INFLUENCE OF PERMANENT MAGNETS DESIGN OVER THE PERFORMANCE OF AXIAL FLUX SYNCHRONOUS MOTORS

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REZUMAT. În utimii ani, maşinile cu flux axial şi magneți permanenți au beneficiat de o atenție sporită față de construcțiile clasice, datorită posibilității utilizării lor în spații mici, a cuplului mare şi şi a unor necesități minime de mentenanță. Scopul acestestei lucrări este studiul influenței geometriei magneților permanenți asupra performanțelor maşinii cu flux axial şi rotor interior. Cazurile studiate în această lucrare iau în discuție grosimea, factorul de acoperire polară şi tipul de magnetizare a magneților permanenți.

Cuvinte cheie: Maşina cu flux axial şi rotor intern, magneți permanenți, analiza FEM.

ABSTRACT. In the recent years, the Axial Flux Permanent Magnet Motors have got more attention over the classical machines, due to their small size, high torque and low maintenance. The aim of this paper is the study of the influence of permanent magnets over the performance of internal rotor Axial Flux Permanent Magnet Motors. The studied cases take into discussion the width, the polar pitch factor and thee magnetization type of the permanent magnets.

Keywords: Internal rotor axial flux machine, permanent magnets, FEM analysis.

1. INTRODUCTION

The Axial Flux Permanent Magnet (AFPM) machine, also called the disc-type machine, is an attractive alternative to the cylindrical Radial Flux Permanent Magnet (RFPM) machine due to its pancake shape, compact construction and high power density. AFPM motors are particularly suitable for electrical vehicles, pumps, fans, valve control, centrifuges, machine tools, robots and industrial equipment. The large diameter rotor with its high moment of inertia can be utilized as a flywheel. AFPM machines can also operate as small to medium power generators. Since a large number of poles can be accommodated, these machines are ideal for low speed applications, as for example, electromechanical traction drives hoists or wind generators [1].

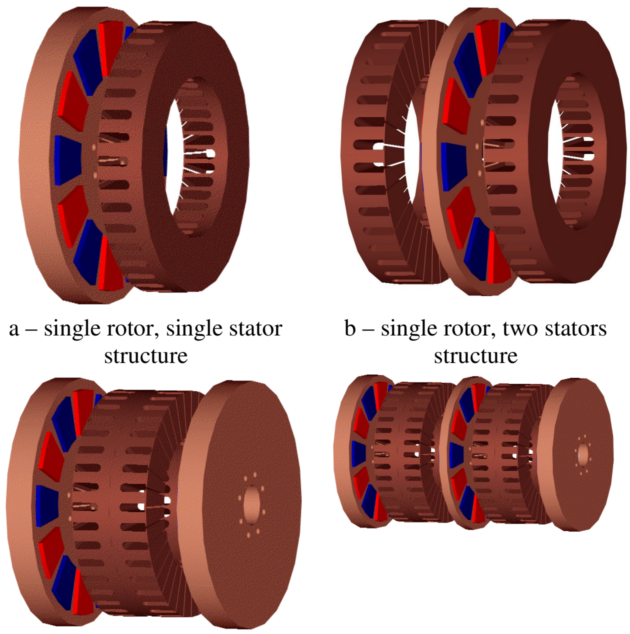
These machines with their unique profile of rotor and stator can be used in various designs. Also these machines can be designed in various structures, for example with one air gap or multiple air gaps, with slotted, slotless or even totally ironless armature.

AFPM machines ask for a careful attention in the design of the rotor – shaft mechanical joint because it may cause the failure of the disc type machines.

The vast majority of the applications use the AFPM machines as a d.c. brushless motor. Encoders, resolvers or other rotor position sensors are thus a vital part of brushless disc motor [1].

One of the most important elements in the construction of these machines is the permanent magnet. The most common types used are: ferrite, alnico, ceramics, samarium-cobalt and neodymium-iron- boron. As regards the permanents magnets made of Nd (neodymium), there are 2 distinct types with rather different magnetic properties: bonded and sintered. These permanent magnets have a high coercitive field strength H_c of 750–2000 kA/m and a remanent magnetic flux density B_r of 1.0–1.4 T, but a low Curie temperature T_c (310–400 C^0), which makes them unusable for applications at high temperature.

