International Journal of Mechanical and Production
Engineering Research and Development (IJMPERD)
ISSN (P): 2249–6890; ISSN (E): 2249–8001
Vol. 10, Issue 6, Dec 2020, 461–470

DEVELOPMENT OF A LINEAR PERMANENT MAGNET GENERATOR TOPOLOGY FOR LOW POWER THROUGH FINITE ELEMENTS

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ABSTRACT

One of the main problems of linear generators is that due to the low speed of translation of their moving part, in order to generate large powers the machine must withstand great efforts which leads to very large devices, therefore, through the use of multiple Medium-power devices instead of a low number of high-power devices, a more suitable waveform is achieved for their integration into the network [1]. In this article, two different linear generator topologies are proposed with characteristics obtained from a compilation of scientific literature, the parameters taken into account for the design and their respective modeling are presented through 2D simulations in COMSOL, as a contribution to the research project TOPOLOGIES OF LOW POWER WIND GENERATOR. The results obtained highlight the second of the proposed topologies, being the one with the best behavior under load, a cleaner terminal signal and greater power output in the face of variations in the magnitude of the load.

KEYWORDS: Linear generator, Magnetic flux, Permanent Magnets, Finite elements, Simulation

Original Article

Received: Nov 18, 2020; **Accepted:** Dec 09, 2020; **Published:** Dec 23, 2020; **Paper Id.:** IJMPERDDEC202051

I. INTRODUCTION

The development of high-efficiencygenerationdevices for low-power applications is important, given the versatility they can have and their ability to be coupled to renewable technologies, such as wind turbines or buoys at sea, to power smallloads but fundamental, such as telemetry [2, 3]. A low power linear generator will be more compact, smaller in size and will have a lighter and simpler mechanical system, accompanied by high efficiency and high power density depending on the geometry used [4-7].

A flat lineargenerator (figure 1) has the most basic and simple geometry of this type of machine, it increases the magnetic flux in the coils by optimizing their shape and reducing the distance between them and the permanent magnet. Planar geometry generators commonly use high-grade ferromagnetic cores, as they reduce coreloss and reduceheatgeneration. Optimal geometry design is essential for good efficiency. [6, 8-10].

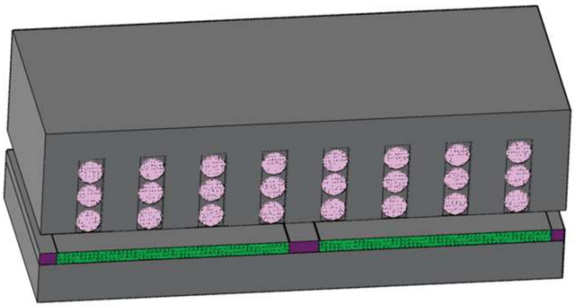


Figure 1: Linear permanent magnet generator flat [Own Elaboration].

Different configurations oflinearpermanent magnetgenerators have been developed so far, a study carried out in [11] performs a classification of the topologies addressed so far, classifying them according to the aspect that is sought to improve in the generator and / or the problem that is being solved, in table 1 the result is observed.

Table 1: Classification of topologies according to their approach [11].

Classification	**Subdivision**	**Aspect that is improved**	**Aspect to consider**
Thought in geometry	• lat • ubular • ultilateral	Dispersion fluxes and efficiency	Construction time and costs
Thought in the location of magnets and coils	• oving coil • oving magnets	Response time and efficiency.	Effective cooling and moving mass.
Thought in the air gap	• arge magnets • mall magnets	Magnetic flux density in the air gap	Attraction force between magnets
Thought about the cogging effect	• f slotted armor • f armature without slots	Harmonics, braking torque, efficiency and cogging effect	Flux density quantity
Thought in the Stator-Traslator relationship	• hort movable stator • ixed short stator • hort movable translator • ilateral with external traslator • ilateral with internal translator	Active surface of the stator-traslator interaction and power density	Construction cost, Joule losses and End effect
Thought in the arrangemen	•	Efficiency, power and machine load angle	Total mass of magnets, transients

Classification	Subdivision	Aspect that is improved	Aspect to consider
t of the magnets	tacked layout ● urface disposition		and short circuits
Thought in magnetization patterns	● adial ● xial ● albach ● uasi-Halbach	Flux density, harmonic distortion and power output	Distance between the end points of each magnet (leakage fluxes)
Thought in the concatenation of the magnetic flux	● ongitudinal flux ● ross flux ● ir core	Dispersion fluxes and rated power per air gap area	Simple construction, magnitude of synchronous reactance, thrust fluctuations and need for compensation

The same topology can bring together several aspects of the different classifications previously exposed, which allows not only to improve a single aspect or to solve a single problem in the machine, it opens a range of possibilities for new designs allowing a certain degree of flexibility when proposing a new topology. When determining the topology to be worked on, it is necessary to bear in mind that what is mainly being sought is a machine with the best possible characteristics and with mechanical forces in the range of those required so as not to compromise the operation of the generator.

