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A RESEARCH VISION

Axial generator for a low power wind generator, selection, design and simulation in COMSOL multiphysic

Generador axial para un generador eólico de baja potencia, selección, diseño y simulación en COMSOL multiphysic

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ABSTRACT

Axial flux generators are machines used in wind generation systems, and given the growing interest in small-scale renewable energy, it is required to look for new configurations to address the increase in energy needs globally. This document discusses the selection, design and simulation of three topologies of a dual-rotor permanent axial flux magnet generator for low-speed, low-power (10 watt) applications, which are modeled by applying the finite element method in COMSOL 2D software, as a contribution to the Low Power Wind Generator Topologies research project. Thanks to this method it is possible to optimize the design and observe the density of magnetic flux in the teeth of the stator, air gap and magnetic poles. The results obtained are compared taking as reference the output power generated under the loads of 10, 40,100, 150 and 260 ohms, in addition indicate that topologies 1 and 3 (purely coreless and slotted stator) exhibit better behavior both in no-load and under load, when looking to reduce the weight of the machine implemented a HALBACH type matrix on the magnetic poles of the rotors.

RESUMEN

Los generadores de flujo axial son máquinas utilizadas en sistemas de generación eólica, y dado el creciente interés por las energías renovables a pequeña escala se requiere buscar nuevas configuraciones que permitan enfrentar el aumento de las necesidades energéticas a nivel mundial. En este documento se analiza la selección, diseño y simulación de tres topologías de un generador de imanes permanentes de flujo axial de doble rotor para aplicaciones de baja velocidad y baja potencia (10 watios), las cuales se modelan aplicando el método de elementos finitos en el software COMSOL 2D, como aporte al proyecto de investigación Topologías de Generador Eólico de Baja Potencia, gracias a este método es posible optimizar el diseño y observar la densidad de flujo magnético en los dientes del estator, entrehierro y polos magnéticos. Los resultados obtenidos se comparan tomando como referencia la potencia de salida generada bajo las cargas de 10, 40,100, 150 y 260 ohmios, además indican que las topologías 1 y 3 (puramente sin núcleo y estado ranurado) presentan un mejor comportamiento tanto en vacío como bajo carga, al buscar reducir el peso de la maquina implementado una matriz tipo HALBACH en los polos magnéticos de los rotores.

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1. Introduction

Currently, increasing energy needs requires finding new solutions so that permanent magnet generators can easily supply power by coupling with small-scale wind turbines without suffering voltage accumulation and without running the risk of excitation losses, that is, a permanent magnet generator is a machine that can convert wind kinetic energy into electric power [1]. An alternative to this is the axial flux permanent magnets generator, thanks to its high number of poles and application for low speed [2].

The axial flux permanent magnet double-rotor generator is a machine formed by an axis that passes through the stator and two rotor discs [3], in which the axial magnetic excitation is generated by permanent magnets located in the rotor to produce a magnetic field parallel to the axis of rotation, from this arises the term axial flux [4-6].

The advantages of this generator in wind turbine applications are: better cooling, shorter axial length thanks to its compact and lightweight structure, plus the ability to deliver electric power at low revs, with acceptable efficiency [7, 8], so this work seeks to remove from the rotor disc and reduce the weight of the machine, for this purpose a HALBACH type magnetization matrix is used for permanent magnets of the rotor, in order to design, simulate and compare the three proposed topologies for double rotor generator.

The increasing research on the design and construction of axial flux permanent magnet generators has attracted increasing scientific interest in recent years, however, there are very few studies on low-speed and low-power generators, therefore, this document aims to design and simulate three proposed topologies for an axial flux permanent magnet double-rotor generator for low speed and low power , for this purpose, it is advisable to use finite element programs to refine the design of the machine, avoiding problems of rebuilding it.

2. Topologies of Axial Flux Permanent Magnet Generator

The topologies of an axial flux permanent magnet generator arise from the arrangement and quantity of rotor and stator discs, such as single-sided or one-sided, double-sided or two-sided (two rotors and one stator or two stators and one rotor) and multiple disc [8-11]. These topologies are shown in Figure 1.

Figure 1. Topologies a) Single-sided [12], b) Two-sided [9], c) Multi-disc [12].