Regarding the architecture of axial machines, there are a lot of structures. Among them, four types are commonly used: the simple structure with one rotor and one stator (Fig. 1a), the double sided structure with one stator between two rotors (Fig. 1c), the double sided structure with one rotor between two stators (Fig. 1b) and the multistage structure including several stators and rotors (Fig. 1d) [2].



a – single rotor, single stator structure

b – single rotor, two stators structure

c – single stator, two rotor structure

d – multistage structure

Fig. 1. Axial-flux machine configurations [2].

The aim of this paper is the study of the influence of permanent magnets over the performance of internal rotor AFPM. It has been taken into discussion the influence of width, polar pitch factor and magnetization type of the permanent magnets.

2. ANALYTICAL DESIGN OF AXIAL MACHINE WITH INTERNAL ROTOR AND TWO EXTERNAL STATORS

Any design procedure starts with the nominal data: U_N = 400V, P_N = 1850W, n_N = 3000 rpm, f_N = 100 Hz, Y connection.

The analytical design of the stator is similar to the design of the stator of an induction machine. Consequently, the number of stator slots is obtained with the equation (1):

$$Z_1 = 2 \cdot p \cdot m_1 \cdot q_1 = 36 \qquad (1)$$

where:

p = number of pole pairs, in this case 2;

q_1 = number of slots per pole per phase = 4;

m_1 = number of phases = 3;

The most important geometrical parameters are the outer diameter D_e = 17 cm and the inner diameter D_i = 10cm.

The current density in the stator winding is assumed J_a = 4.5 A/mm^2, so the cross section area of the stator wire is s_a = 0.65mm^2.

Considering the slot fill factor k_u to be 0.7, the cross section of the stator slot should be, approximately, s_{cr} = 30.94 mm^2.

From the design algorithm resulted pole pitch factor α_i = 0.65. The 3D final geometry of the machine is shown in figure 2.

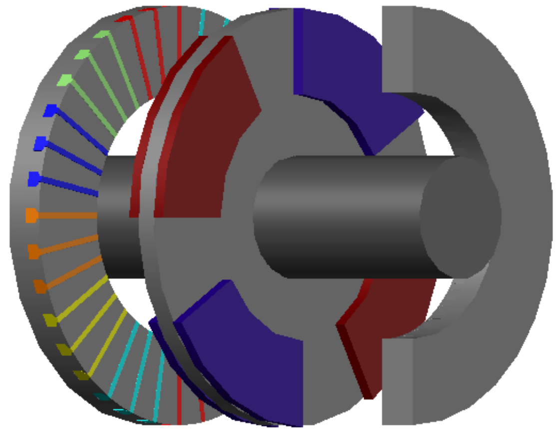


Fig. 2. 3D geometry of the AFPM.

The main parameters of the studied machine are shown in table 1:

Table 1

Main parameters

Symbol	**Name**	**Value**	**Measure unit**
U_N	Nominal voltage	400	V
P_N	Rated power	1850	W
n_N	Rated speed	3000	rpm
f_N	Nominal frequency	100	Hz
I_a	Rated current	2.95	A
B_{mg}	Airgap flux density	0.7	T
D_e	Outer diameter	17	cm
D_i	Inner diameter	10	cm
Z_1	Number of stator slots	36	
g	Length of airgap	1	mm
p	Number of pole pairs	2	

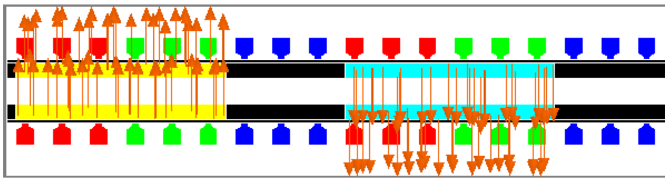
Concerning the permanent magnet system, we have analyzed in this paper six distinct cases that modifies the polarization of the system, the magnitude of the pole pitch factor and the volume of the magnets:

- normal polarization, α_i=0.65 and V_{PM} = 48.24cm^3;
- normal polarization, α_i=0.95 and V_{PM} =70.5cm^3;
- normal polarization, α_i=0.95 and V_{PM} = 48.24cm^3;
- inverted polarization, α_i=0.65 and V_{PM} = 48.24cm^3;
- inverted polarization, α_i=0.95 and V_{PM} =70.5cm^3;
- inverted polarization, α_i=0.95 and V_{PM} = 48.24cm^3.