For design calculations, electromagnetic theory is used to determine essential aspects, such as the minimum cross-sectional area that the conductor must have to withstand the maximum current allowed at an established current density for naturally-cooled generators, and the linear load that the generator supports to avoid overstressing the ferromagnetic material. The other calculations are based on the formulas listed in table 2, in order to estimate the electromotive force generated for a speed of 1 m / s, a current density equal to 0.6 T, and unit shape and distribution factors.

Table 2: Design formulas [11, 12].

Variable	Formula	Where
Minimum cross-sectional area of conductor	$A_{C\_minimum} = \frac{I}{Jc}$	I = Maximum allowed current Jc = Current density
Number of turns per coil	$N_{coil} = \frac{F_{ll} * h * W}{Ac}$	F_{ll} = Filling factor h = Groove height W = Groove width Ac = Cross-sectional area of selected conductor
Number of turns per phase	$N_{phase} = C_{phase} * N_{coil}$ $N_{phase} = q * pu * N_{coil}$	N_{coil} = Number of turns per coil C_{phase} = Coils per phase Pu = useful pole pairs q = Slots per pole and phase
Linear load	$L_{linear} = \frac{N_{coil} * I}{\tau}$	N_{coil} = Number of turns per coil I = maximum allowed current

Variable	Formula	Where
		τ = groove pitch
Conductor length	$L_c = (2 * W + 2 * P) * N_{phase}$	W = Groove width P = Groove depth N_{phase} = Number of turns per phase
Resistance per phase	$R_{phase} = L_c * R_c$	L_c = Length of conductor R_c = conductor resistance
EMF generated	$EMF = 2 * k_{ff} * k_d * N_{phase} * V_{maximum} * L_{stator} * B$	k_{ff} = Form factor k_d = Distribution factor $V_{maximum}$ = Maximum speed L_{stator} = Stator length B = Density of magnetic flux in the air gap
Design load resistance	$R_{10w} = \frac{(EMF)^2}{P_{design}} - R_{phase}$	EMF = Electromotive force generated P_{design} = Design Power R_{phase} = Resistance per phase

II. PROPOSED TOPOLOGIES

Emphasizing the space occupied by the linear generator, two bilateral topologies are proposed that allow a better distribution of the generator parts. For the first topology, a bilateral flat iron slotted core generator with moving magnets is proposed, and a concatenation of the magnetic flux longitudinally to obtain a small synchronous reactance. In addition, a stacked arrangement of small magnets is chosen to avoid short circuits and large mechanical stresses, and a Halbach magnetization pattern is used for the longest internal translator.

Since the power generated will be on a small scale, the need to mitigate the cogging effect by reducing the length of the end teeth is not taken into account. Additionally, each external stator will house one coil per phase that is connected in series with the coil of the opposite stator, observing the need for a number of 12 slots as shown in Figure 2.

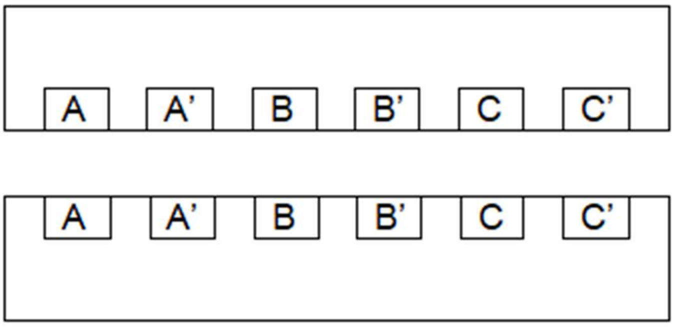


Figure 2: Estator bilateral con devanado de una capa [Ownelaboration].

The expected power is defined at 10 W per phase and the load resistance is estimated at 716 ohms for a generated emf of 84.66 V at a speed of 1 m / s and an air gap of 5 mm, in figure 3 the resulting structure is observed.

