Optimal Design of PM Axial Field Motor Based on PM Radial Field Motor Data

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Abstract: - In this paper the fundamental differences between axial and radial flux machines are explored. The choice of machine type for given application is a complex task and often depends upon designer's experience and preconceptions. Radial field permanent magnet machines, for good reasons, have traditionally made up the majority of commercial PM machines. The use of axial field permanent magnet machines has increased in the recent years in a wide range of applications. The aim of the paper is to compare axial and radial flux arrangements on a structural and electromagnetic basis.

Key-Words: - PM axial field motor, PM radial field motor, optimal design, genetic algorithm, FEM analysis

1 Introduction

In recent years, axial flux motors (AFMs) have been the objects of numerous research studies. Different motor structures and geometries, for different applications, have been proposed as an alternative to the conventional radial flux motors (RFMs).

Besides the technological and manufacturing differences, it is interesting to compare AFMs and RFMs to understand when and where the AFMs show potential advantages.

A general comparison of AFMs versus RFMs is not possible, due to the large number of possible technical solutions; thus the comparison is focused on the specific type of surface-mounted permanent magnet (PM) synchronous motors:

- the most common RFMs with external stator and one internal rotor;
- the AFMs with two external stators and one internal rotor.

Traditionally, in the literature, the comparison between electric motors is performed using the "sizing equations". These equations link the motor electromagnetic torque to the motor length and motor diameter through coefficients depending on the electric/magnetic material consumption. The coefficients and the electric and the magnetic loading are chosen onto experience basis. However, for novel motor prototypes, this experience usually is not available.

In this paper, the comparison procedure is based on geometric and electro-magnetic field analysis of an already made RFM and an optimal designed AFM. To fairly compare the two motors, the torque, the rotational speed, the number of rotor poles, the supply voltage and the magnetic materials are kept unchanged.

2 Structure definition of the motors

The comparison is limited to radial field and axial field permanent magnet brushless motors with sinusoidal back electromotive force and isotropic rotor surface (surface-mounted rare-earth magnet-$SmCo_5$). The considered motors have slotted stators.

2.1 RF PM synchronous motor

The considered radial field (RF) structure is common one with one external cylindrical stator and one internal cylindrical rotor. This RFM is widely used in different applications; thus, it is considered the reference solution.

The motor geometry is presented in Fig. 1 and the dimensions are listed in Table 1.

2.2 AF PM synchronous motor

Among the axial field (AF) structures, several different geometries have been proposed. In particular, the sandwiched structures with more than one stator and/or rotor seemed to be the most attractive. The motor considered in this paper is realised by two external stators and one internal rotor. Such structure does not require, in principle, any rotor yoke; hence the overall axial length is rather short. The advantage of this construction is cancellation of the axial attractive force between the rotor and the stator that always exists due to the force of attraction between the magnets and the stator steel. Fig. 2 shows the motor view and the main dimensions reported in Table 2.

In the AFMs, the active core length useful for the torque generation is $(D_o\text{-}D_i)/2$.