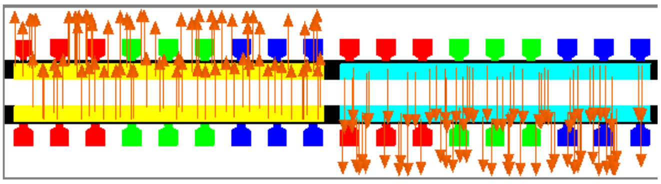
The normal polarization refers to the cases where the magnets placed face-to-face on the rotor have N-S and S-N magnetization (Fig. 3a,b,c). The inverted polarization changes the polarity of the magnets on one side of the rotor and the face-to-face polarization is N-N and S-S (Fig. 3d,e,f).

The value of the pole pitch factor has been increased from $\alpha_i=0.65$ (Fig. 3a,d) to $\alpha_i=0.95$ (Fig. 3b,c,e,f).

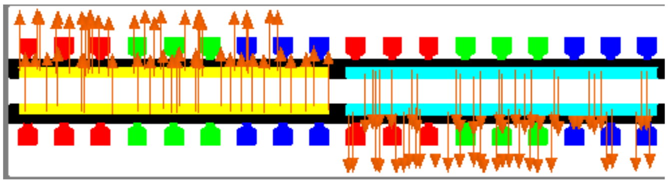
As regarding the volume of the permanent magnets, we have taken into discussion three cases: the first consider the volume calculated for the pre-established air-gap flux density value and $\alpha_i=0.65$ (Fig. 3a,d). The second increases the pole pitch factor to $\alpha_i=0.95$, which leads to an increase of the volume (Fig. 3b,e). The third case come back to the initial volume by maintaining the pole pitch factor to $\alpha_i=0.95$ but decreasing the width of the magnets (Fig. 3c,f).



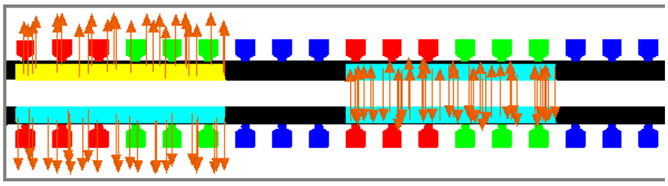
(a) normal polarization, $\alpha_i=0.65$ and $V_{PM} = 48.24cm^3$



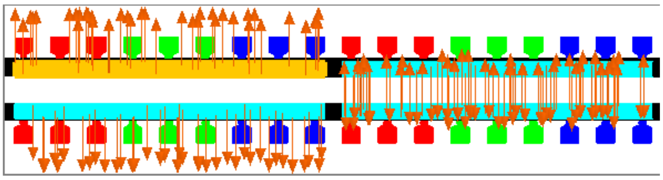
(b) normal polarization, $\alpha_i=0.95$ and $V_{PM} = 70.5cm^3$



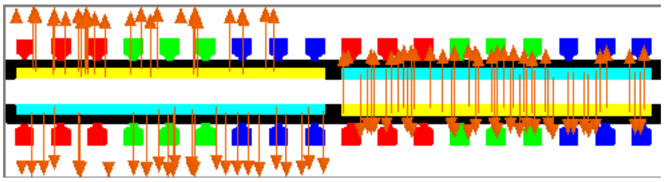
(c) normal polarization, $\alpha_i=0.95$ and $V_{PM} = 48.24cm^3$



(d) inverted polarization, $\alpha_i=0.65$ and $V_{PM} = 48.24cm^3$



(e) inverted polarization, $\alpha_i=0.95$ and $V_{PM} = 70.5cm^3$

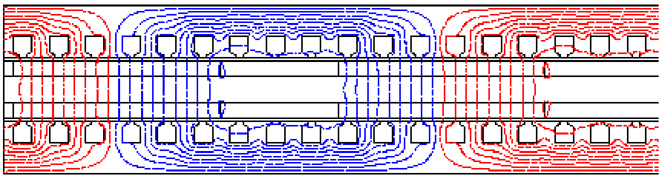


(f) inverted polarization, $\alpha_i=0.95$ and $V_{PM} = 48.24cm^3$

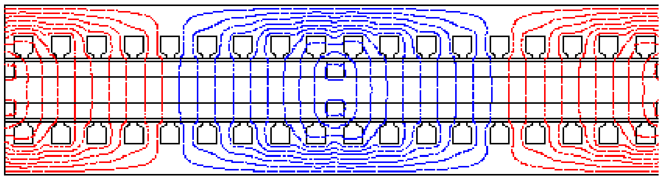
Fig. 3. Geometry and permanent magnets polarization.

