Electromagnetic analysis of an axial flow machine with permanent magnets for use in wind turbines

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Abstract. Nowadays, there is a global trend for searching new sources of energy with lower possible aggression to the environment and to humans in generation of electric power. According to the Brazilian Electricity Regulatory Agency (ANEEL), the generation through wind power now is around 1200MW of installed power, and the government has already signed 140 new projects to be installed until the end of 2013, with which the country would produce about 5000MW. This favorable scenario for the development of wind power, leads to several jobs in the area of forecasting and designs of electrical machines for wind turbines. This paper deals with the study of a 50 kW Torus generator with rare-earth permanent magnets applied in wind turbines. Such topology is compact, simple and has a high efficiency.

Key words

Machine design, wind power, permanent magnets axial flux machine.

1. Introduction

Although the Brazilian energy matrix be considered "clean". The research in renewable energies, such as solar energy, biomass and wind energy, has grown considerably. Several new researches are focused on efficient electric generators, so that the kinetic energy of wind is converted into electricity with lower losses.

Among the topologies of electrical machines, those using permanent magnets are widely studied.

In recent years, the process optimization and falling costs of rare-earth magnets, like Neodymium-Iron-Boron, and the fast development of power electronics, make the axial flow machines be overexploited.

The rare-earth magnets are used to replace the field windings of classical electrical machines like synchronous machines and DC machines [1] [2].

The axial flow machines which have the coils wound around a stator are called Torus machines. Furthermore, it can be assembled with or without slots. The first axial flux permanent magnet machine without slot dates from the 1980s [3], [4], [5].

The Torus machine can operate as motor or generator and several literatures discuss its advantages and disadvantages.

Among the advantages of this topology, it can be characterized the simple construction and the low cost. Moreover, the use of Neodymium-Iron-Boron permanent magnets enables a volume and mass reduction [3]. The compact arrangement and the natural action of the rotor disks generate a good refrigeration of the stator windings, since they are exposed to air [6]. Another advantage is that the machine without slots generates small variations of magnetic flux thus reducing the eddy current losses in the rotor discs and magnets [7].

The Torus topology is displayed in many applications in the literature, such as fans, motors for water pumping, aircraft, electric vehicles and mainly in low power wind generators, the latter is subject of this study.

The magnetic flux in these structures is showed in two derivations, the Torus-NN and the Torus-NS, as shown in the Figures 1 (a) e 1 (b). The depicted figures show a slotted stator, however the flux directions are also valid for stators without slots.

The Torus machine may appear in the form of multi-stages flows which also shows the types NS and NN.

The objective of the paper is to present a design of an axial flow generator with 50 kW of mechanical power, Torus type with permanent magnets of Neodymium-Iron-Boron which will be validated through electromagnetic simulations.
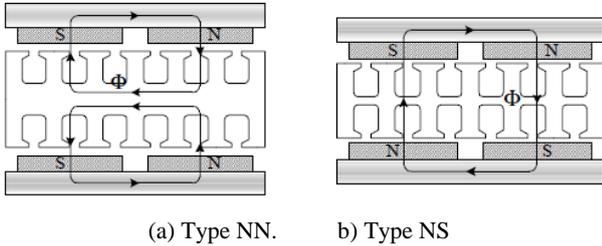

(a) Type NN. b) Type NS

Fig. 1 – Direction of the flux for axial flux machines with slotted rotor type NN and NS [5]

2. Design of the Torus axial flux machine and simulations

For the design of such machines are necessary some design parameters which will be determined using one-dimensional models, based on the following references [8], [9].

A. Design of the Torus axial flux machine

In [9], it is said that the maximum torque occurs when the ratio of the inner diameter and outer diameter, k_d, is different from $\dfrac{1}{\sqrt{3}}$, then it was assumed a value of 0.6 for k_d.

Other design parameters were determined due to the topology that will be used. Since the chosen machine has a toroidal winding, the winding factor, k_{w1}, the power factor, $\cos \varphi_n$, can be considered by definition equal to 1, as discussed in the reference [9].

The rotor will turn with a rated speed of 230 RPM, n_{rnom}, as result it can be computed that the number of pole pairs (2p) should be 20.