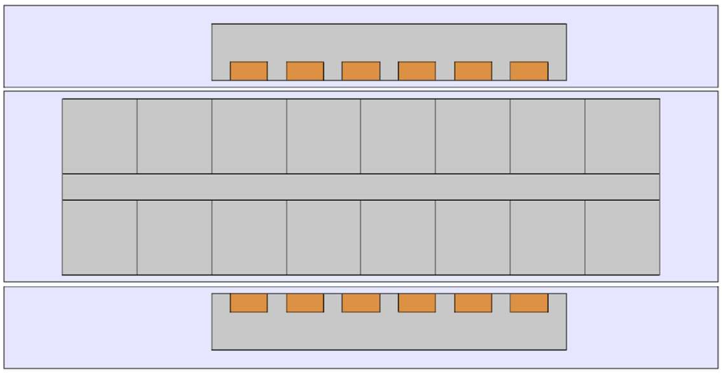


Figure 3: First proposed topology [Own elaboration].

In the same way as in the first topology, the generator will not be designed by shortening the end teeth to reduce the cogging effect, with the difference that an internal stator is chosen that will house two coils per phase connected in series, observing the need for a number of 6 slots for a 3 layer winding as seen in figure 4.

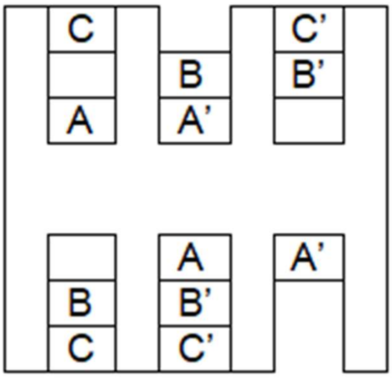


Figure 4: Bilateral stator with three-layer winding and two coils [Own elaboration].

The expected power is defined at 10 W per phase and the load resistance is estimated at 178 ohms for a generated emf of 42.33 V per stator at a speed of 1 m / s and an air gap of 5 mm, in figure 5 the resulting structure.

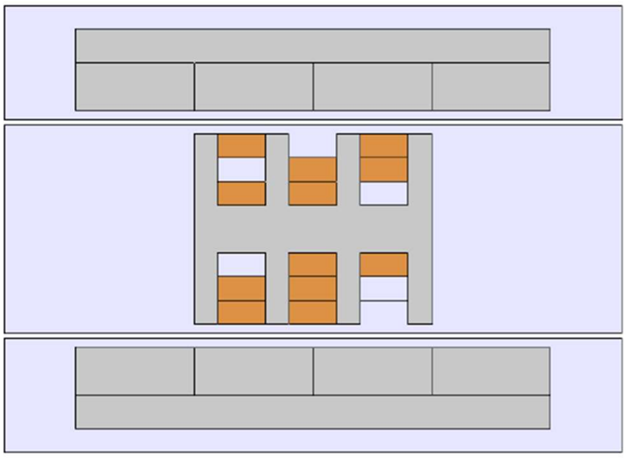


Figure 5: Second topology proposed [Own elaboration].

The dimensions of each topology are shown in Table 3.

Table 3: Dimensions of the proposed topologies [Own elaboration].

Topology	Variable	Quantity	Dimensions
First	Magnets	16	20 x 20 x 40 mm
	Total slots	12	10 x 5 x 40 mm
	Total teeth	14	5 x 5 x 40 mm
	Stators	2	95 x 15 x 40 mm
	Traslators	1	160 x 47 x 40 mm
	Total turns Winding	184	22 AWG
	Load resistance	716Ω	----
	Expected induced voltage	84.66 V	----
	Expected power per phase	10 W	----
Second	Magnets	8	25 x 10 x 40 mm
	Total slots	6	10 x 15 x 40 mm
	Total teeth	8	5 x 15 x 40 mm
	Stators	1	50 x 40 x 40 mm
	Traslators	2	100 x 17 x 40 mm
	Total turns Winding	184	22 AWG
	Load resistance	178Ω	----
	Expected induced voltage	42.33 V	----
	Expected power per phase	10 W	----

III. MODELING WITH FINITE ELEMENTS IN COMSOL

Once the design calculations are finished, the resulting topology is modeled in COMSOL, in order to simulate a movement scenario of the moving part of the generator in which the behavior of the output is observed in no-load and under load, the procedure is repeated making variations in the load and the results of the variation of the output power are recorded. Figure 6 and Figure 7 show the magnetic flux distributions in the generators.