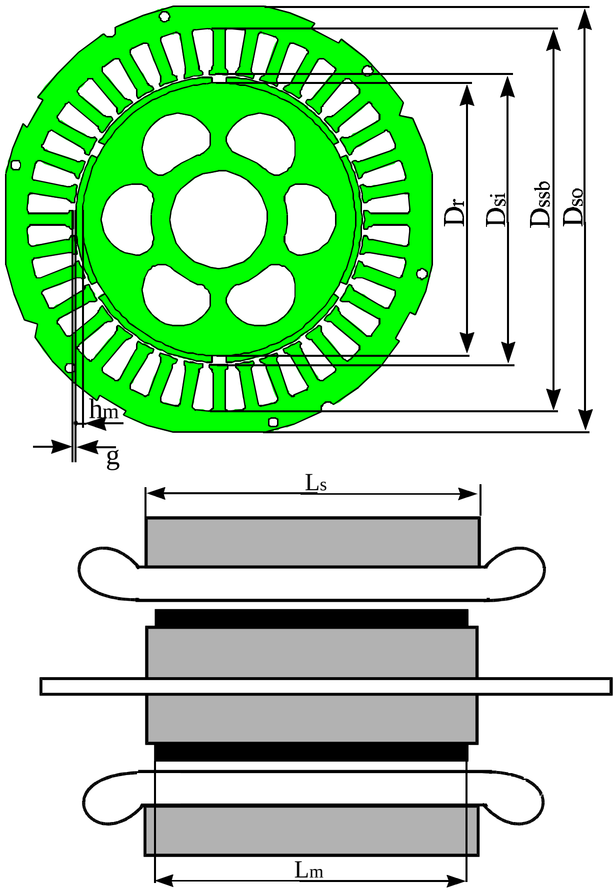

Fig. 1. Main dimensions of the RF PM motor

Table 1. Main RF PM motor dimensions

Axial stator core length [m]	L_s
Axial PM length [m]	L_m
Outer stator diameter [m]	D_{so}
Stator slot bottom diameter [m]	D_{ssb}
Inner stator diameter [m]	D_{si}
Outer rotor diameter [m]	D_r
Magnet radial length [m]	l_m
Magnet radial length [m]	h_m
Air gap radial thickness [m]	g
Fraction of the PM	a_m

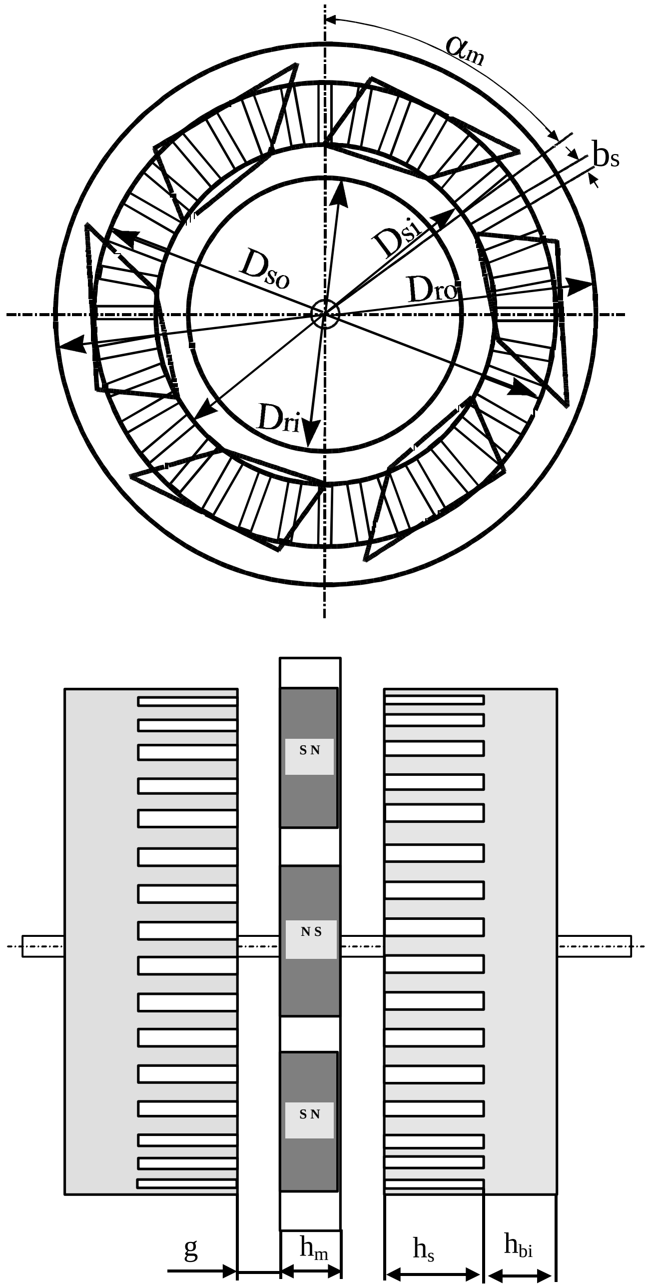

Fig. 2. Main dimensions of the AF PM motor

Table 2. Main AF PM motor dimensions

Axial PM length [m]	h_m
Outer stator diameter [m]	D_{so}
Inner stator diameter [m]	D_{si}
Outer rotor diameter [m]	D_{ro}
Inner rotor diameter [m]	D_{ri}
Air gap radial thickness [m]	g
Fraction of the PM	a_m
Stator slot width [m]	b_s
Stator back iron thickness [m]	h_{bi}
Stator slot height [m]	h_s

3 Optimal Design of Axial Field PM Motor

The comparative analysis of the RF and AF PM motors is performed on a RF produced motor and an optimal designed AF motor. The AF PM motor is designed on the basis of the RF motor where the torque, the rotational speed, the number of rotor poles, the supply voltage and the magnetic materials are kept constant. The reason for an optimal design approach is the complexity of the AF motor, its design procedure and non-linearity.