For the appropriate sizing of the generator, other parameters must be determined. These parameters are the magnetic flux density, B_{mg}, and the linear current density, A_m [9].

The peak value of magnetic flux density, B_{mg}, has its value expressed by the equation (1).

$$B_{mg} = \frac{1}{\alpha_i \cdot \pi} \cdot \frac{\varphi_{f1}}{\left(\dfrac{D_{out}^{\,2} + D_{in}^{\,2}}{8 \cdot p} \right)} \tag{1}$$

where:

$\varphi_{f1} \rightarrow$ Magnetic flux (peak value).
$\alpha_i \rightarrow$ Ratio between the mean value and the peak value of flux density.

The current loading , A_m, is the ratio of the number of phases, rated current and the number of turns by the average diameter, as can be seen in equation (2) [10].

$$A_m = \frac{2 \cdot \sqrt{2} \cdot m_1 \cdot N_f \cdot I_{nom}}{\pi \cdot \left(\dfrac{D_{ext} + D_{in}}{2} \right)} \tag{2}$$

where:

$m_1 \rightarrow$ Number of phases.
$N_f \rightarrow$ Number of turns per phase.
$I_{nom} \rightarrow$ Rated current (RMS value).
$D_{ext} \rightarrow$ Outer diameter.
$D_{in} \rightarrow$ Inner diameter.

Getting the dimensions of the generator to be studied, it is necessary to use several equations. The first to be approached is the equation (3), which defines the electromotive force generated in the toroidal winding.

$$E_f = \frac{1}{\sqrt{2}} \cdot N_f \cdot k_{w1} \cdot 2 \cdot \pi \cdot f \cdot \varphi_{f1} \tag{3}$$

where:

$f \rightarrow$ Frequency.

After being defined, the magnitudes A_m e B_{mg} can be related to active power of the generator through the nominal voltage and current as shown in equations (4) and (5).

$$P_{nom} = m_1 \cdot \frac{E_f}{\varepsilon_f} \cdot I_{nom} \cdot \cos(\varphi_n) \tag{4}$$

where:

$E_f \rightarrow$ Back-EMF (line-to-neutral RMS value).
$\varepsilon_f \rightarrow$ Relative value of the EMF force in terms of the nominal machine voltage.

$$P_{nom} = m_1 \cdot \frac{\alpha_i \cdot \sqrt{2} \cdot n_{rnom} \cdot \pi^2 \cdot N_f \cdot k_{w1}}{\varepsilon_f} \cdot \frac{A_m \cdot \pi \cdot (D_{out} + D_{in})}{4 \cdot \sqrt{2} \cdot m_1 \cdot N_f} \tag{5}$$

Since the nominal power value is known, the value of outer diameter can be determined in function of the variables expressed in equation (6).

$$D_{out} = \sqrt[3]{\frac{32 \cdot \varepsilon_f \cdot P_{nom}}{\alpha_i \cdot \pi^3 \cdot k_{w1} \cdot \dfrac{n_{rnom}}{60} \cdot B_{mg} \cdot A_m \cdot \cos \varphi_n \cdot k_D}} \tag{6}$$

where:

$k_D = \left(1 - k_d^2 \right) \cdot \left(1 + k_d \right)$ e $k_d = \dfrac{D_{in}}{D_{out}}$.

Using the equation (6) and all design parameters displayed in Table 1, it is possible to obtain the outer

diameter. Hence, with the outer diameter, we can calculate the inner diameter.

B. Simulations

After the machine parameters design, it was draw a three dimensions model using a commercial software called Computer Simulation Technology Suite (C.S.T. Suite). Then, electromagnetic simulation will be performed to validate the previous calculated dimensions of the machine.

Table 2 shows the outer and inner diameters of the rotors and stators, the permanent magnet size (bounded at the rotor's surface), the winding overhang length, the number of turns and the current through the machine coils that will be analyzed. These data are used to create the software model.

Table 1 – Input parameters for sizing the generator.

