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Study of an Outer-Rotor PMSG for use in Small Wind Applications

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Abstract.

Among the renewable energies, wind power has reached undoubtedly the greatest degree of maturity, although such maturity is based on the development of large-scale installations using larger machines every time. In recent years interest has grown in small wind generators, which allow access to this type of energy to small farms and to areas with difficult access. In this work, is performed the study of a permanent magnet synchronous generator (PMSG) using finite elements for such small applications. Various tests have been carried out to simulate no-load and short circuit conditions at different speeds in order to obtain data from these trials about their future behaviour.

Key words

Finite Elements, PMSG, Outer-rotor, Wind Energy.

1. Introduction

Several factors have promoted the development of renewable energy in recent years, among them, and probably as the most important, we could mention on the one hand, the need of reducing CO_2 emissions causing greenhouse effect collected in international agreements like the Kyoto Protocol and, on the other hand, the problems of using nuclear energy [1] revealed by accidents such as Chernobyl and, more recently, Fukushima.

Among renewable energies, wind power has probably been the one that has most developed in recent decades due to the high availability of wind and the degree of maturity reached by this technology. The trend at industry levels is to create even larger generators every time, being able to focus the size of the currently installed generators from 5 to 7 MW [1 – 3].

In contrast, smaller-scale generators may be an appropriate solution for remote areas such as islands, mountains and rural areas [4]. The American Wind Energy Association (AWEA) defines small wind generators as those whose power reaches up to 100 kW, producing an increase in the U.S. market of 15% in 2009 [5].

This paper describes the study of a PMSG for its use in a small wind generator of about 11 kW power. By means of a finite element model, we simulate various tests on the machine, in order to predict the future behaviour of the machine.

2. The analyzed machine

The machine analyzed in this paper, is a small outer-rotor generator with magnets on the surface, the stator has a double layer lap winding with skewed slots. Table I shows some of the main design parameters.

TABLE I. Details of the analyzed machine

Number of poles	24
Number of stator slots	72
Rotor outside diameter (mm)	364
Rotor inner diameter (mm)	339
Stator outer diameter (mm)	327
Permanent magnet material	NdFeB
Thickness of the magnet (mm)	5
Minimun air gap (mm)	1
Relative permeability	1.22
Remanent flux density (T)	1.2

Figure 1 shows a detail of the geometry of the machine on the angle occupied by one of its magnets. It can be seen both the geometry of the stator slots with tooth structure of constant width and a slot opening of 3 mm, such as the one used in the magnet which, having no radial development, generates a variable air gap with a minimum value of 1 mm in the symmetry axis.

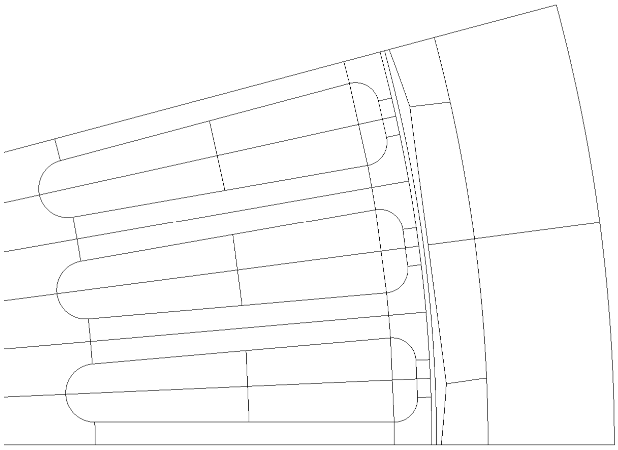

Fig 1. Details of the analyzed machine

3. The developed models

For the study finite element software FLUX-V-10.3 has been used. Initially a 2D model has been developed, from which and using the FLUX-SKEWED module, perform a more accurate model of the machine. FLUX-SKEWED module allows to take into account the inclination of the slot machine breaking down into several sections, the model obtained this way is more accurate than the one achieved with an application in 2D, but without the complexity of 3D models.