Design optimisation of electrical machines, and in particular axial field permanent magnet motors, is a very important but quite complicated problem. In general, the optimal design of electrical machines is a complex multi-variable, non-linear and constrained optimisation procedure. The non-linear nature of the active materials (cores), together with the discreteness in change of some design parameters (wires), renders the task of optimisation as a mixed real number programming problem. A reasonably simplified form of the design procedure may be attacked by various approaches accumulated into two main topics: classical optimisation techniques (deterministic methods) versus genetic algorithm (stochastic methods).

For a long time researchers have been using classical (usually gradient based) optimisation techniques for accomplishing this task. However, recently, evolutionary computation techniques such as Genetic Algorithm (GA) have been used for optimisation procedures. Such methods are claimed to be more successful in converging to a global optimum avoiding the local optimum [1]. Even more, they avoid the problem of starting the search from a suitable feasible solution, often encountered in classical optimisation techniques.

3.1 Genetic algorithm

The selected and applied stochastic optimisation method is the Genetic Algorithm (GA), which is an attractive and very powerful evolutionary search method based on the mechanics of natural selection and natural genetics. The search starts from a randomly created population of strings representing the chromosomes and obtains optimum after a certain number of generations by applying genetic operations. The main genetic operators of the genetic algorithm are reproduction, crossover and mutation. After the operators perform their functions, the new generation of members, which have gained new information through the exchange between pairs, is produced. The better traits of the "parent" chromosomes are carried along to the future generations. The optimal solution of the AFM is selected as the best solution of the GA search. The GA created for the optimal design of the AFM uses real number representation, elitism, arithmetic crossover and linear fitness scaling as an improvement and better reliability of the GA search. The only less competitive property of the GA optimisation search is the big number of objective function calculations. The values of the GA parameters used for the optimal design of the AFM are presented in Table 3.

Table 3. GA parameters

GA parameter	Value
Population size N	20
Probability of crossover p_c	0.85
Probability of mutation p_m	0.07
Number of generations G	1500

3.2 RFM description

The radial flux motor used for this comparison analysis is an existing prototype permanent magnet motor with radial topology. The front and side view of the motor is presented in Fig. 1. The RFM rated data are presented in Table 4.

Table 4. RFM rated data

Motor parameter	Value
Torque [Nm]	10
Current [A]	17.6
Voltage [V]	48
Speed [rpm]	1000
Number of rotor poles	6
PM remanent flux density [T]	0.95
PM coercitive field [kA/m]	-720
Number of stator slots	36
Number of turns in a slot	9
Number of phases	3

3.3 Optimal design procedure of AF PM motor

According to the design characteristics of AFM, some of the parameters are chosen to be constant and some to be varying, such as: inside radius of the stator cores $\boldsymbol{R_i}$, outside radius of the stator cores $\boldsymbol{R_o}$, magnet fraction $\boldsymbol{a_m}$, magnet axial length $\boldsymbol{l_m}$, air-gap $\boldsymbol{g}$, single wire diameter $\boldsymbol{d_w}$ and sloth width $\boldsymbol{b_s}$. Some of them are presented in Figure 2.

The efficiency of the motor is taken to be the objective function of the optimisation:

$$efficiency = \frac{T \cdot w_m}{T \cdot w_m + P_{Cu} + P_{Fe} + P_s} \quad (1)$$

where: T-rated torque, w_m-synchronous speed, P_{Cu}-copper power loss, P_{Fe}-iron power loss and P_s-other constant losses calculated from no load test of the machine. The optimal design process is a maximisation problem of the objective function, where the torque is one of the constraints.

Due to the fact that the optimised motor is a novel type of motor, at this stage it is important to define some of the motor parameters and their dependence on the optimisation variables. The copper power loss P_{cu} can be described with the following equation:

$$P_{cu} = N_{ph} \cdot I_{ph}^2 \cdot R_{ph} \quad (2)$$

and the phase resistance R_{ph} with the equation:

$$R_{ph} = \frac{N_{st} \cdot r \cdot W_s \cdot N_{sp}[2(R_o - R_i) + 1.65(t_{ci} + t_{co})]}{n \cdot S_w} \quad (3)$$

where:
N_{ph} - number of phases
I_{ph} - phase current
N_{sp} - slots per phase
N_{st} - number of stators
W_s - number of turns per coil
t_{ci} - coil pitch on the inside radius
t_{co} - coil pitch on the outside radius
n - number of strands in parallel
S_w - cross-section area of the wire

