DESIGN AND MODELING OF AN AXIAL FLUX PERMANENT MAGNET GENERATOR WITH DOUBLE LAYER TOOTH-CONCENTRATED FRACTIONAL WINDINGS

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KEYWORDS
Axial Flux Permanent Magnet Generator, Current Linkage, Space Harmonics, Tooth-Concentrated Windings.

ABSTRACT

Axial Flux Permanent Magnet Machines benefit from manufacturing advantages and reduction in end winding length through the use of tooth-concentrated fractional windings but display increased space harmonic content, leading to higher eddy current losses in the rotor iron and permanent magnets. The choice of a double layer tooth-concentrated fractional winding for the modeling and design of a 24 Slots/20 poles Axial Flux Permanent Magnet Generator is justified by a comparison between the single and double layer winding.

INTRODUCTION

Axial Flux Permanent Magnet Generators (AFPMG) have become an interesting choice for use as low speed generators because of their compact design, high power density, and possibility to add a high number of poles, without the need of a mechanical gearbox. By using tooth-concentrated windings the manufacturing of the AFPMG can be simplified and copper losses can be reduced, due to the short end windings (Jussila 2009). The disadvantage of the tooth-concentrated fractional windings is represented by a high current linkage space harmonic content, because of their low number of slots per pole and phase (Salminen 2004; Cistelecan 2010), which induce additional eddy current losses in the rotor iron and in the permanent magnets (PM).

The theory of the tooth-concentrated windings and methods to reduce the eddy current losses in the rotor iron have been studied over the last years. It has been determined that to reduce the cogging torque, to obtain a higher value of the fundamental winding factor and to generate a sinusoidal back-emf, the right combination of number of stator slots Q_s and number of rotor poles 2p has to be chosen (Bianchi et al. 2006; Bianchi et al. 2007). Another approach lies in the use of nonconductive materials, such as fiberglass, for the rotor iron and in the segmentation of the permanent magnets (Jussila 2009)

The influence of the number of winding layers in tooth-concentrated winding machines has also been taken into consideration in (El-Rafaie and Jahns 2006) , and it has been shown that by using a higher number of winding layers and using unequal number of turns for each coil, the current linkage harmonics can be completely reduced, with a small influence on the winding factor (Cistelecan 2010).

ANALYTICAL DESIGN OF THE AFPMG

The topology of the studied AFPMG is a two stator one internal rotor with 24 stator slots and 20 rotor poles. The PMs are glued inside the rotor and define the rotor thickness. The two stators are connected in series.

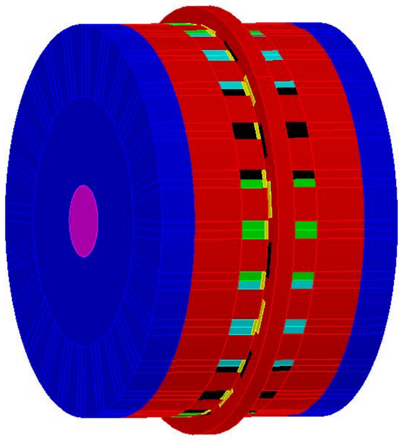

Figure 1: Topology of the Studied AFPMG

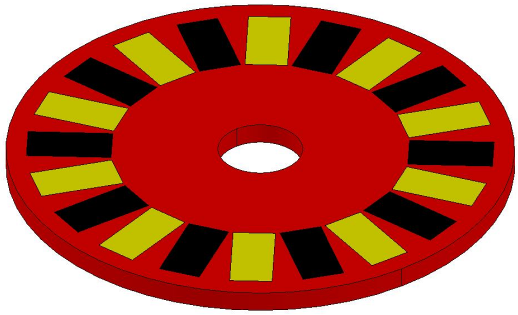

Figure 2: Rotor of the Studied AFPMG

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The most important parameters used for the design of the AFPMG are the outer diameter D_e and the inner diameter D_i. The dimensions of external and internal diameters are very important because the length of the stator stack is obtained from the difference of the two :

$$l_s = \frac{D_e - D_i}{2} \tag{1}$$

Another factor that contributes to the performance of the machine as well as to its manufacturability is the inner-to-outer diameter ratio, which can be defined as:

$$k_d = \frac{D_i}{D_e} \tag{2}$$

In (Parviainen 2005) it is advised to obtain $k_d = 1/\sqrt{3}$ to benefit from the highest possible torque, however this can lead to manufacturing difficulties when using lap windings, especially in small machines. The problem lies in the limited space between the rotor shaft and stator, which makes it very difficult to arrange the end windings.
By using tooth-concentrated windings, the length of the end windings can be reduced and more space can be freed up between the stator and the rotor shaft.
Table 1 contains the main parameters of the studied AFPMG that have been obtained from the analytical design, which have been further used for the modeling.