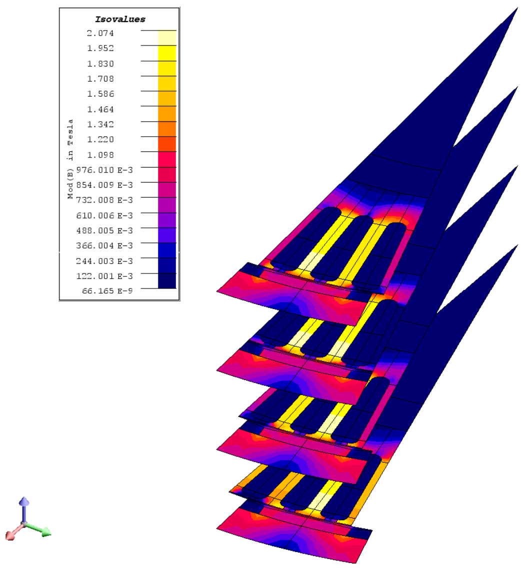

Fig 2. Magnetic flux density for a given position.

In regard to the geometry of the machine, and given the symmetries, a model that includes the angle of a pair of poles has been used. A detail of the model is shown in Figure 2, it shows the machine broken down into 5 sections, in which the distribution of magnetic flux for a given position is simulated.

In addition to the model of the machine geometry, for some of the simulations a model of the electrical circuit has been made (Fig. 3). This model includes data on the number of conductors, its resistance and so on. The different load conditions of the machine can be simulated by including in the elctrical circuit different resistive, inductive or capacitive elements. This circuit can also take into account the effect of the end-winding not represented in the geometrical model of the machine.

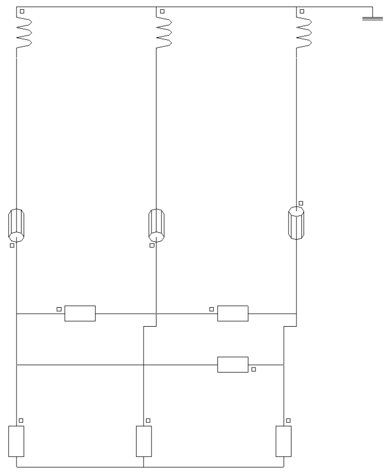

Fig 3. Electrical circuit for the model.

4. Performed Tests

Based on previous models, several tests have been simulated for the machine from which data will be obtained about their future behaviour. Some of these tests are the following:

- *Calculation of Cogging Torque.*
- *No-load characteristic.*
- *Short-circuit characteristic.*

Cogging Torque

Cogging torque, is the result of the interaction (magnetic attraction) between the magnetic flux from the magnets and stator geometry, producing a variable reluctance related with the angular position of the rotor. This torque, overlaps the generator load torque causing not only stress and vibration, but also an absence of power delivery at small wind speeds [6]. Cogging torque can be expressed mathematically by the following equation [7], [8]:

$$T_{cog} = -\frac{1}{2}\phi_g^2 \frac{d\Re}{d\theta} \quad (1)$$

where Φ_g is the magnetic flux density, $\Re$ is the air-gap reluctance and θ the rotor angular position.

Since reluctance varies periodically, it can also be expressed as a Fourier series by the following expression [7], [9], [10]:

$$T_{cog} = \sum_{k=1}^{\infty} T_{mk} sen(mk\theta) \quad (2)$$

where, T_{mk} is a coefficient which indicates the amplitude of each component of the series, m is the least common multiple between the number of stator slots and pole number of the machine and k is an integer. It can be proved that the number of cogging torque cycles per revolution of the rotor is equal to m.

Given the cyclical nature of cogging torque is not necessary to study it for a full rotation of rotor, restrigting the study to smaller angles, for example, the–stator slot pitch angle. The number of periods of cogging torque during rotation of one slot pitch *(N)*, can be determined easily using the expression showed below [11], [12]:

$$N = \frac{2p}{GCD(2p,Q)} \tag{3}$$

where *GCD* is the maximum common divisor between number of poles (*2p*) and slot number (*Q*). In general,we can assume that, increasing the number of cycles of the cogging torque, the maximum value for this will be lower.

Table II shows number of stator slots (Q), number of poles, number of slots per pole and phase (q), number of cogging torque cycles per revolution of the rotor (m) and number of cycles per stator slot pitch (N) of the analized machine.

TABLE II. Number of cycles of cogging torque

Q	*2p*	*q*	*m*	*N*
72	24	1	72	1

Figure 3 shows the cogging torque calculated using the initial 2D model of the machine, the figure shows the 4 cycles of this couple in the corner occupied by two slots.