The iron loss P_{Fe} can be described with the equation:

$$P_{Fe} = N_{st} r_{fe} \left(V_{st} \Gamma_{B_{mst},f} \left(\frac{B_{st}}{B_{mst}} \right)^2 + V_{bi} \Gamma_{B_{mbi},f} \left(\frac{B_{bi}}{B_{mbi}} \right)^2 \right) \quad (4)$$

where:
r_{fe} - stator steel mass density
$\Gamma_{Bm,f}$ - stator steel core loss density
B_{bi} - stator back iron flux density
B_{st} - stator teeth flux density
V_{bi} - stator back iron volume
V_{st} - stator teeth volume

The volumes of the stator back iron and stator teeth are defined with equation:

$$V_{bi} = k_{st} \cdot p \cdot \left(R_o^2 - R_i^2\right) \cdot w_{bi}$$
$$V_{st} = k_{st} \cdot p \cdot \left(R_o^2 - R_i^2\right) \cdot d_s - Z(R_o - R_i) \cdot d_s \cdot b_s \quad (5)$$

where:
k_{st} - lamination stacking factor
w_{bi} - back iron width
d_s - total slot depth
b_s - total slot width
Z - number of stator slots

On the other hand, the values of the flux densities in the back iron and stator teeth are defined with the following equations:

$$B_{st} = \frac{\Phi_g}{N_{sm} \cdot S_{st} \cdot k_{st}} \quad (6)$$

$$B_{bi} = \frac{\Phi_g}{2 \cdot w_{bi} \cdot (R_o - R_i) \cdot k_{st}} \quad (7)$$

where:
F_g - air gap flux
N_{sm} - number of slots per pole
S_{st} - stator tooth area

These are only a part of the equations representing the complex mathematical model of the axial field motor [2] developed for the optimisation design procedure.

The stopping rule while the genetic algorithm works is selected to be the number of generations. The values of the upper and lower bound for each design variable are introduced in Table 5, and the design constraints are presented in Table 6.

Table 5. Upper and lower bound of the variables

Variable	Unit	Lower bound	Upper bound
R_i	[m]	0.03	0.04
R_o	[m]	0.05	0.1
a_m	[/]	0.6	0.9
l_m	[m]	0.004	0.011
g	[m]	0.0005	0.001
d_w	[m]	0.001	0.002
b_s	[m]	0.001	0.004

Table 6. Optimisation design constraints

Description	Parameters	Value
Torque	T [Nm]	10
PM residual flux density	B_r [T]	0.95
Number of PM	N_m	6
Number of stator slots	Z	36
Stator back iron flux density	B_{mbi} [T]	≤ 1.5
Stator teeth flux density	B_{mst} [T]	≤ 1.5
Stator steel mass density	r_{bi} [kg/m^3]	7800

3.3 AF PM motor GA optimisation results

After the operators are defined, several different runs for different values of the GA operators are performed. The values of the optimisation variables and the value of the efficiency for the best optimisation search are presented in Table 7.

Table 7. AF PM motor GA optimisation results

Variable	Unit	AF PM motor
R_i	[m]	0.031122
R_o	[m]	0.068155
a_m	[/]	0.62499
l_m	[m]	0.010994
g	[m]	0.0005162
d_w	[m]	0.0019915
b_s	[m]	0.0039964
efficiency	[/]	0.9351
No. iterations	[/]	30000

The convergence of the efficiency value during the GA optimisation search for 1500 generations is shown in Fig. 3.

