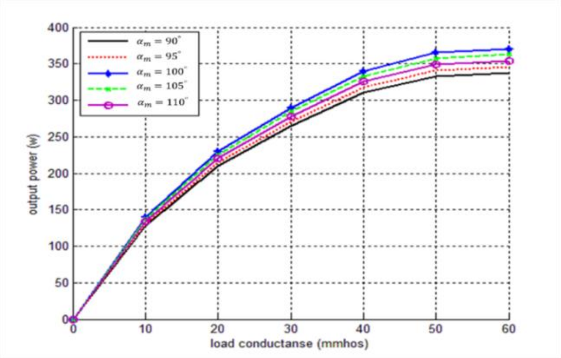


Figure 13. The effect of α_m on the waveform of the output power of the PMLG with trapezoidal magnets

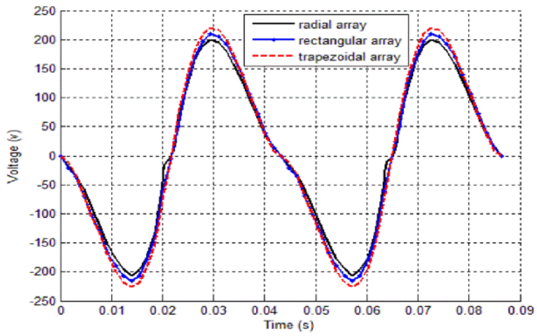


Figure 14. Back EMF waveform of the three generators

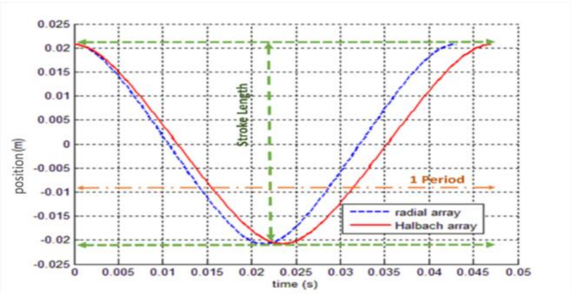


Figure 15. The translator position profile for both designs of radial and quasi-Halbach arrays

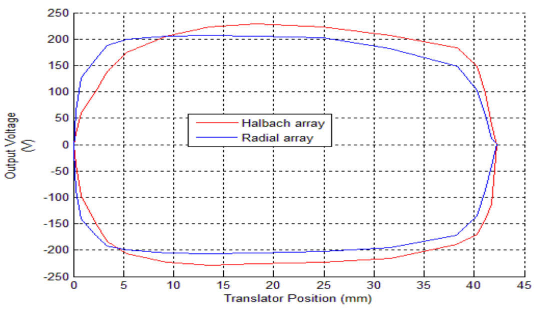


Figure 16. The output voltage versus position

Table 4. Performance of radial array and quasi-halbach array in free piston generator.

	radial array	quasi-Halbach array (Rectangular shape)	quasi-Halbach array (Trapezoidal shape)
Rms force (N)	2208	2465	2632
Voltage (v)	66	74	85
Load power (w)	315	336	359

There is a gap between the magnets with radial array as illustrated in Figure 2, while the magnets are bonded together with quasi-Halbach array. Because of this, the translator with quasi-Halbach array is heavier than the one with radial array. Hence, the reciprocating frequency of the translator with quasi-Halbach array (21.27 Hz) is slightly lower than the one with radial array (23.53 Hz) [1]. The profiles of translator position are shown in Figure 15 for both cases of radial and quasi-Halbach arrays. It is worth mentioning that the translators with quasi-Halbach array with either rectangular or trapezoidal shapes have the same weight. Also, the output voltage versus position is shown in Figure 16 for both cases of radial and quasi-Halbach arrays. The increase in the output voltage of the PMLG is seen in the sequence: radial, rectangular quasi-Halbach, trapezoidal quasi-Halbach.

7. CONCLUSIONS

In this paper, PMLG with rectangular and trapezoidal quasi-Halbach magnet arrays were proposed for free-piston generator system. The ICA was employed to optimize the shape of the rectangular quasi-Halbach array, based on the corresponding analytical model for the air gap magnetic flux density distribution and thrust force. Also, a transient FE model was developed by which the performance of the reciprocating PMLG was examined by incorporating moving mesh techniques. The results from the proposed numerical model of the PMLG with radial array were in good agreement with experiments.