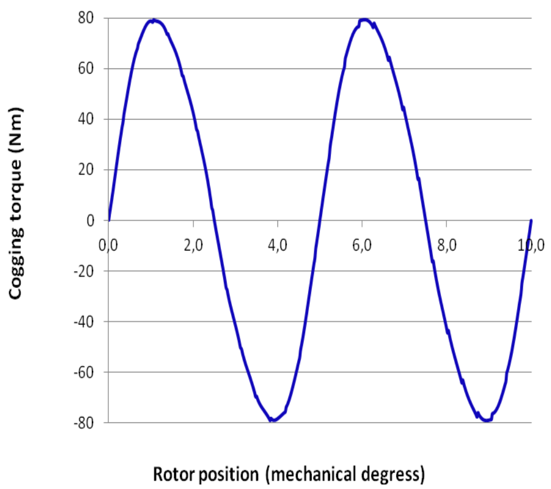

Fig. 3.Cogging torque using a 2D model.

Several methods [6-10] have been proposed to reduce cogging torque, in the case of the machine studied, this has the stator slots skewed, which requires, for its proper study, to use a more accurated model than the 2D model. Figure 4 shows cogging torque calculated from the full model (FLUX-SKEW) and taking into account the slot inclination.

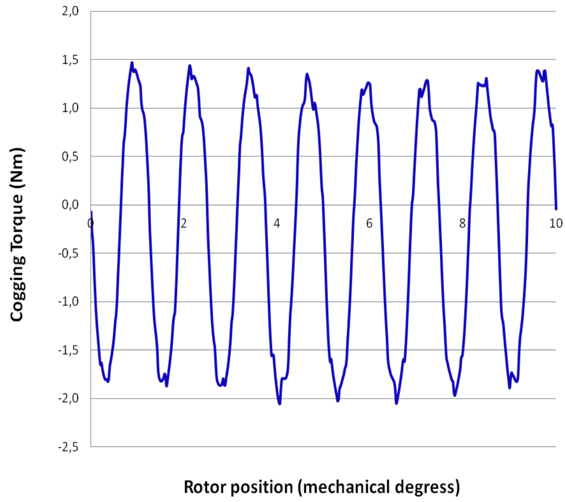

Fig. 4 Cogging torque taking into account the spot inclination.

The graph shows, like it happened in the figure 3, the angle occupied by two stator slots. The comparison between both graphs allows to check that the use of skewed slots, although not completely eliminating cogging torque, it does significantly reduce its values.

No-load characteristic

In a conventional synchronous machine with field winding this feature relates the value of the field current to the electromotive force (EMF) of the machine in its operation as a generator without load current. In the permanent magnet machines, the incapacity to regulate the current field makes this feature in a no load operation point for a given speed. Mathematically, we can express the value of this EMF as [13]:

$$E_f = \pi \sqrt{2}\, f\, N_1\, Kw_1\, \phi_f \tag{4}$$

Where N_1 is the number of turns per phase, f the frequency, Kw_1 winding factor, Φ_f magnetic excitation flux.

Figure 5 shows the EMF of the tested machine to a rated speed of 50 rpm (10 Hz). Besides the graphical representation, some of the main calculation values obtained from the simulation of the no load operation are as follows:

Mean values:	*-0,000*
Rectified mean values:	*105,4352*
Rms values:	*117,4383*

Equally interesting is to know the harmonic content of the EMF generated by the m achine, the program allows to know this content by applying to the previously calculated waveform an analysis by fast Fourier transform (FFT).

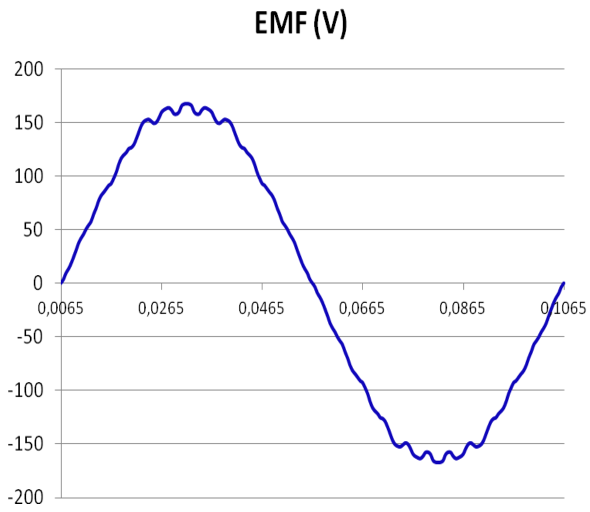

Fig. 5. No load EMF for 50 rpm.