Table 1: Main Parameters of the Studied AFPMG

Number of stator slots Q_s	24
Number of pole pairs P	10
Number of slots per pole and phase	0.4
Aparent power S_n	50 [VA]
Rated speed n_s	300 [rpm]
Line-to-line voltage in star connection U	230 [V]
Rated current I_n	0.157 [A]
Nominal frequency f	50 [Hz]
Airgap flux density B_g	1 [T]
Winding turns in series per stator winding N_1	1568
Lenght of airgap g	0.001 [m]
Stator outer diameter D_e	0.11 [m]
Stator inner diameter D_i	0.07 [m]

HARMONICS OF TOOTH-CONCENTRATED FRACTIONAL WINDINGS

In comparison to integral slot winding machines, which operate at the fundamental component of the flux density, the machines having tooth-concentrated fractional windings operate with some of the flux density harmonics (Jussila 2009).
The winding arrangement of the 24 slots 20 poles AFPMG is the same as in the case of a 12 slots-10 poles base machine equipped with tooth-concentrated fractional windings, but repeated two times. Both of the machines have the same number of slots per pole and phase $q = 0.4$ and operate with the same harmonic. Thus the problem of determining the main harmonic of the AFPMG can be reduced to the study of the winding arrangement for just one half of the generator.
The harmonics of a three phase ($m=3$) 12 slot-10 poles machine can be determined by use of the following equation:

$$\nu = 1 \pm 2km; k \in N \tag{3}$$

The resulting harmonics are:

$$\nu = [1, -5, +7, -11, +13, -17, +19 ...] \tag{4}$$

for the ordinals of the current linkage. The machine operates at the fifth harmonic $\nu = -5$ which also has the highest winding factor. The fundamental $\nu = +1$ has a high amplitude compared to the fundamental and rotates five times the speed of the fifth harmonic and in the opposite direction, resulting in high losses through eddy currents in the rotor iron.

Advantages of double layer windings over single layer windings

To determine the right number of winding layers a comparison between the harmonic spectra of both winding arrangements, presented in Figure 3, has been carried out.

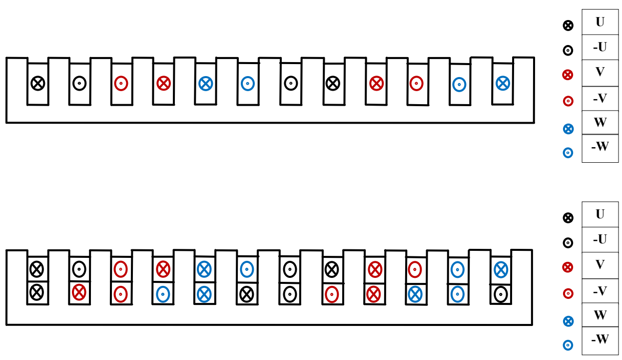

Figure 3: Winding Arrangement for the 12 Slot-10 Poles Machine with Single Layer and Double-Layer Tooth-Concentrated Fractional Winding

Starting from the definition of the current linkage (5) the winding function for each phase has been defined.

$$\Theta = N_s \cdot i \quad (5)$$

N_s number of turns in a slot

i current passing through the conductor

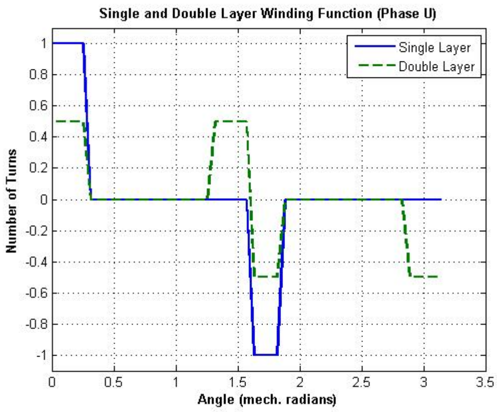

Figure 4: Single and Double Layer Winding Function of Phase U for 12 Slots and 10 Poles