3. SIMULATION RESULTS

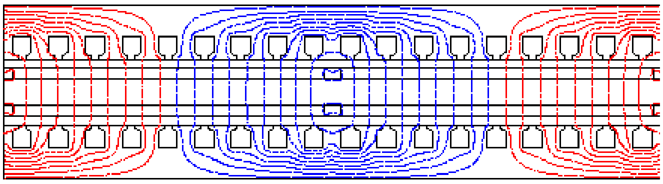
The simulation was carried out by using Flux 2D software package from Cedrat. It is about a magnetostatic type analysis applied on an unreeled model of the machine that takes into consideration only the presence of the permanent magnets (no rotor rotation, no currents in stator windings). Figure 4 displays the flux lines distribution. One can see the difference in line paths between normal and inverted polarization.



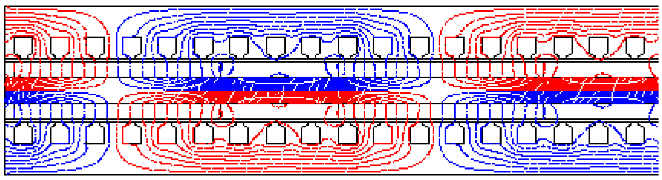
(a) normal polarization, $\alpha_i=0.65$ and $V_{PM} = 48.24cm^3$



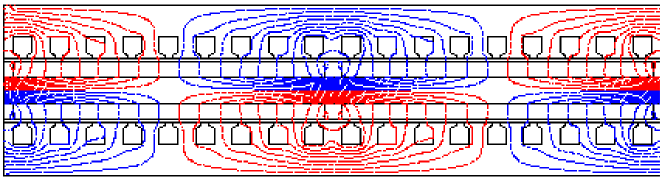
(b) normal polarization, $\alpha_i=0.95$ and $V_{PM} = 70.5cm^3$



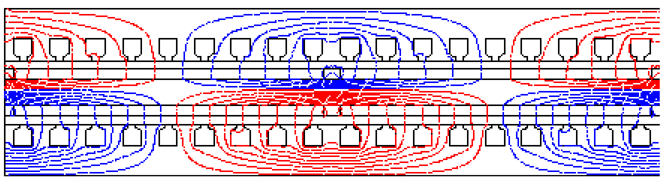
(c) normal polarization, $\alpha_i=0.95$ and $V_{PM} = 48.24cm^3$