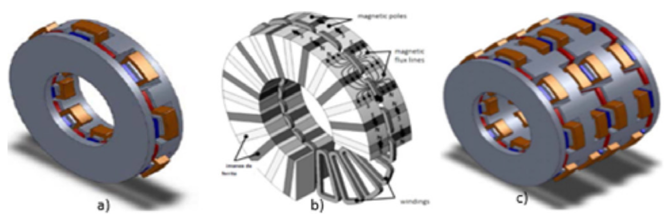


Table 1 exposes and compares the topologies for this generator.

Table 1. Comparison of the topologies of an axial flux permanent magnet generator.

Topology	Single sided	Double sided	Multiple disc
Characteristics	It consists of a stator and a rotor disc, where the coils and magnets are located respectively, this configuration can only have a magnet arrangement with North-South-North-South polarization [6, 8, 13].	This topology consists of three discs, two of which can be stator discs and one rotor, or two rotor discs and one stator [6, 13, 14].	This topology includes two or more stator and rotor discs, which arise from magnetically attaching the dual rotor topology, or double stator [3, 8].
Advantage	The stator or rotor balance configurations have the lowest torque density values [10, 15].	Mechanical forces between rotor and stator are canceled during machine operation due to the presence of double mechanical air spaces in such topologies [8]. The dual rotor configuration has the highest torque density and efficiency [10, 15].	It has high power density without increasing machine diameter and good efficiency [16]. You can connect or disconnect modules depending on temporary requirements that may exist [6].
Disadvantage	There are attractive forces not compensated that occur between the stator and rotor, which implies the requirement of bearings to balance it or an additional balance disc [8]. It is the least efficient due to a smaller number of poles [3, 17].	It has great magnetic attraction force between the permanent magnets of the rotor, either it is located inside the rotor or on the surface [16-20].	Axial magnetic attraction forces between the stators and rotors can cause construction problems, due to the multiple interns between each rotor and stator [7]. It has high magnetic attraction force between all rotor discs [16].

Source: own.

3. Stator configuration

The axial flux permanent magnet generator can also be classified according to the stator configuration and winding topology, as shown in Table 2. Therefore, the stator can be constructed with ferromagnetic material (core type) or with non-magnetic materials (coreless), and a core type stator can be slotted or slotless [7, 11, 13].

Table 2. General features for any topology based on the stator core configuration.

Coreless	Slotted Core
Configuration with higher power density in generation systems [20]. Eliminate the toothed pair [20]. No losses on the stator [21]. Increased reduction on machine weight [20, 21]. There is no direct attraction between the rotor and a stator [14, 22]. The windings of the stator will not be influenced by the heating of the core, in addition, the winding when in contact with the air, can be removed more quickly from the surface [20]. It has greater ease of construction [2]. It has a high power/size ratio [14, 22, 23].	It has flux ripple, high gear torque and high losses in the stator tooth [1]. It is the most economical topology of all [8]. Reducing the air space of the machine, as a result the required number of magnets is reduced and, therefore, the price of the generator [8]. Better heat dissipation thanks to the slotted, caused by friction between the stator and the magnet [24].
	Eliminates tooth torque losses, but has higher eddy current losses [24]. Heat caused by friction between a magnet with a magnet accumulates in the stator [24]. Eliminates slotted torque, so there is no vibration caused by slotted [25]. The value of the air gap determines the effectiveness of a slotless generator design [26].
	Slotless Core

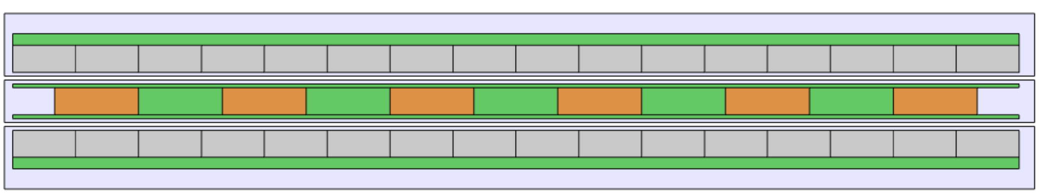
Source: own.