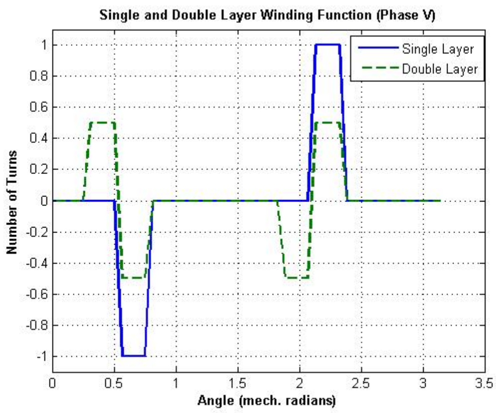

Figure 5: Single and Double Layer Winding Function of Phase V for 12 Slots and 10 Poles

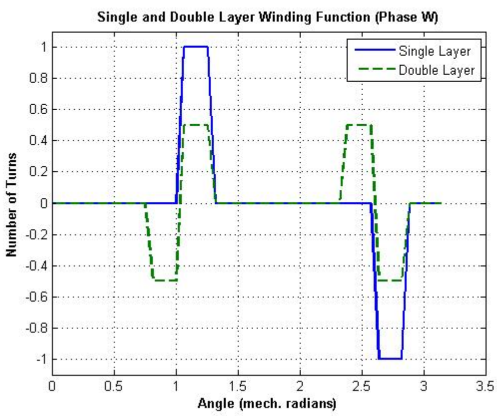

Figure 6: Single and Double Layer Winding Function of Phase W for 12 Slots and 10 Poles

The winding functions presented in Figures 4, 5, 6 have been drawn for the single layer and double layer tooth-concentrated fractional winding. The number of turns for each slot has been kept $N_s = 1$. As it can be seen, by doubling the number of layers, the number of turns in a slot for each phase is halved.

To obtain the variation of the current linkage, the winding functions are further multiplied with the values of the phase currents for one chosen moment. In this case the values taken into consideration have been :

$$i_u = 1; i_v = -1/2; i_w = -1/2 \quad (6)$$

After the multiplication the resultant of the current linkage is obtained by summing up the current linkages for each phase.

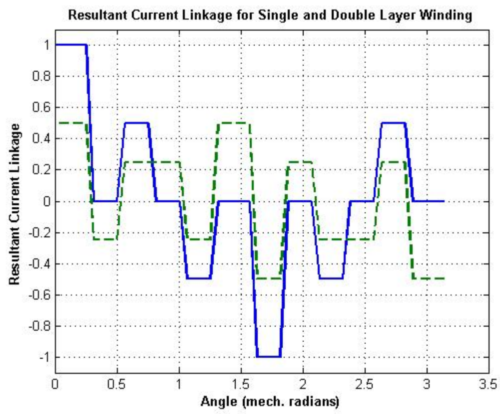

Figure 7: Resultant Current Linkage for Single and Double Layer Winding

The harmonics of the resultant current linkages for one and two layers are obtained through the use of the FFT algorithm implemented in Matlab and are presented in Figure 8.

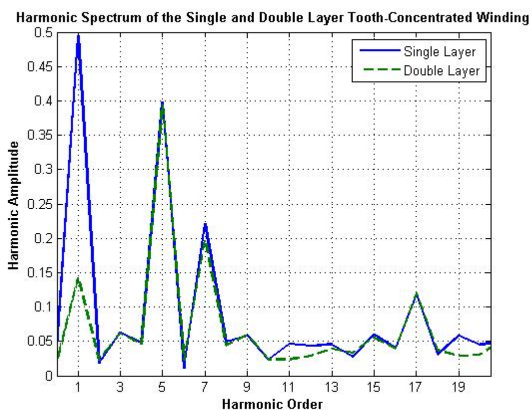

Figure 8: Current Linkage Harmonic Content for Single and Double Layer Winding

To verify the results obtained through the analytical method, two radial flux machine models of the AFPMG have been implemented and simulated in Cedrat Flux 2D. To determine the current linkage generated by the three phased windings, the PM material has been replaced with air. The motor has been used at the synchronous speed namely 300 rpm.