Parameters	Value
K_d	0.6
η	0.92
A_m	50000 A/m
P_{nom}	46 kW
p	10
V	380 V
n_{est}	2
α_i	0.775
n_{rnom}	230rpm
B_{mg}	0.75 T
ε_f	1.05
J_a	5.10^6 A/m^2

Table 2 – Data relating to the size of the generator

	Dimensions (mm)
Outer diameter	602.00
Inner diameter	362.00
Width of the air gap	2.0
Gap between magnets	7.5
Thickness of magnet	11.00
Length of the magnet	110.00
Stator width	33.00
Inner rotor width	17.00
Outer rotor width	34.00
Winding overhang length	5.8
Generator total length	223.00

3. Results and Discussions

In order to obtain the electromagnetic results for the designed generator, simulations were carried out using the software CST, where a 3d-model was built, which uses the data shown in Table 2. The 3d-model is displayed in Fig. 2.
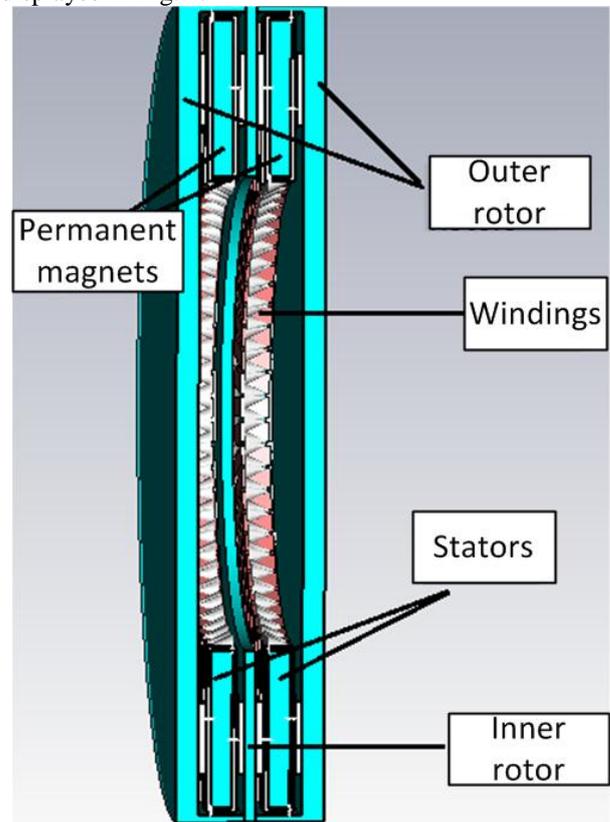

Fig. 2 - Torus machine components after being represented in the C.S.T.

The purpose of this analysis is to validate the designed model and to determine the magnetic flux density in the air gap, B_{mg}, where new changes in the design can be proposed for the optimization of the generator's dimensions.

The magnetic field density in the air gap of the machine is shown in Fig. 3. Based on the color density of the arrows, it is possible to verify that the magnetic field density variation is situated between a range of 0.472T and 0.786T. Furthermore, it has a peak value of 0.786, diverging in 0.036 compared with the assigned B_{mg} value

shown in Table 1. The average value of this range is 0.614T. Therefore, the ratio of the magnetic flux density average value and the peak value is $\alpha_i = 0.781$, which is a very near to the input value used to design the generator, presented in the previously subsection.

In Fig. 4, it is shown the surface current density in the machine's surface, which was generated due to the current in the coils with the maximum value of $1.21326 \times 10^7 A/m^2$. The colors of the arrows represent the values in a range that goes from 4.93×10^6 to 6.82×10^6 A/m^2. The average current density value is around 5.875 A/m^2, then 0.875 A/m^2 above the used input value.

Table 3 shows the comparison between the input parameter values and the obtained results from the CST simulation.

Table 3 – Comparison between the parameter input values and the result values.

