DESIGN AND SIMULATION OF AN AXIAL FLUX PERMANENT MAGNET GENERATOR FOR LOW POWER AND LOW SPEED USING FINITE ELEMENTS

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ABSTRACT

Axial flux generators are machines used in wind power generation systems, therefore, this document presents an analysis of an axial flux permanent magnet generator for low speed and low power. The proposed topology is a purely coreless double rotor generator, with trapezoidal winding, with a Halbach matrix for permanent Neodymium magnets in order to eliminate iron in the rotor discs, and has 12 magnetic poles. The topology design and arrangement of the windings and magnets around the circumference of the disks is described. 2D finite element analysis in COMSOL software is used to simulate the proposed topology, the results obtained show that the purely coreless topology has good performance and can be used for low power and low speed applications.

KEYWORDS: Axial Generator, Double Rotor, Low Power, Low Speed, Finite Elements

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1. INTRODUCTION

Currently, the increase in energy needs requires finding new solutions so that permanent magnet generators can easily supply energy with small-scale wind turbines without suffering voltage accumulation and without running the risk of excitation losses, that is, a generator of permanent magnets is a machine that can convert the kinetic energy of the wind into electrical energy [1].

The axial flux permanent magnet generator (AFPMG) is a machine made up of rotor and stator discs mounted on the same axis that passes through its center [2], in which the excitation is replaced by permanent magnets located on the disc rotor with axial magnetization, for which the term axial flux arises, since when the rotor rotates it produces a magnetic field parallel to the axis of rotation and induces a voltage in the stator windings [3-5].

This type of generators have several advantages compared to other machines, such as a more compact structure, due to a shorter axial length, higher power / weight ratio and torque density, a more flexible magnetic field produced by permanent magnets and better cooling, which makes them more suitable for low-speed wind turbines [6], and various industrial applications, such as the propulsion of ships, and electric vehicles [7].

The increasing research on the design and construction of AFPMG 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 a fully coreless axial flux permanent magnet generator for low speed and low power, for this, it is advisable to use finite element programs to refine the design of the machine, avoiding problems of rebuilding the machine.

2. TOPOLOGIES OF AXIAL FLUX PERMANENT MAGNET GENERATOR

The AFPMG are characterized by the arrangement and quantity of discs, since it allows variations, this means that they have several possibilities of structure in relation to the stator and rotor discs, which results in different topologies [3,8-11]:

- Single sided
- Doublesided: Two rotors and a single stator

TORUS

Rotors variants.

Two stators and a single rotor (AFIR).

- Multidisc

On the other hand, the AFPMG can also be classified according to the type of stator, therefore, the stator can be built with ferromagnetic material (core type), and this can be slotted or slotless, or with non-magnetic materials (coreless) [7,8,11-14].

2.1. Single Sided Generator

The single-sided generator, shown in figure 1a, includes two discs, one is the stator disc and the other is the rotor disc, in which the windings and permanent magnets are placed respectively. The arrangement of the magnets in this topology is North-South-North-South (NSNS) around the circumference of the rotor [3,8,12], as seen in figure 1b.

Figure 1: Single-Sided Generator: a) Topology [3], b) Magnet Arrangement [8].

This configuration is the simplest of all [12], however, it presents a great force of attraction between the magnets of the rotor and stator, causing the displacement of some of the discs, therefore, to prevent this displacement without the need for implement a magnetic bearing, two variants are generated by adding an additional stator or rotor disc, so that the force is balanced [3, 10], which are described in figure 2.

Variant with Stator Balance

Another stator disc is added, to prevent the rotor from moving in the direction parallel to the axis of rotation, and thus introduce an effective way to balance the force of attraction between the discs, for which, it is necessary to put permanent magnets in the opposite side of the rotor, to produce the necessary magnetic field and induce the balancing force [10].

Variant with Rotor Balance

An additional magnet rotor is added to the construction, whereby, the length of the stator must be extended to provide a path for the magnetic field through which the balancing force will be induced. Due to its design characteristics, this construction uses more materials than the variant with stator balanced [10].

Figure 2: Variants with Disc Balance.

2.2. Double Side Generator

The double-sides generator is also called two-side generator, since it is composed of three discs, of which two can be rotor

discs and one stator disc (double rotor), or they can be two stator discs and a rotor disc (double stator), as seen in figure 3. This topology does not present great concern due to the mechanical forces between rotor and stator, since they cancel out during operation, due to the double air gap it makes the total force affecting the internal disks small [8,15,16].

Figure 3: Two-Sided Generator: a) Double Stator b) Double Rotor [3].