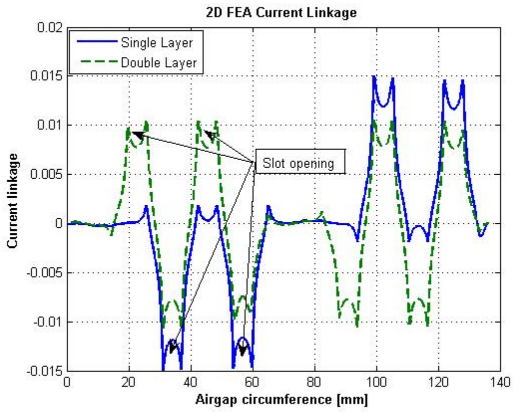

Figure 9: 2D Finite Element Analysis (FEA) Current Linkage obtained at the Airgap Circumference for Single Layer and Double Layer Winding

The variation of the current linkage for the simulated machines has been drawn in Figure 9. When compared to the analytical method, the simulations takes also the slot openings into account, which have an impact on graphical representation of the current linkage.

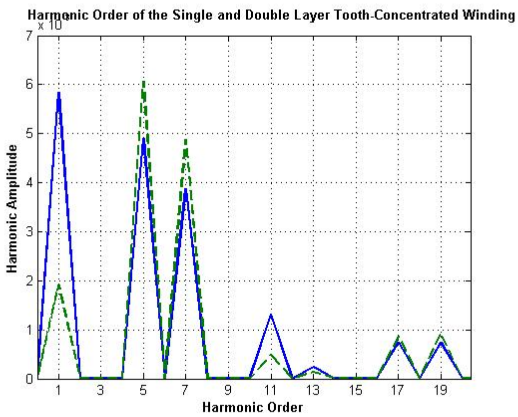

Figure 10: Current Linkage Harmonic Content for the 2D FEA for Single Layer and Double Layer Winding

The harmonics of the three phase current linkage have been determined by means of the FFT algorithm implemented in Matlab and are displayed in Figure 10.
When comparing the results from the analytical and 2D FEA Method in table 2, we can observe that there is a big difference between them for both single and double layer windings. The relative amplitude of the other harmonics to the working harmonic is different for each of those methods, the most accurate results being for the 1st harmonic. Another factor that influences the harmonic content are the slot openings. The 2D FEA method takes into consideration the slot openings, whereas the analytical method does not. This can considerably hinder the correct determination of the harmonic content of the current linkage. As can be seen from the two harmonic spectra the 2D FEA method determines correctly the harmonics of the tooth concentrated winding compared to the analytical method which identifies also other harmonics.

Table 2: Comparison between the main harmonics for the analytical and 2D FEA method

Harmonic	% of the fundamental MATLAB		% of the fundamental 2D FEA	
	Single layer winding	Double layer winding	Single layer winding	Double layer winding
1	124	36.2	118	31.5
5	100	100	100	100
7	55.8	50.1	79.1	80.1
11	11.7	5.96	27.3	8.2
13	11.4	9.9	5.1	2.2
17	30	30.5	15	14.1
19	14.8	7.2	14.7	15.4

MODELING OF THE AFPMG USING TOOTH-CONCENTRATED FRACTIONAL WINDINGS

Axial Flux Machines come in a variety of topologies sharing one common feature namely the flux is flowing in the axial direction instead of the radial one. The direction in which the flux is flowing has an impact on the FEA of the AFPMG, because the model of the machine should be made in 3D.
However the research has shown that the FEA of Axial Flux Machines can be simplified to a 2D model, namely the machine is modeled as a liniar (Gieras 2004; Parvianen 2005) or as a radial flux machine (Jussila 2009). The plane at which the analysis is carried out is either at the arithmetic (Gieras 2004; Jussila 2009) or at the geometric mean radius (Valtonen 2007).