(d) inverted polarization, $\alpha_i=0.65$ and $V_{PM} = 48.24cm^3$

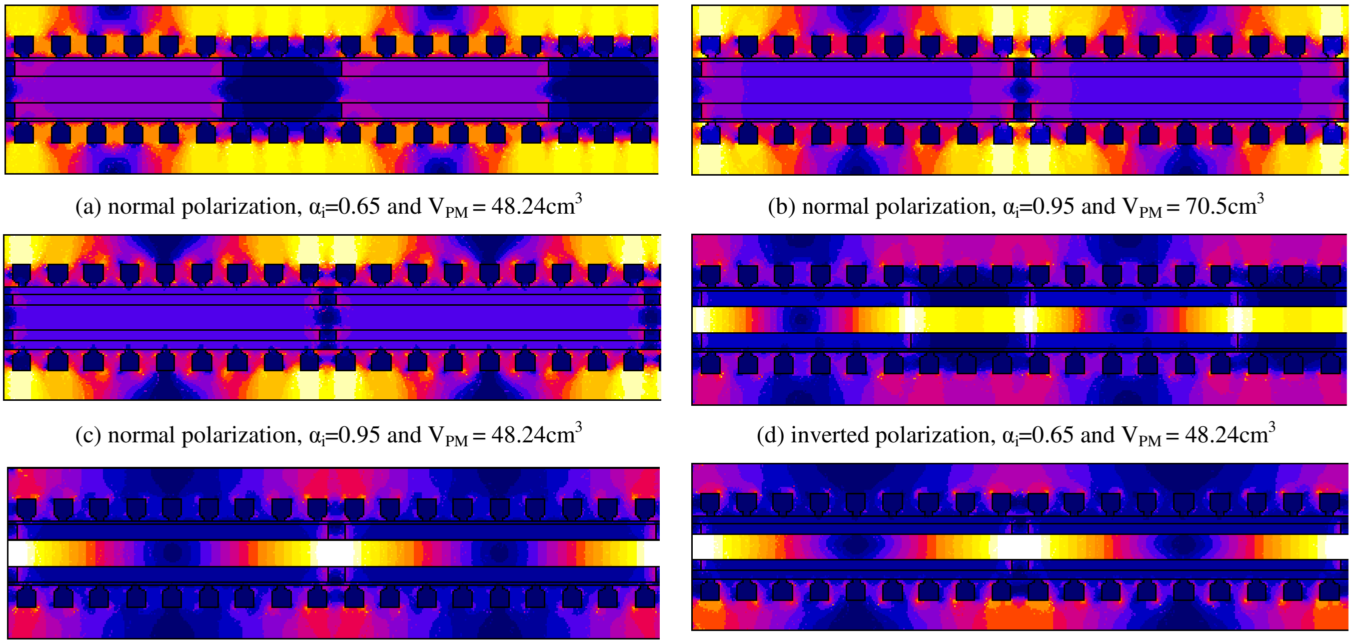


(e) inverted polarization, $\alpha_i=0.95$ and $V_{PM} = 70.5cm^3$



(f) inverted polarization, $\alpha_i=0.95$ and $V_{PM} = 48.24cm^3$

Fig. 4. Flux lines distribution.



(a) normal polarization, α_i=0.65 and V_{PM} = 48.24cm^3 (b) normal polarization, α_i=0.95 and V_{PM} = 70.5cm^3

(c) normal polarization, α_i=0.95 and V_{PM} = 48.24cm^3 (d) inverted polarization, α_i=0.65 and V_{PM} = 48.24cm^3

(e) inverted polarization, α_i=0.95 and V_{PM} = 70.5cm^3 (f) inverted polarization, α_i=0.95 and V_{PM} = 48.24cm^3

Fig. 5. Flux density color map.

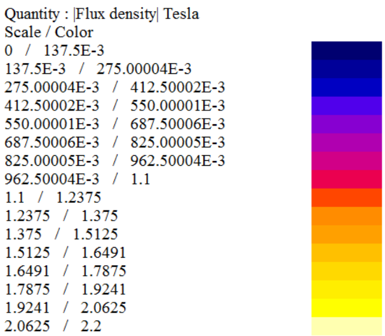
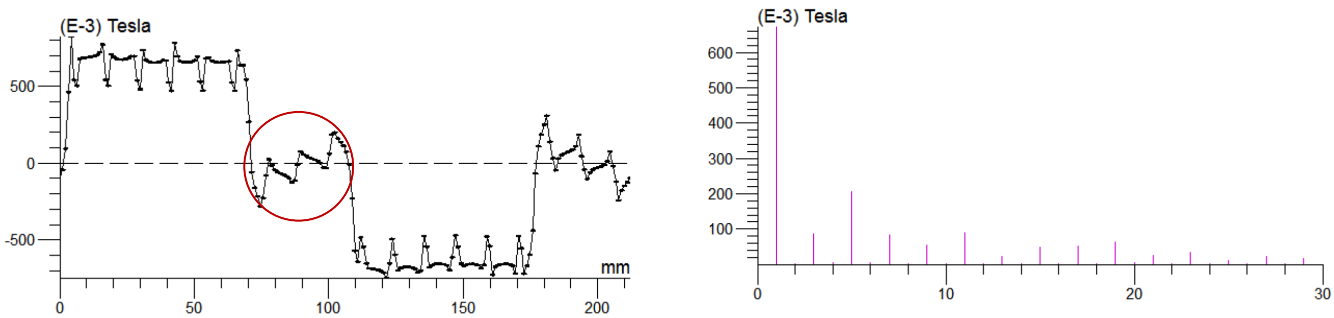


Fig. 6. Legend of the flux density color maps.

Figure 5 shows the flux density color map across the magnetic circuit. One can see that normal polarization loads mainly the stator yokes while the inverted polarization loads the rotor yoke. Consequently, a different approach has to be adopted at the design stage.