Parameters	Input value	Simulated value	Error (%)
J_a	0.75T	0.786T	5
α_i	0.775	0.780	0.6
B_{mg}	$5 \times 10^6 A/m$	$5.875 \times 10^6 A/m$	14

Table 4 – Variation's parameters range used for the design of axial flow machines. [8]

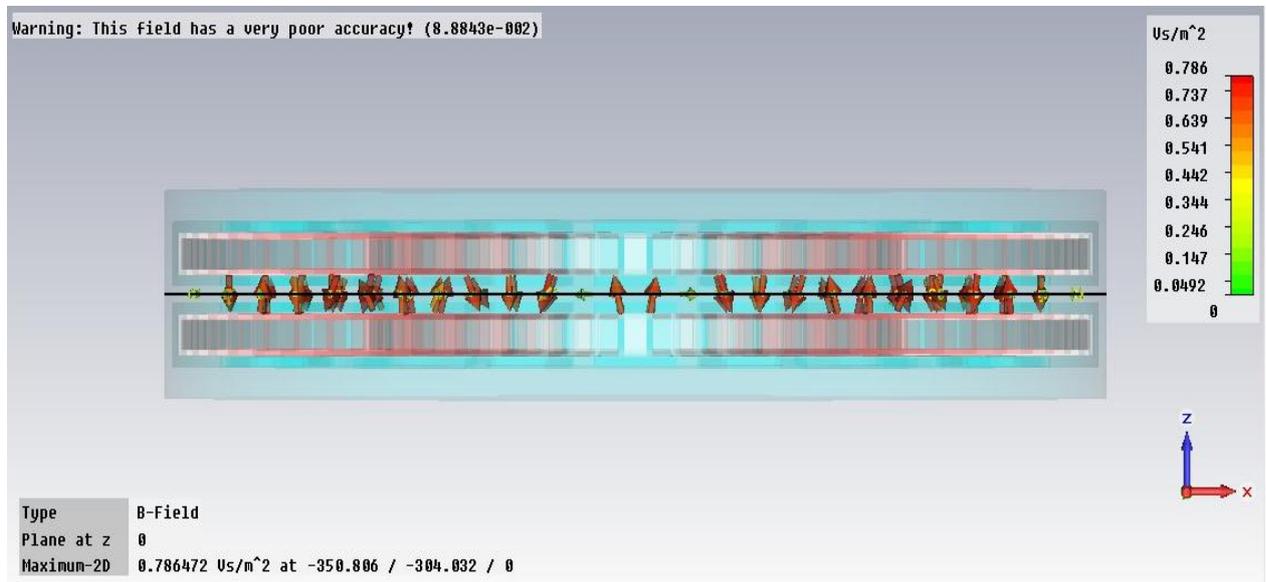| Parameters	Range values
J_a	$3x10^6 \longleftrightarrow 9x10^6 A/m^2$
A_m	$8x10^3 \longleftrightarrow 62x10^3 A/m$
B_{mg}	$0.30 \longleftrightarrow 0.80T$
k_d	$0.4 \longleftrightarrow 0.8$

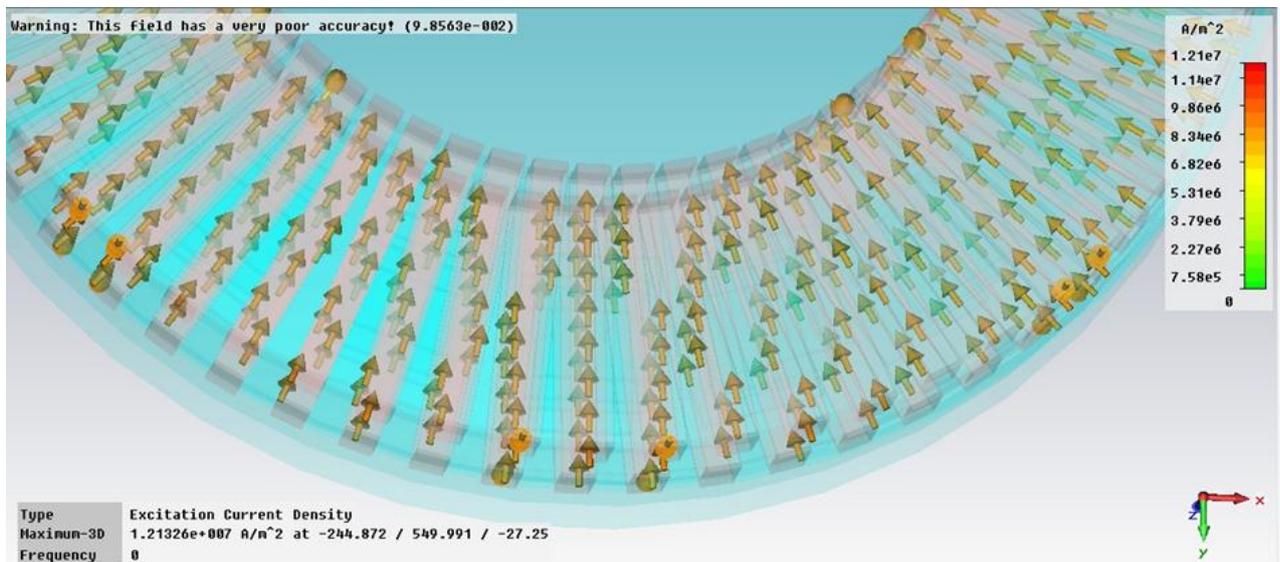Fig. 3 - Magnetic field density in the air gap.