4. Proposed topologies

Referencing the information in Table 1 and Table 2, it is noted that the generator that best suits low-speed and/or low-power applications is the double-rotor topology, so 3 variations are analyzed for this configuration in the present section. It is important to note that all 3 topologies are designed with a HALBACH-type matrix for the arrangement of permanent neodymium magnets on rotor discs in order to reduce the total weight of the generator by removing iron in it:

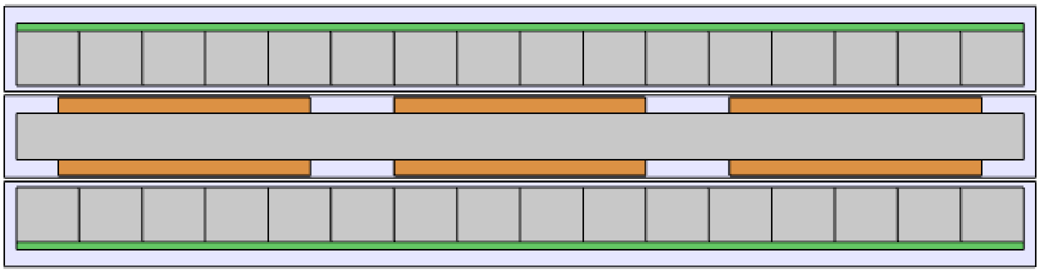
The first topology is a purely coreless configuration, that is, all discs are designed with non-magnetic materials (both ironless rotors and the coreless stator with epoxy material). This is an advantage, eliminating core losses in the stator, toothed torque and gear torque, and greater efficiency in low power applications. To facilitate the distribution of coils in the rotor, concentrated trapezoidal windings are used to achieve greater flux link and symmetrical distribution in the generator circumference. This configuration is shown in Figure 2:

Figure 2. First proposed topology 2D view [27].



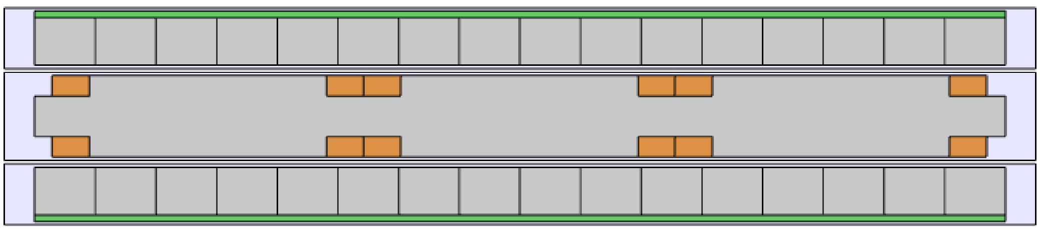
The second topology is a slotless TORUS configuration shown in Figure 3, ensuring good ventilation for the machine, despite needing more air space for the accommodation of the toroidal winding around the stator core, there is also a space between them for fixing purposes:

Figure 3. Second proposed topology 2D view [27].



The third topology consists of a slotted stator, with short end tooth, so concentrated pole windings are used, as shown in Figure 4, this allows for a possible increase in power density in the generator's stator by reducing air space thanks to the type of stator core and windings used.

Figure 4. Third proposed topology 2D view [27].



5. Design of topologies

The main parameters for sizing a double-sided generator are [2, 9]:

- The outer and inner diameter of the rotor,
- Number of poles,
- Number of coils,
- Number of turns per phase,
- Number of turns per coil,
- Polar step
- Number of revolutions,
- Output power,
- Magnetic flux density and
- Output voltage
- Number of slotted per phase
- Wide and high the tooth

Within the design, it is important to take into account the relationship between poles and coils for suitable choice of them in application for low power and low speed, in addition, the value of the air gap, since this can determine the effectiveness of the generator especially in topologies with slotless stator [2,10,27].

The design of the topologies described in paragraph 4 refers to a maximum output power of 10 watts, a minimum wind speed of 1.8 m/s, and a maximum rotor outer diameter of 300mm. Table 3 shows the steps to follow for design, it is important to note that purely coreless and TORUS topologies use steps 1 to10 for their design, while the slotted stator applies steps 1 to 15 in addition to taking into account the cross-sectional area of the selected cable, for this case it is 22 AWG (0.326mm2):

Table 3. Design steps [27].