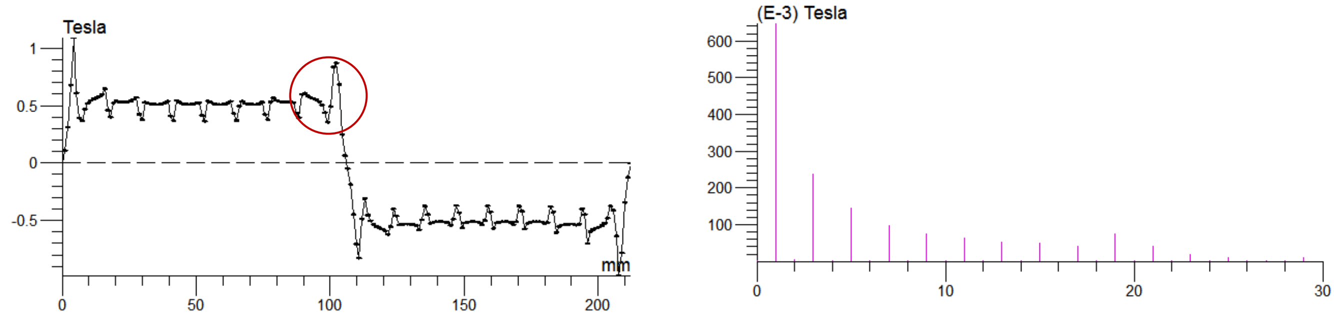
Of great importance in our study are the air-gap flux density curve and its content in high-order harmonics, figure 7. It can be seen that in the first case the fundamental has a value of 0.673 T and a significant number of high-order harmonics. There is also an “ill” area in the flux density air-gap curve (marked with a circle). In the second case, the fundamental has a value of 0.648 T, with a smaller number of high frequency harmonics. In addition, the bad zone disappeared. However, there are still some spikes in flux density air-gap curve. In the third case, the fundamental has a value of 0.585 T, without the spikes from case 2, and the flux density air-gap curve is cuasi-trapezoidal.

In the cases 4, 5 and 6 the fundamental have small values, respectively 0.288, 0.257 and 0.2T. It is a normal fact due to the modification of magnetic lines paths. For the case 4 the bad zone is still present. Also, there is a big number of high frequency harmonics.

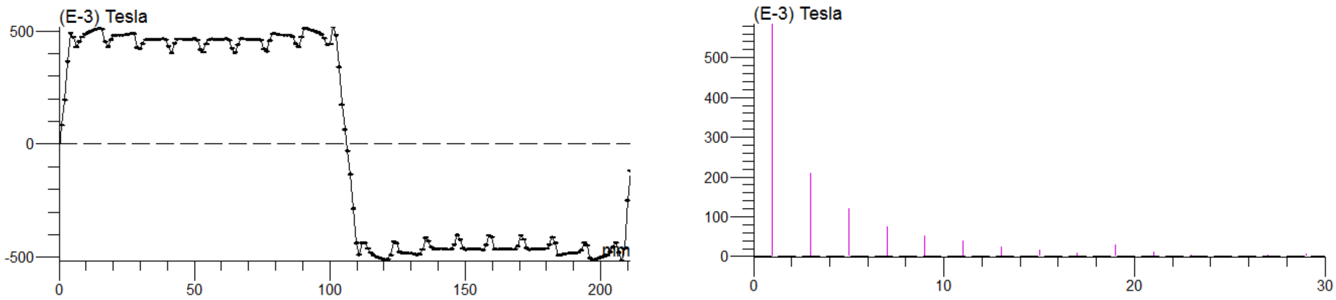


(a) normal polarization, α_i=0.65 and V_{PM} = 48.24cm^3

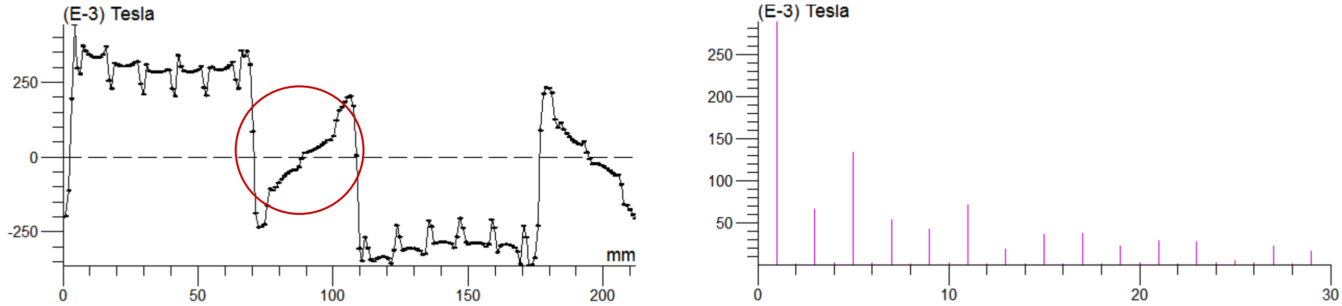
Fig. 7. Air-gap flux density curve and content in high-order harmonics.