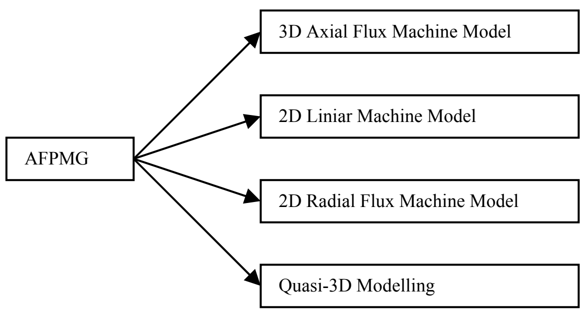

Figure 11: AFPMG Modeling Options

In (Jussila 2009) it is mentionend that if the arithmetic or geometric mean radius is used, the magnet width-to-pole-pitch ratio should be constant at different radii and the stator should not be skewed. The 2D FEA of an Axial Flux Machine is accurate enough for power, voltage and cogging torque calculation, but for determining the iron losses, 3D FEA should be employed.
Another method to determine the iron losses without using the 3D FEA has been presented in (Parviainen 2005) and it's called the quasi-3D method. The principle of this method lies in cutting the stator stack in many planes of interest and determine the parameters for each plane. The average diameter D_{avg} of a specific computation plane *i* starting from the outer diameter is expressed as follows:

$$D_{avg,i} = D_e - j \cdot \frac{l_s}{N} \quad (7)$$

Where N represents the number of computation planes and $j = 2i - 1$. All the other parameters are determined for each individual computation plane, summed up and divided by the number of computation planes N, to get an accurate picture regarding the iron losses, induced voltage, flux density or other parameters of interest.

Modeling of the Studied AFPMG

The topology of the AFPMG presented in this article has been modeled as a radial flux Permanent Magnet Synchronous Machine (PMSM) by means of 2D FEA at the arithmetic and geometric mean radius. For the modeling of the AFPMG only the use the double layer tooth-concentrated fractional winding has been considered.
The arithmetic mean radius, which is usually used as a design plane (Gieras 2004; Jussila 2009), can be calculated as follows:

$$R_{arith} = \frac{R_e + R_i}{2} \quad (8)$$

The definition of the geometric mean radius is given by (9):

$$R_{geom} = \sqrt{R_e \cdot R_i} \quad (9)$$

Where R_e is the outer radius and R_i is the inner radius of the Axial Flux Machine.
The steps by which the geometry of an AFPMG has been converted into a 2D model of a radial flux machine, at the arithmetic or geometric mean radius can be observed in the Figure 12.

The obtained dimensions for the two radial flux machines are shown in Table 3. As can be seen from the table the most important changes lie in the dimensions of the teeth and in the inner and outer stator and magnet radii.
The other dimensions like the length of the stator stack, the height of the tooth, the opening of the slot and the magnet width and height are kept the same.

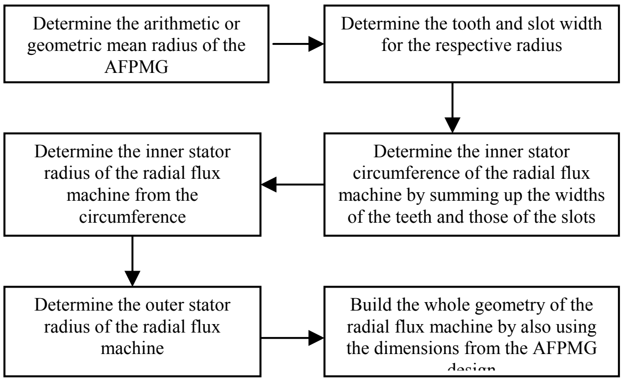

Figure 12: Steps to model the Axial Flux Machine as a Radial Flux Machine

Table 4: Dimensions of the AFPMG

Modeled Machine / Dimension	AFPMG	Radial Flux Machine (Arithmetic Mean Radius)	Radial Flux Machine (Geometric Mean Radius)
Inner stator radius	35 [mm]	43.92 [mm]	42 [mm]
Outer stator radius	55 [mm]	66.42 [mm]	64.5 [mm]
Inner magnet radius	35 [mm]	40.42 [mm]	38.5 [mm]
Outer magnet radius	70 [mm]	42.92 [mm]	41 [mm]
Length of the stator stack	20 [mm]	20 [mm]	20 [mm]
Tooth width	4 – 9 [mm]	6.5 [mm]	6 [mm]
Tooth height	8 [mm]	8 [mm]	8 [mm]
Slot opening	5 [mm]	5 [mm]	5 [mm]
Magnet width	10 [mm]	10 [mm]	10 [mm]
Magnet height	2.5 [mm]	2.5 [mm]	2.5 [mm]

The induced phase voltages which has been obtained for the arithmetic and geometric mean radii can be observed in Figure 13.