Step	Variable	Ecuation	Where
1	An outer diameter value of ≤ 300mm is chosen. The outer diameter value determines the inner diameter [28, 29]:	$\lambda = \frac{D_{inner}}{D_{outer}} \simeq \frac{1}{\sqrt{3}}$	λ: ratio factor D_{inner}: inner diameter D_{outer}: outer diameter
2	A number of poles are chosen for the machine design which must be an even number.	p	p:# polos
3	The number of coils for the stator is determined [9, 30, 31]:	$N_c = \frac{3}{4}(p)$	N_C: total number of coils
4	The number of coils per phase is determined.	$N_{CP} = \frac{N_C}{m}$	N_{CP}: coils per phase m=3, three phases
5	With the number of poles the polar step is calculated	$P_P = \frac{360°}{p}$	Pp: polar pass
6	Since the rotor has an outer diameter and an inner diameter the polar pitch, it is calculated for both the inner and outer diameters.	$P_{protor} = P_P * \frac{\pi}{180°} * \frac{D_{rotor}}{2}$	P_{rotor}: polar pitch depending on the internal or external diameter
7	The working frequency for the generator is determined [28, 31, 32].	$f = \frac{N_s * \#pp}{60}$	f: frequency N_s: synchronous speed #pp: pairs of poles
8	The maximum flux $\phi_{máx}$ is calculated at the magnetic poles.	$\phi_{máx} = B_{mg} * A_m$	B_{mg}: magnetic flux density A_m: area
9	The equation is used to determine the number of turns per coil per phase. The winding factor K_w is equal to 1, due to the type of winding and stator used for the proposed topology.	$N_{CP} = \frac{E_p}{4{,}44 * f * K_w * Ø_{máx}}$	N_{CP}: number of turns per phase E_p: induced phase voltage K_w: winding factor
10	The number of turns per coil is determined	$N_{tc} = \frac{N_{CP}}{3}$	N_{tc}: number of turns per coil
11	The number of slotted per phase and pole is determined	$q = \frac{s}{p * m}$	s: total # of slots m=3
12	The coil occupation area is calculated.	$A = N_{tc} * 0{,}326\text{mm}^2$	A: coil occupation area
13	Taking a fill factor of 0.7, an area larger than that calculated for accommodation of winding in the stator is chosen. This value chooses the width and height of the slot.	$A_a = 1{,}31 * A$	A_a: coil end occupancy area
14	The total space of slots in a stator is calculated.	$g = s_{wide} * n$	g= total air space s_{wide}: slot width n: total slots
15	The width of the tooth is determined	$d_{wide} = \frac{P_{stator} - E_r}{nn}$	d_{wide}: tooth width P_{stator}: perimeter of the stator nn: total tooth

The 3 topologies are designed with 12 magnetic poles on the rotor and an external rotor diameter of 250 mm, taking into account the final accommodation of the windings of each of the configurations, based on this the

TORUS topology and the configuration of slotted stator are designed with a 240mm stator, finally the expected induced voltage for each of the topologies is 10 volts for purely coreless configuration, 18 volts for TORUS configuration, and 63 volts for slotted stator [27]. Table 4 shows the dimensions obtained for the 3 proposed topologies:

Table 4. Dimensions obtained for the proposed topologies.

Parameter		Dimension Topology 1	Dimension Topology 2	Dimension Topology 3
Rotor outer diameter	D_{outer}	250 mm	250 mm	250 mm
Rotor inner diameter	D_{inner}	140 mm	140 mm	140 mm
Number of poles	$\#\ poles$	12	12	12
Number of coils	N_C	9	9	9
Coils per phase	N_{BP}	3	3	3
Air gap	g	3 mm	3 mm	3 mm
Outer pole passage	Pp_{outer}	65,45 mm	65,45 mm	65,45 mm
Inner pole passage	Pp_{inner}	36,65 mm	36,65 mm	36,65 mm
Synchronous speed	N_s	137,51 rpm	137,51 rpm	137,51 rpm
Frequency	f	13,75 Hz	13,75 Hz	13,75 Hz
Number of turns per phase	N_{CP}	270	525	420
Long IP	IP_{large}	55 mm	55 mm	55 mm
Outdoor wide IP	$IP_{outwide}$	16,36 mm	16,36 mm	16,36 mm
High IP	IP_{high}	7 mm	13 mm	13 mm
Indoor wide IP	IP_{inwide}	9,16 mm	9,16 mm	9,16 mm
High stator	$Stator_{high}$	7 mm	12 mm	12 mm
Stator outer diameter	$D_{outerstator}$	-	240 mm	240 mm
Stator inner diameter	$D_{innerestator}$	-	150 mm	150 mm
Coil height	$Coil_{hihg}$	-	4 mm	6 mm
Slotted width	S_{wide}	-	-	20 mm
High slotted	s_{high}	-	-	6 mm

Source: own.