In addition, the rectangular quasi-Halbach array was changed to trapezoidal quasi-Halbach array, and the performances of the three mentioned PMLG were compared as shown in Table 4. The results show a performance enhancement of the PMLG with quasi-Halbach trapezoidal magnets compared to the PMLG with radial magnetized topology, by increasing the output power up to 13%.

REFERENCES

[1] Cawthorne WR. *Optimization of a brushless permanent magnet linear alternator for use with a linear internal combustion engine* (Doctoral dissertation, West Virginia University Libraries).

[2] W. R. Cawthorne, P. Famouri, J. Chen, N. N. Clark, T. I. McDaniel, R. J. Atkinson, S. Nandkumar, C. M. Atkinson, and S. Petreanu, "Development of a linear alternator-engine for hybrid electric vehicle applications," *IEEE Transactions on vehicular technology*, vol. 48, pp. 1797–1802, 1999.

[3] Van Blarigan P. Advanced internal combustion engine research. DOE Hydrogen Program Review NREL/CP-570-28890. 2000:1-9.

[4] J. Faiz, B. Rezaeealam, and S Yamada, "Reciprocating flux concentrated induction generator for free-piston generator," *IEEE Transactions on Magnetics*, vol. 42, no. 9, pp. 2172-2178, September. 2006.

[5] J. Faiz, B. Rezaeealam, and S Yamada, "Coupled finite-element/boundary-element analysis of a reciprocating Self excited induction generator in a harmonic domain," *IEEE Transactions on Magnetics*, vol. 41, no. 11, pp. 4250-4256, November. 2005.

[6] W. M. Arshad, P. Thelin, T. Backstrom and C. Sadarangani, "Use of transverse-flux machines in a free-piston generator," *IEEE Transactions on Industry Applications*, vol. 40, no. 4, pp. 1092-1100, 2004.

[7] Y. Li, M. Jian, Y. Qiang and L. Jiangyu, "A novel direct torque control permanent magnet synchronous motor drive used in electrical vehicle," *International Journal of Power Electronics and Drive Systems*, vol. 1, no. 2, p.129-138, 2011.

[8] D. L. Trumper, W. J. Kim, and M. E. Williams, "Design and analysis framework for permanent-magnet machines," *IEEE Transactions on Industry Applications*, vol. 32, pp. 371–379, April. 1996.

[9] J. Wang, and D. Howe, "Tubular Modular Permanent-Magnet Machines Equipped With Quasi-Halbach Magnetized Magnets—Part I: Magnetic Field Distribution, EMF, and Thrust Force,'' *IEEE Transactions on Magnetics*, vol. 41, no. 9, pp. 2470-2478, september. 2005.

[10] K. J. Meessen, B. L. J. Gysen, Johannes J. H. Paulides, and Elena A. Lomonova, "Halbach permanent magnet shape selection for slotless tubular actuators," *IEEE Transactions on Magnetics*, vol. 44, no. 11, pp. 4305-4308, November. 2008.

[11] S. Vaez-Zadeh and A. H. Isfahani, "Enhanced modeling of linear permanent-magnet synchronous motors," *IEEE Transactions on Magnetics*, vol. 43, no. 1, pp. 746-749, January. 2007.

[12] L. Jinghui, Z. Xiaofeng, Q. Mingzhong and L. Geng, "Multifield Coupling Analysis of Integrated Motor Propulsor," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 10, no. 7, pp.1897-1903, 2012.
[13] J. Wang, W. Jewell and D. Howe, "A General Framework for the Analysis and Design of Tubular Linear Permanent Magnet Machines," *IEEE Transactions on Magnetics*, vol. 35, no. 3, pp. 1986-2000, MAY 1999
[14] M. Bashiri and M. Bagheri, "Using imperialist competitive algorithm in optimization of nonlinear multiple responses," *International Journal of Industrial Engineering & Production Research*, vol. 24, no 3. pp. 229-235, September 2013.