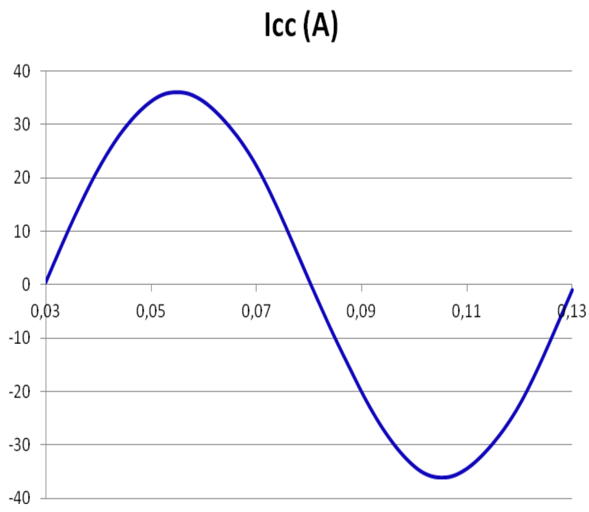

Fig. 7. Short circuit current for 50 rpm.

Figure 6 shows this analysis for the voltage waveform shown before in which we can see the low harmonic content of the same.

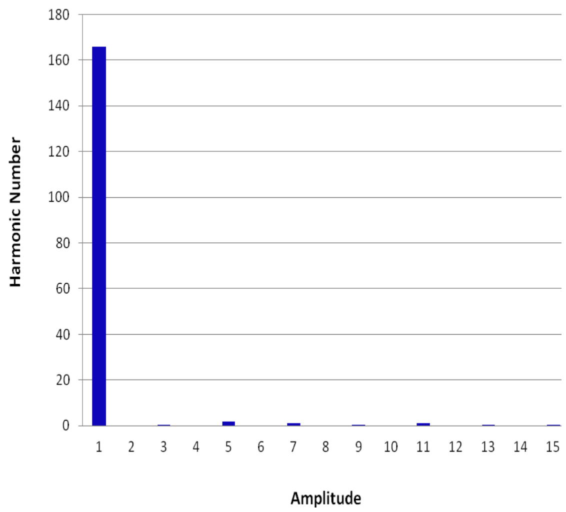

Fig. 6. FFT for the calculated EMF.

Short-circuit characteristic

As in the previous case, this feature, applied to a PMSG, becomes in a short circuit point, defined as the operating status of the machine in short-circuit permanent situation, that is, once transient phenomena have disappeared from it.

Regarding the model, in order to simulate the short circuit situation, the electrical model must be modified of to suit to the load situation of a short circuit.

Figure 7 shows the evolution of a cycle of the short circuit current of the machine for a similar speed that the used in the no-load characteristic (50 rpm - 10 Hz).

Numerically, some of the values obtained from the simulation of short circuit condition are:

Mean values:	*0,6499*
Rectified mean values:	*22,6494*
Rms values:	*25,1243*

In the short circuit situation, besides current, have also been calculated braking torques generated by the machine, for, from these values, to study possible support systems both electric braking (braking resistors), and mechanical. Figure 8 shows the braking torque calculated for a short circuit developed at a speed of 50 rpm.

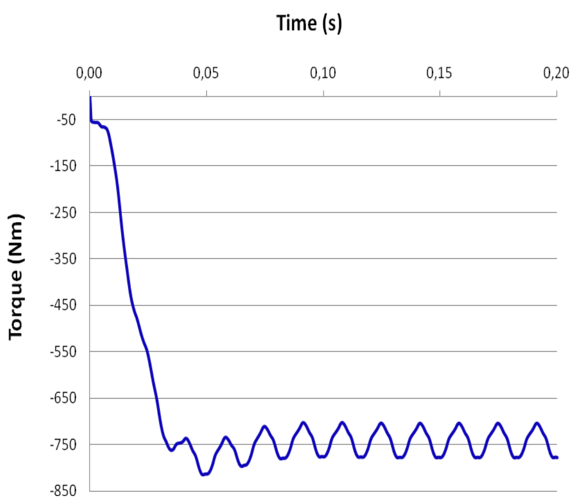

Fig. 8. Braking torque evolution in short-circuit situation.