6. Results

The flux density obtained for the three topologies is shown in Figures 5 to 7. Topology 1 (Figure 5), is the most dispersed flux topology presents.

Topology 2 (Figure 6) shows a decrease in dispersed flux due to the presence of core in the stator, in addition to the previous topology, they have a very close value of flux density between them.

Figure 5. Flux Density Topology 1 [27].

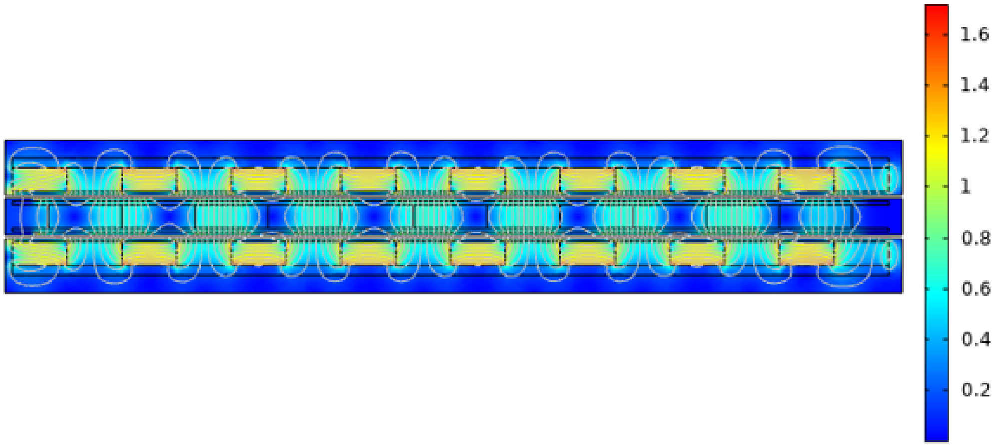


Figure 6. Flux Density Topology 2 [27].

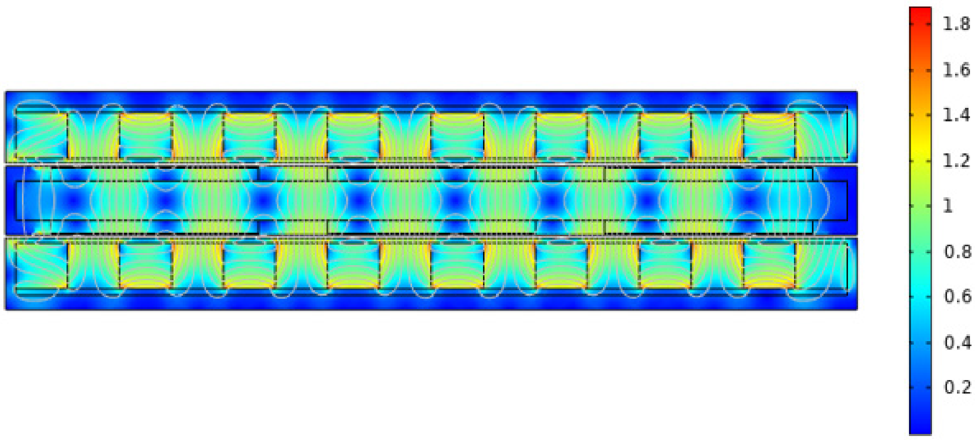
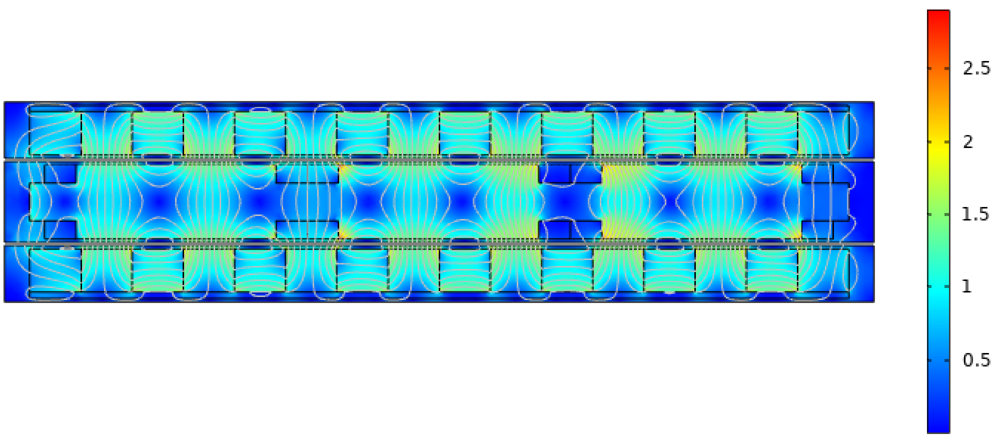


Figure 7. Flux Density Topology 3 [27].