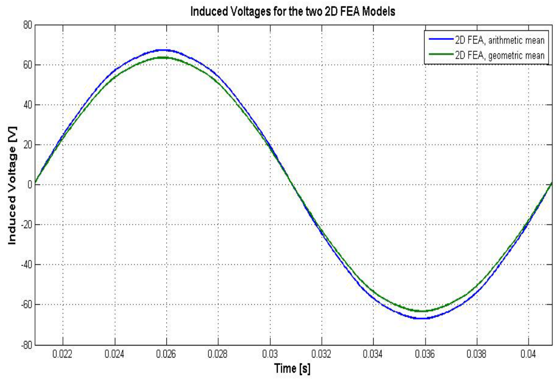

Figure 13: Induced Voltages for the Arithmetic and Geometric Mean Radius

The values of the induced phase voltages are half of the values obtained through the analytical design because just one stator and only half of the rotor have been simulated. Because the stators are connected in series the actual value of the induced voltage is double of that obtained in the simulations.

The amplitude of the induced phase voltage for the model that uses the geometric mean radius is smaller than in the case of the model that uses the arithmetic mean radius. By use of the geometric mean radius to model the AFPMG as a radial flux machine the width of the stator tooth as well as of the inner and outer stator radii are reduced, as can be seen from Table 4.

Table 5: Reduction in Induced Voltages in Function of the Reduction in Machine Dimensions

Modeled Machine / Dimension	Radial Flux Machine (Arithmetic Mean radius)	Radial Flux Machine (geometric mean radius)	Reduction
Inner stator radius	43.92 [mm]	42 [mm]	-4.4%
Outer stator radius	66.42 [mm]	64.5 [mm]	-2.9%
Inner magnet radius	40.42 [mm]	38.5 [mm]	-4.8%
Outer magnet radius	42.92 [mm]	41 [mm]	-4.5%
Tooth width	6.5 [mm]	6 [mm]	-7.7%
Induced voltage	67.15 [V]	63.4 [V]	-5.6%

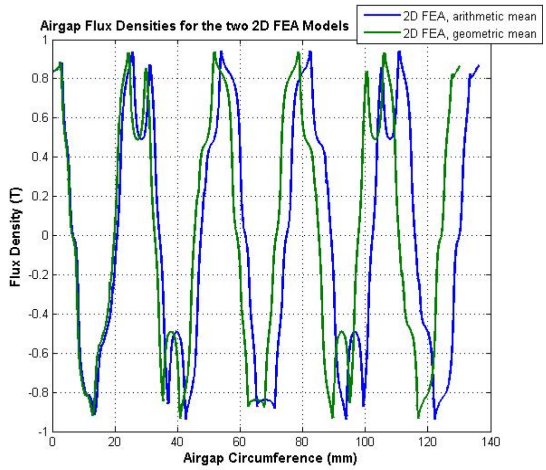

Figure 14: Airgap Flux Density for the Arithmetic and Geometric Mean Radii taken for 12 slots/10 poles

The two simulated radial flux machines display the same amplitude and form of the airgap flux density but the two curves can not be superimposed . This comes from the fact that the circumference of the airgap at which the flux density was determined is shorter in the case of the machine modeled at the geometric radius.

CONCLUSIONS

Axial Flux Permanent Magnet Generators using tooth-concentrated benefit from construction advantages but display increased current linkage space harmonic content which can be determined by means of analytical or 2D FEA methods.

A comparison between the use of single and double layer tooth-concentrated fractional windings has been made with the conclusion that the use of double layer winding for the AFPMG leads to the reduction of the current linkage harmonic content. Another comparison between two modeling methods of the AFPMG with the help 2D FEA has been presented and the results show only a small variation in the induced voltage and in the airgap flux density.

Further research in improving the analytical method to determine the current linkage harmonics and in validating the 2D FEA with the results from 3D FEA is necessary.

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