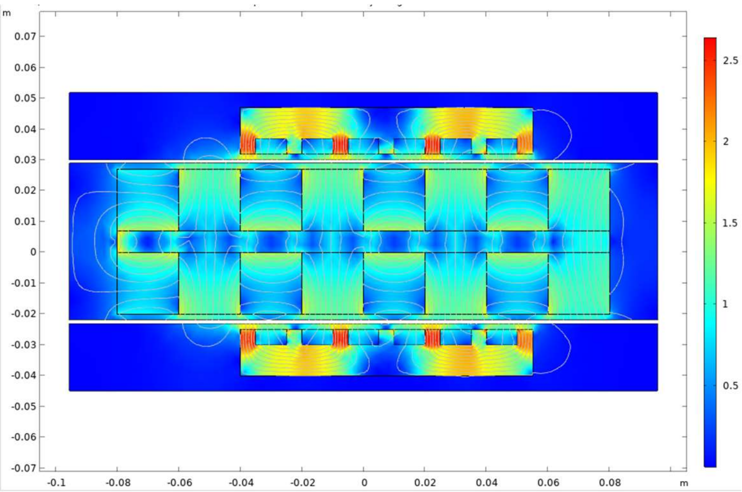


Figure 6: Modeling of first topology [Own elaboration].

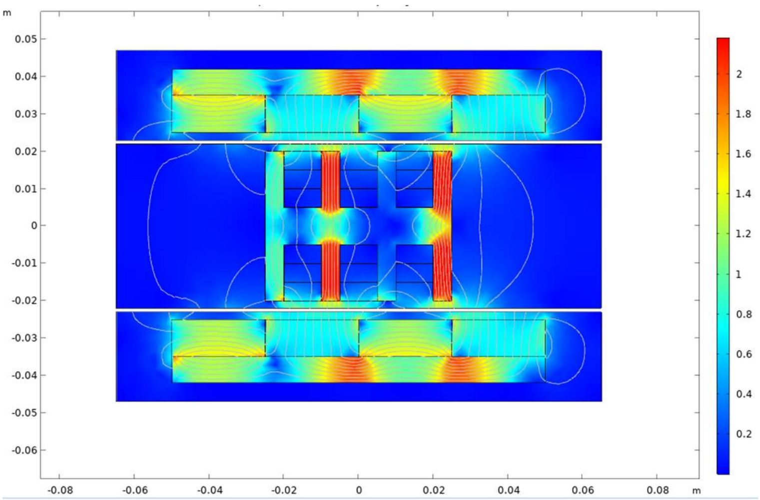
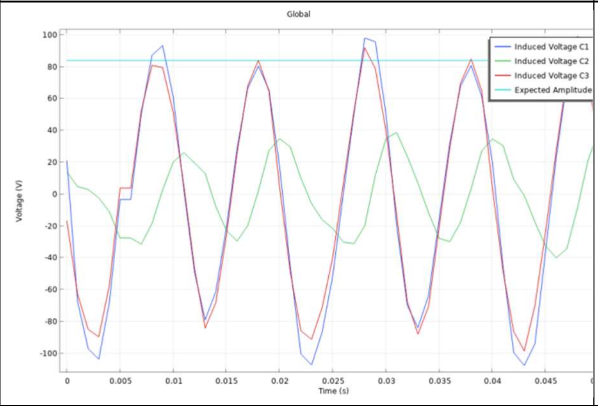
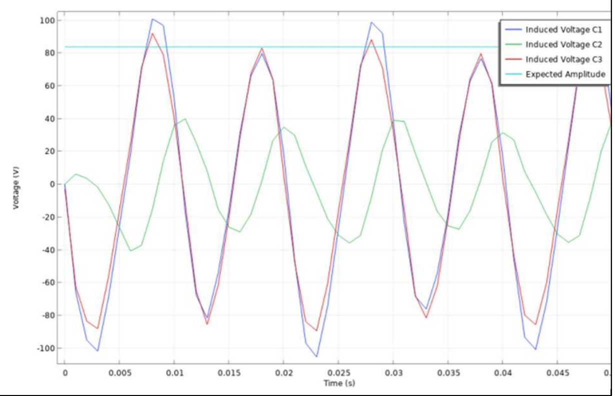
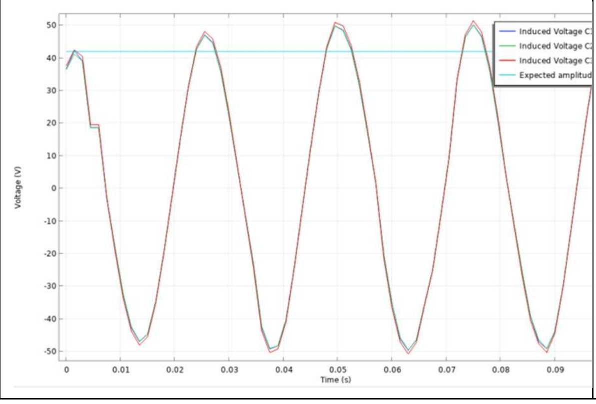
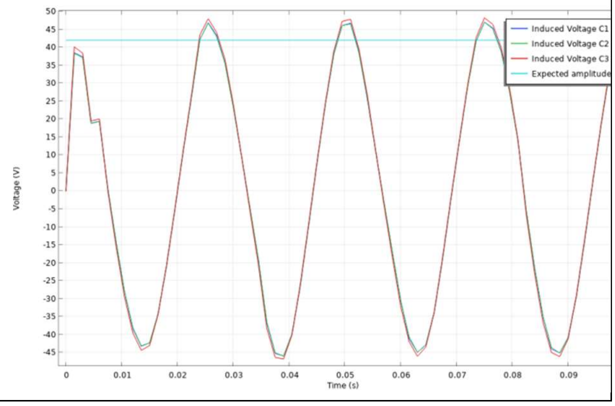