As topology 3 (Figure 7) expected, it has an increase in density compared to the other two.

The behavior analysis of the exposed double rotor topologies was performed by comparing the output voltages first in no-load and then under load. Figure 8 shows the output voltage results for topology 1, in no-load (14 volts) and under a design load of 10 ohms (6 volts).

Figure 8. Topology 1: a) No-load voltage; b) Voltage under design load [27].

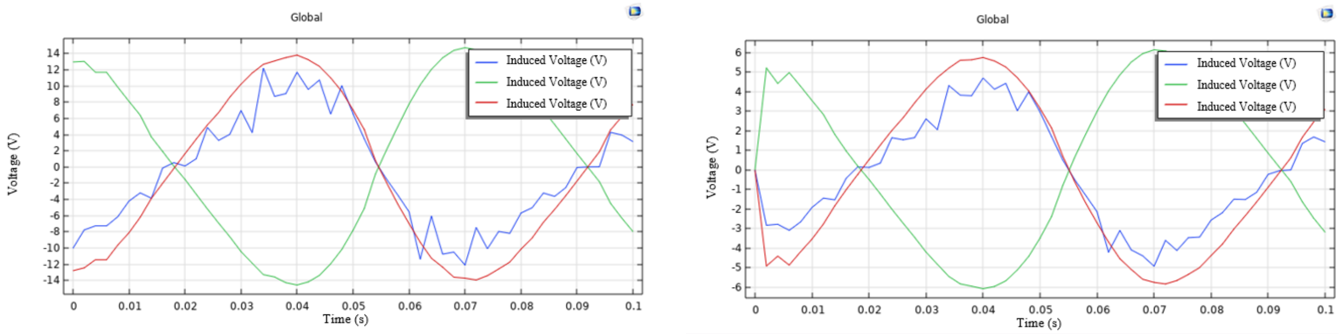


Figure 9 shows the no-load output voltage and under a design load of 40 ohms for topology 2, which are 21 volts and 13 volts respectively.

Figure 10 shows the no- load output voltage and under a design load of 260 ohms for topology 3, which are 60 volts and 58 volts respectively.

Figure 9. Topology 2: a) No-load voltage; b) Voltage under design load [27].

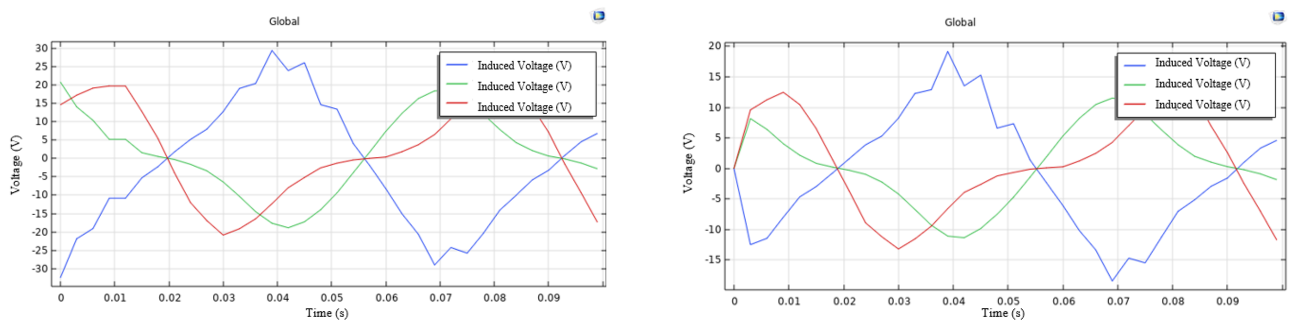
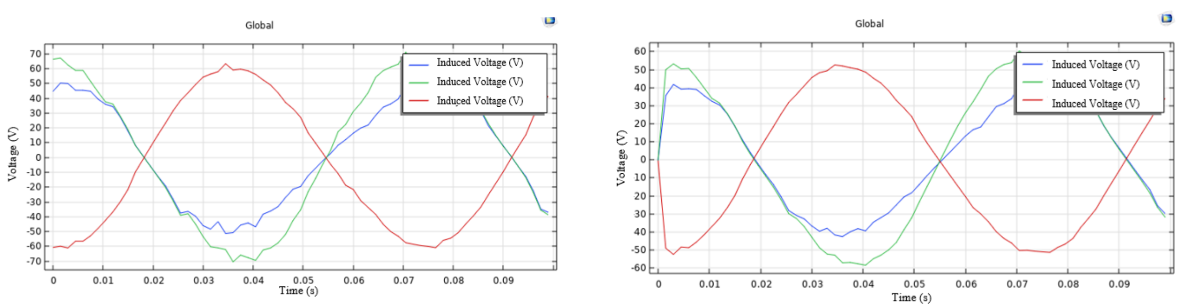