Direct and quadrature axis reactances (X_d , X_q) and phasor diagram of the machine

The no-load and short-circuit characteristics are two of the tests collected in EN 60034-4 to determinate the magnitudes of synchronous machines. In this standard, the calculation of the direct axis reactance (X_d) it is proposed from no-load EMF values, and short-circuit current obtained for a given value of field current. In the case of permanent magnet machines, given the impossibility to regulate the field current, the value of this reactance can be calculated for a given speed and frequency, from EMF values and calculated short-circuit current.

As for the quadrature axis reactance (X_q), given the geometry of the machine, with magnets on the surface, their value can be considered similar to that found for the case of X_d , could be said then:

$$X_q \approx X_d = \frac{E_f}{I_{sc}} \tag{5}$$

Using these reactances, it is possible to trace the phasor diagrams of the machine based on the equation (6) that describes its operation as a generator [13]:

$$E_f = V_1 + I_{ad}(R_1 + jX_d) + I_{aq}(R_1 + jX_q) \tag{6}$$

According to the equation expresed above the phasor diagram of the machine would be as shown in Figure 9:

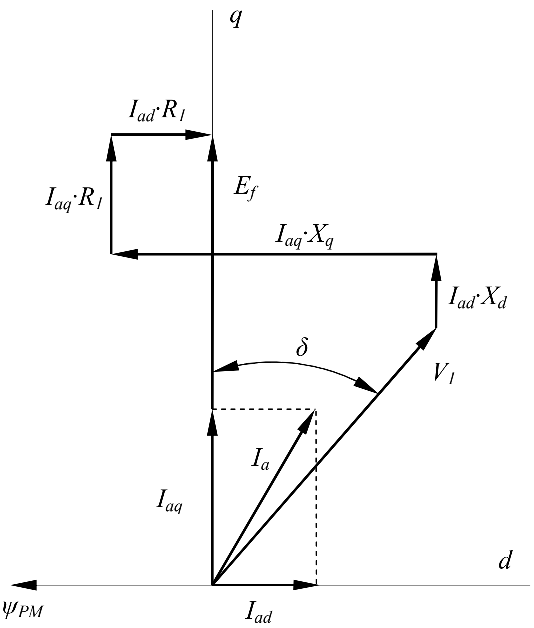

Fig. 9. Phasor diagram of the synchronous generador.

Where E_f is the no-load EMF, V_1 is the imput voltage and δ is the torque angle of the machine for a given load state

In this diagram, the armature current (I_a) appears decomposed into its components of direct and quadrature axis (I_{ad}, I_{aq}). Some expressions for these currents can be calculated from the projections of the voltage V_1 on the d and q axis.

$$V_1 \; sen\delta = I_{aq}X_q - I_{ad}R_1 \tag{7}$$

$$V_1 \cos\delta = E_f - I_{ad}X_d - I_{aq}R_1 \tag{8}$$

Developing the equations (7) and (8), is possible to obtain some expressions for the currents I_{ad} , I_{aq}, as shown in (9) and (10).

$$I_{ad} = \frac{X_d\left(E_f - V_1 \cos\delta\right) - R_1 V_1 \; sen\delta}{X_d X_q + R_1^2} \tag{9}$$

$$I_{aq} = \frac{R_1\left(E_f - V_1 \cos\delta\right) + X_d V_1 \; sen\delta}{X_d X_q + R_1^2} \tag{10}$$

These last expressions allow to calculate the components of the armature current on the d and q axis according to V_1, E_f, X_d, X_q, δ y R_1.

5. Conclusions

This paper has developed a model of PMSG by using finite element based software. From an initial model in 2D, a more accurate model has been developed , without reaching the complexity of 3D models, that allows to take into account the skewed-slots which is especially important when calculating the cogging torque of the machine. The model takes into account both the geometry and the electrical model of the winding of the machine being able to simulate two typical laboratory tests such as the no-load and the short-circuit, from which some interesting facts are obtained such as the harmonic content of generated EMF or the synchronous reactances of the machine.

The performed simulations and the obtained results show the utility of finite element method as a design tool for these machines, allowing to obtain results and predictions about future behaviour of these machines from the design stages.

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