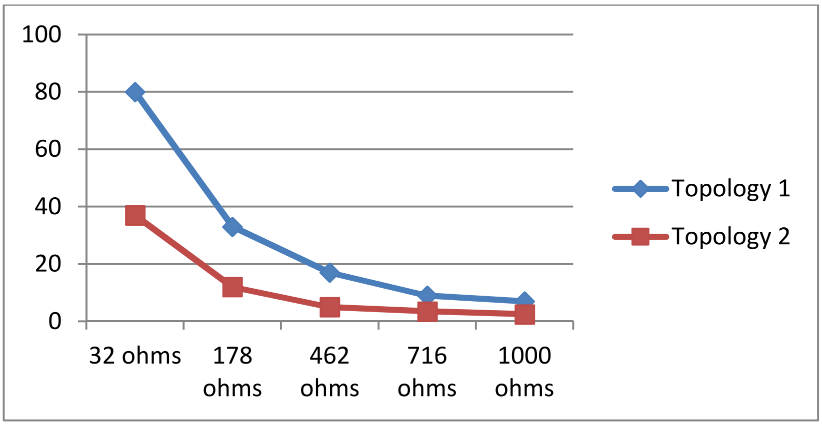
Figure 7: Modeling of second topology [Own elaboration].

Table 4 shows the results of the voltage at the generator terminals for the no-load and under-load scenarios of each of the proposed topologies, the estimated magnitudes of the voltages are plotted as a constant and the simulation times are adapted according to according to the frequency of each generator. It is observed that there is no change in the magnitude of the voltage under load in any of the topologies, however for topology one, phase 2 presents a lower voltage than the estimated one and phase one a greater magnitude than it, somewhat that does not occur in topology two whose phases are not out of phase but have the same magnitude.

Table 4: Results of the modeling with finite elements [Own elaboration]

Top	No-load voltage	Voltage under design load
1		
2		

For the variation of the output power to the change in the load, the results are recorded in graph 1 under different magnitudes in the load, in order to determine the topology that presents the best behavior under these conditions. For this, the average power per phase of each simulation is taken into account, observing a higher power output from topology 1, however, it was observed that the power in this topology is distributed in a greater way in phase one and three. In phase two, in addition to the voltage drop, the power decreases significantly.



Graph 1: Power variation at different loads [Own elaboration].

IV. CONCLUSIONS

The topology that showed the best behaviors in a state under load and when empty was topology two, whose behavior was not affected by variations in load, additionally, the space occupied by it is the smaller of the two proposed topologies, which It gives you additional value in a structural way.

The second topology presents certain dispersion flows that must be taken into account if an efficiency analysis of the generator is made, caused by the distance between each translator and the end effect that characterizes this type of generator.

Despite the fact that the second topology presents a voltage drop in phase two, its applicability can be improved by adapting devices or additional elements for signal processing, which, in the same way, allow correcting the signal lags as in the case of the first topology.

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