2.2.1. Two Rotors and Single Stator.

In this configuration the permanent magnets can be arranged in a NSNS way as mentioned above [8, 12, 13], or in such a way that all the N-pole magnets are on one rotor disc and the S-pole magnets on the other disc. [8], as shown in figure 4:

Figure 4: Rotor Discs with Permanent Magnets: a) NSNS Arrangement, b) N Poles on one Rotor and S Poles on the other [8].

The unique characteristic for this arrangement (N Pole of one rotor faces the S Pole of the other rotor), allows the magnetic flux to pass from one rotor to another crossing the stator thus completing the magnetic circuit, which allows the stator disc have a non-conductive or non-magnetic material, which makes it lighter [2].

It is important to note that this is the most widely accepted topology in low-speed power applications since, due to its configuration, a greater flow is achieved in the air gap, it also requires the lowest mass of permanent magnets, a low starting torque and a low weight [9,17]. Some variations of the double rotor topology are presented in the literature:

2.2.1.1. Toroidal Stator Generator or TORUS

The name TORUS was adopted to indicate the toroidal nature of both the core and the stator winding [18], which can be seen in figure 5.

Figure 5: Generator with Toroidal Stator [19].

The main characteristics of this topology are [10, 18]:

- The rotor discs and magnets naturally act as fans, ensuring good ventilation and cooling of the stator winding, even

at low rotational speed.

- Greater air space, making this configuration the most suitable for low power wind turbine applications.

2.2.1.2. Built-in Radio Type Variants (See Table 1).

This variation arises from replacing the rotor iron with permanent magnets in the form of parallel bars and interleaved pieces of iron, which are the magnetic poles of the rotor. This built-in radio type arrangement allows a higher flux density in the magnetic poles, offers the following benefits and reduces the air gap due to the integration of the magnets in the rotor [6, 20]:

Table 1: Built-in Radio Type Double Rotor Variants

<p>A rotor disc structure with built-in ferrite permanent magnets and interleaved iron pieces is presented, which constitute the magnetic poles of the rotor, thus avoiding the rear iron of the same (figure 6a) [6].</p>	<p>The ferrite magnets and interleaved iron bars are the magnetic poles of the rotor [6]. The only structural change of the rotor resides in the partial cutting of the ferromagnetic core of each rotor pole with the dual purpose of increasing the flux density of the air space and reducing the total weight of the generator (figure 6b) [6,20].</p>	<p>In this structure, each magnetic pole of the rotor consists of five parts (see figure 6c): Two ferrite magnet bars Two pieces of iron intercalated, separated by a central bar of magnet (Neodymium, Iron and Boron) with axial magnetization [6].</p>
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Figure 6: Double Rotor Variants: a) Built-in Radio Type, b) Built-in Radio Hollow type, c) Quasi-Halbach Arrangement [6], [20].

2.2.2. Two Stators and Single Rotor (AFIR)

This topology is also called axial flux internal rotor (AFIR) permanent magnet generator [8]. Its main characteristic is the permanent magnets on both sides of the rotor, which creates a balance between the forces of the stator and the rotor [13]. Furthermore, the windings of both stators must have the same number of coils and turns [10], and their electrical connection can be in parallel to obtain a higher current or in series if a higher voltage is required [13].

2.3. Multidisc Generator (Multi-Stator, Multi-Rotor)

In this case, two or more stator and rotor discs mechanically coupled on the same axis [2,8,14] are included, as shown in figure 7.

Figure 7: Conventional Multi-Stator Multi-Rotor Model [21].

Its main characteristics is the possibility of cascading multiple stages using double rotor or double stator configurations [21], therefore, it is possible to connect or disconnect modules depending on the time requirements that may exist [3]. However, the magnetic attraction forces due to the multiple air gaps between stator and rotor can cause problems in construction [7].

2.4. Stator Configuration

In the above-described topologies, the stator can be of the slotted core, slotless core or coreless type (figure 8).