Fig. 4 - Surface current density

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Although the difference with the value of the input parameters, the results are within the acceptable range value for such topology, as shown in Table 4.

4. Conclusions

The design of a Torus generator is a complex process due to the nature of the machine, and the great computational efforts for the simulation. The obtained results were faced with some input parameters. These results present small errors comparing with the input parameters. However they stay within the acceptable range for a generator with Torus topology. As we can seen in the presented results, the values of the magnetic field density in the air gap and the values of the surface current density were close to the design parameters values utilized in the dimensional analysis. Hence, the values obtained from the electromagnetic simulations are considered valid. Another important value is the computed α_i, which agrees with the assumed design parameter value.

The 3D simulation is important for the analysis of one project due to similarity between the designed machine and the real machine.

In future work, it can be utilized the obtained simulated values as input parameters, optimizing the analysis and minimizing the error.

Acknowledgement

References

[1] A. E. FITZGERALD, C. K. JÚNIOR, A. KUSKO, "Electrical Machines", McGraw-Hill, 326 p. São Paulo, 1975.

[2] G. TIBOLA, "Small wind system for electricity generation with maximum power tracking.", pp. 285, Master thesis in Electrical Engineering, Santa Catarina Federal University, Florianópolis, Brazil, 2009.

[3] L. T. dos R. LOUREIRO, "A study on the Torus machine.", pp. 106, PhD Thesis in Mining Engineering, Metallurgical and Materials, Rio Grande do Sul Federal University, Porto Alegre, Brazil, 2008.

[4] A. PARVIAINEN, "Design of axial flux permanent-magnet low-speed machines and performance comparison between radial-flux and axial-flux.", pp. 153, PhD Thesis, University of Technology, Lappeenranta, Finland, 2005.

[5] M. AYDIN, S. HUANG, T. A. LIPO, "Design and 3d eletromagnetic field analysis of non-slotted and slotted TORUS type axial flux surface mounted permanent magnet disc machines.", In: INTERNATIONAL ELECTRICAL MACHINE AND DRIVE CONFERENCE PROCEEDINGS, 2001, pp. 645-651.

[6] J. O. M. OSÓRIO et al, "Analysis of a machine Torus with different formats permanent magnets.", In: XVIII BRAZILIAN CONGRESS OF AUTOMATIC, Bonito-MS, 2010, pp. 4911-4917.

[7] C. SABIONI et al, "Coupling techniques of electromagnetic and thermal design of an axial flow generator permanent magnets for wind turbines operating in low speed.", In: XVIII BRAZILIAN CONGRESS OF AUTOMATIC, Bonito-MS, 2010, pp. 4933-4940.

[8] T. The C. MAIA, "Design and construction of a permanent magnet generator axial flow turbine for low power.", pp. 165, Master thesis in Electrical Engineering, Minas Gerais Federal University, Belo Horizonte. 2011.

[9] J. F. GIERAS, Rj. WANG, M. J. KAMPER, "Axial flux permanent magnet brushless machines.", 2ed. Springer, 2008, pp. 325.

[10] T. W. WEKKEN. Kema Consulting, "Power quality and utilization guide", Wind power, Leonardo Energy, 2006.