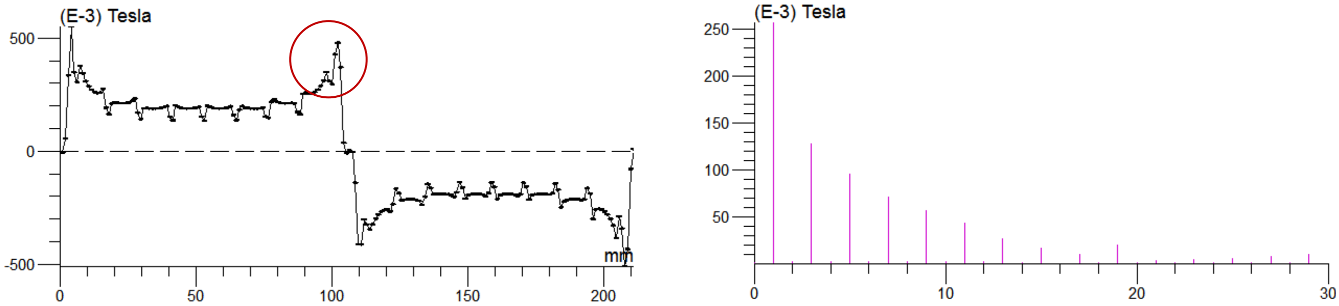
(b) normal polarization, α_i=0.955 and V_{PM} = 70.5cm^3



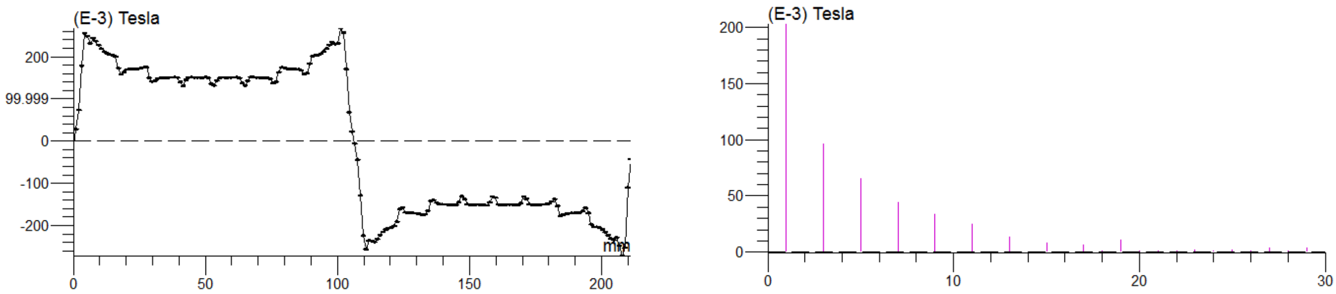
(c) normal polarization, α_i=0.95 and V_{PM} = 48.24cm^3



(d) inverted polarization, α_i=0.65 and V_{PM} = 48.24cm^3



(e) inverted polarization, α_i=0.95 and V_{PM} = 70.5cm^3



(f) inverted polarization, α_i=0.95 and V_{PM} = 48.24cm^3

Fig. 7 (continued).

4. CONCLUSIONS

The aim of this paper is the study of the influence of the geometry of the neodim permanent magnets on the performance of an axial flux machine. Three parameters have been modified: pole pitch factor, width and magnetization.

This study was performed by using the Flux 2D simulation software package. No doubt, despite the theoretical recommendation concerning the value of the pole pitch factor, $\alpha_i = 0.65$, better results can be obtained by using a higher pole pitch factor. Our analysis proved, for example, that $\alpha_i = 0.95$ determine a more trapezoidal curve and a total disappearance of the unsuitable deformations of the air-gap flux density curve.

Important for the studied structure is also the magnetization of the magnets that are placed face-to-face on the rotor. The design of the magnetic circuit must take into consideration this aspect from the flux density value viewpoint.

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