Slotted Core	Coreless
<p>It has features flux ripple, gear torque, high losses in high frequency rotor and stator teeth [1]. Slotted topologies are cheaper than coreless topologies [8].</p> <p>It reduces the air gap in the machine, thereby increasing the flux density of the air gap and as a result, the number of permanent magnets required is reduced and consequently the price of the generator is reduced [8].</p> <p>A slotted configuration can help diffuse heat caused by stator friction with a magnet, causing it to flow and splitting it into the stator slots [22].</p>	<p>It has several advantages over other topologies, such as easy construction, and a high power / size ratio [5,27,28].</p> <p>Coreless stator topologies have no iron losses in the stator, eliminate toothed torque, machine weight is reduced, and there is no direct axial magnetic attraction between rotor and stator, like core stator topologies [16, 25,26,17].</p> <p>This configuration has high power density [25].</p> <p>The stator windings will not be influenced by the heating of the core and as the surfaces of the windings are in contact with the air it will be able to remove the heat from the surface more quickly [25].</p>
<p>Permanent magnets with slotless stators can eliminate gear torque losses, but it has higher eddy current losses [22].</p> <p>In a non-slotted configuration, the heat caused by friction of the stator with a magnet accumulates in the stator [22].</p> <p>Eliminates slotted torque and vibrations caused by slotted stator [23].</p> <p>In any design without slots, the parameter that determines the effectiveness of the topology is the value of the air gap [24].</p> <p>Slotless core</p>	
<p>Figure 8: General Characteristics for any Topology According to the Stator Core Configuration.</p>	

3. DESIGN OF THE PROPOSED TOPOLOGY

Taking the information in the previous section as a reference, the double rotor topology is chosen due to its characteristics for low speed and low power applications. Therefore, in this document a variant of this topology is proposed. The proposed topology is a purely coreless configuration, that is, a coreless stator, with trapezoidal coils, and an ironless rotor with permanent magnets in Halbach arrangement, this new topology is chosen based on the following aspects:

- In double rotor, due to the proposed arrangement of magnets it is possible to eliminate the iron from the rotor and use an air-core winding, in order to reduce the total weight of the generator.
- For the Halbach type arrangement of the permanent magnets, neodymium magnets are chosen, to allow good ventilation to the new topology with axial magnetization.
- A coreless stator, as it eliminates core losses, toothed torque and gear torque, in addition, the generator becomes lighter.
- Greater efficiency in low power wind turbine applications, by eliminating iron losses, gear torque, and having a

low starting torque.

- Easy fabrication and construction of the topology
- The coils are trapezoidal in shape, to achieve a greater flux, since, by using an air winding, the coil covers the entire pole area, and therefore the winding will be larger than the external diameter of the rotor.
- Concentrated windings are used, as it requires less copper, and improves efficiency by minimizing copper losses.
- As the topology is fully coreless, the outer and inner diameter will be the outer and inner dimensions of the magnet, so the magnet will have a similar trapezoidal shape.

For the design of this topology, the main parameters for sizing are the number of revolutions, output power, number of poles, number of coils, number of turns per coil, outer and inner diameter of the rotor, determination of the magnetic flux, output voltage, and the symmetric distribution of magnets and coils [24, 29]. Another important criterion to take into account in the design is the relationship between poles and coils for their proper choice [26], and the value of the air gap, especially in the case of a stator without slots, since this parameter determines the effectiveness of the generator [24].

In [26, 29] it is proposed that an adequate number of poles is required for correct operation at low wind speeds, in addition, it is possible that both the core and the stator windings are heated, therefore, a way to improve the cooling, is to adjust the air gap distance, the shape of the core [4], or the appropriate combination of poles and grooves [30].

Taking the described parameters as references, the criteria of the machine are a maximum output power of 10 watts, a wind speed of 1.8 m/s and a maximum rotor outer diameter of 300mm. With the value of the outer diameter, the inner diameter is determined (1), with the ratio factor (λ) proposed by [13] :

$$\lambda = \frac{D_{inner}}{D_{outer}} \simeq \frac{1}{\sqrt{3}} \quad (1)$$

A number of poles is chosen for the design of the machine, which must be an even number, and with this the number of coils (N_c) for the stator is determined [21,27,29] :

$$N_c = \frac{3}{4} (\# \text{ poles}) \quad (2)$$

With equation (2) the number of coils per phase, N_{cp} , is determined and $m = 3$ is taken, since the proposed topology is three-phase (3).

$$N_{cp} = \frac{N_c}{m} \quad (3)$$

With the number of poles, the polar step is also calculated with (4)

$$Pp = \frac{360^\circ}{\# \text{ poles}} \quad (4)$$

Since the rotor has an outside diameter and an inside diameter, the pole pitch is calculated with equation (5), for both the inside and outside diameter.

$$P_{protor} = P_p * \frac{\pi}{180^\circ} * \frac{D_{rotor}}{2} \quad (5)$$

Taking into account the synchronous speed ($N_{s,}$, obtained from the wind speed), the outer diameter of the rotor and the number of pairs of poles, the working frequency (f) for the generator is determined [10, 12, 13, twenty-one].