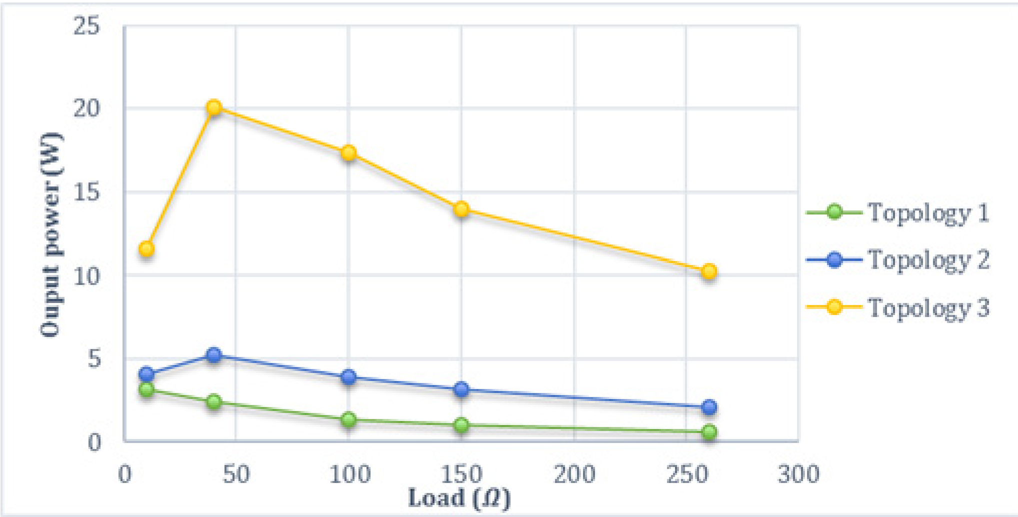
Figure 10. Topology 3: a) No-load voltage; b) Voltage under design load [27].



From Figures 8 to 10, it is analyzed that the three double-rotor topologies have less error in the no-load output voltage relative to the expected voltage for each, this due to the minor difference in value in the no-load output voltage and the expected one. On the other hand, a reduction in output voltage under load, with higher voltage drop in topology 2, is presented for the 3 cases, meaning that topologies 1 and 3 have better behavior for low-speed and low-power applications, further showing a good waveform for both cases.

Figure 11 shows the output power for the three topologies, which shows how to expect topology 3 to have higher output power thanks to design considerations, and in all cases a power reduction as the load increases [33-34].

Figure 11. Comparing powers at different loads [27].



7. Conclusions

The literature proposes the TORUS topology as the most suitable for low-power applications, however, by implementing as a new aspect a HALBACH magnetization matrix, the greatest wave disturbance and deformation compared to other double rotor topologies is presented, in addition, since it has no tooth in the stator, the air space is reduced, which means an increase in the total density of the generator , but does not at the same time show an increase in output voltage, as seen in the short-end tooth slotted stator topology for the same volume of permanent magnets.

A purely coreless design, and slotted stator, presents better behavior and decrease in the presence of undesirable currents, on the contrary, in a slotless design, there is an exposure of the conductors to the flux densities present in the generator, which causes parasitic currents in the duct wires, and is obtained as a result greater loss of copper and core.

Implementing a HALBACH configuration on rotor discs causes increased flux density for all three topologies, allowing for higher output voltage and reduced total machine weight by removing the disc from both rotors.

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