$$f = \frac{N_s \cdot \# \text{ poles}}{120} \quad (6)$$

To determine the number of turns per coil, the equation (7) [17] is used :

$$N = \frac{E_f}{4,44 \cdot f \cdot k_w \cdot \Phi_{max}} \quad (7)$$

The winding factor k_w is equal to 1, due to the type of winding and stator used for the proposed topology. It is known that the maximum flux Φ_{max} at the magnetic poles is, the product between the magnetic flux density and the area:

$$\Phi_{max} = B_{mg} \cdot A_m \quad (8)$$

At the designer's discretion, the air gap distance is chosen in such a way that an induction value is obtained in the east of $B_{mg} = 0,8 \text{ T}$, taking into account that a Halbach matrix will be used for magnetization. With this value, the expected induced voltage (E_f), and replacing equation (8) in (7), the number of turns in the coils is calculated with equation (9).

$$N = \frac{E_f}{4,44 \cdot f \cdot (0,8) \cdot A_m} \quad (9)$$

4. RESULTS

For the purely coreless topology, an outer rotor diameter of 250mm is chosen, taking into account the final accommodation of the concentrated trapezoidal winding, in addition, taken to the long ends, a large number of poles are required, for which 12 poles are chosen, and the expected induced voltage for this topology is 10 volts. Table 2 shows the dimensions obtained for this configuration using formulas (1) - (9):

Table 2: Purely Coreless Topology Dimensions.

Parameter		Dimensions
External diameter	D_{outer}	250 mm
Inside diameter	D_{inner}	140 mm
Number of poles	# poles	12
Number of coils	N_c	9
Coils per phase	N_{cp}	3
Air gap	g	3 mm
Outer pole passage	$P_{p_{outer}}$	65,45 mm
Inner pole passage Synchronous speed	$P_{p_{intinner}}$	36,65 mm
Frequency	N_s	137,51 rpm
Number of turns	f	13,75 Hz
IP large	N	270
IP outdoor wide exterior	IP_{large}	55 mm
IP high	$IP_{outwide}$	16,36 mm
IP indoor wide	IP_{high}	7 mm
High stator	$IP_{indwide}$	9,16 mm
		7 mm

Using the Autocad tool, the location of the magnetic poles and the coils is carried out, taking into account that for a Halbach matrix, 4 magnets form a magnetic pole, figure 9a. shows the location of the coil with respect to the magnetic pole, in which, the long end of the winding, and the covered pole area are observed. The resulting configuration for 12 poles and 9 coils (3 per phase) is shown in figure 9b:

Figure 9: a) Location of the Trapezoidal Winding and Permanent Magnets. b) Magnet and Coil Arrangement Topology.

After carrying out the theoretical calculations for the proposed topology, the configuration is simulated in the COMSOL software, to validate the information through the finite element method.

The results obtained for the magnetic flux density are shown in figure 10, where it is observed that by implementing a Halbach matrix for the permanent magnets and thus avoiding the rotor iron, it does not present a large dispersion flux, which increases density in the air gap and thus improves efficiency.

Figure 10: Magnetic Flux Density Topology.

The output voltages obtained for the topology without load and underload are shown in figures 11 and 12, the voltage value in the winding obtained in empty is close to that calculated in the design with a value of 13 volts in two of the phases, however, in one of the phases there is a distortion in the wave, with a voltage of approximately 10 volts. For the voltage with load, a decrease in value is observed at an output voltage of 6 volts, the same wave form is maintained for all three phases. There are errors in the phase shift for the angles of the wrapping tension due to the low power required for the design and the proposed distribution for the winding.

Figure 11: Voltage of Winding Topology Without Load.

Figure 12: Voltage of Winding Topology with Load.

The output power underload, for the topology, is kept within the established design parameters with a maximum value of 3 watts (figure 13).

Figure 13: Power Output Topology.

5. CONCLUSIONS

This document demonstrated the possibility of implementing a double rotor generator iron less, therefore, the proposed topology uses the Halbach matrix for the location of the permanent magnets in the rotors. This magnetization prevents stray flux from occurring due to the absence of iron, and a higher flux concentration is achieved in the air gap, in addition to reducing the overall weight of the generator. In the analysis based on finite elements, it shows that the behavior of the proposed topology is close to the results obtained by analytical means, thus demonstrating that the fully coreless topology performs well for low power and low speed applications.

Thanks to the implementation of the finite element method in the modeling of a new axial flux generator, it is possible to face the topology to various work scenarios, without the need for a model construction, to analyze the behavior.

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