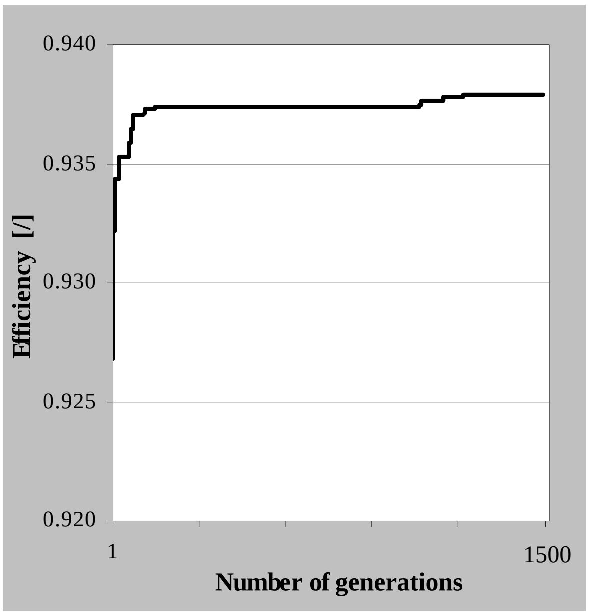

Fig. 3. Efficiency change during GA optimisation

4 FEM Analysis of the Motor Models

In order to be able to get the necessary data for the comparison analysis of the RFM and AFM, a calculation of the magnetic field has to be performed. The 2D analysis is very suitable for both motor topologies, especially for the disc type of geometry and has a lot of advantages over the 3D calculation, such as lower memory storage and reduced time computation.

4.1 Radial Field Motor Modelling

The 2D model of the RFM adopted for the FEM analysis is presented in Fig. 4. In the modelling of the motor the lamination of the stator and rotor are taken into consideration as well as the axial length of the motor.

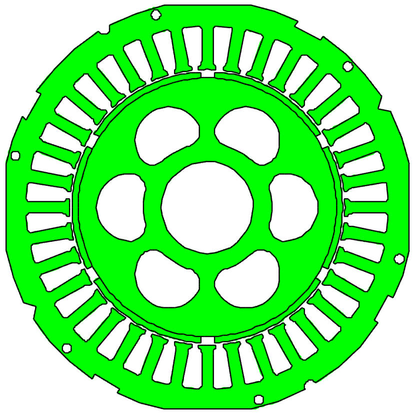

Fig. 4. RFM model for FEM calculation

4.2 Axial Field Motor Modelling

The quasi-3D method which is adopted for this analysis consists of a 2D FEM calculation of the magnetic field in a three dimensional radial domain of the axial field motor. For this purpose, a notional radial cut through the two stators and one rotor of the disc motor is performed and then opened out into linear form, as shown in Fig. 6. By using this linear quasi three-dimensional model of the disc motor, divided into five segments, it is possible to model the skewing of the magnets and also to simulate the vertical displacement and rotation of the rotor. Due to the symmetry of the machine the calculation of the motor is performed only for one third of the axial field permanent magnet motor, i.e. for one pair of permanent magnets.

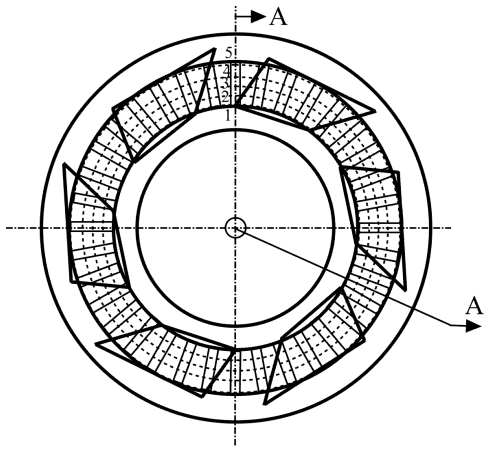

Fig. 5. Radial division of the AFM into 5 segments

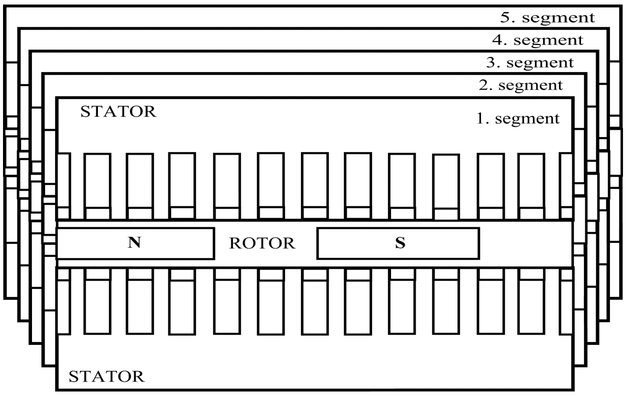

Fig. 6. 2D presentation of the 5 AFM segments

4.3 Magnetic field calculation

After the proper modelling of the two types of topologies and an adequate mesh size refinement, especially in the air gap, a magnetic field calculation is performed for each geometry topology and for different current loads. In this paper the results are presented only for no load. In Fig. 7 a presentation of the magnetic field distribution for the PM radial field motor at no load is shown, while in Fig. 8 is presented the air gap flux density distribution at the same operating condition.

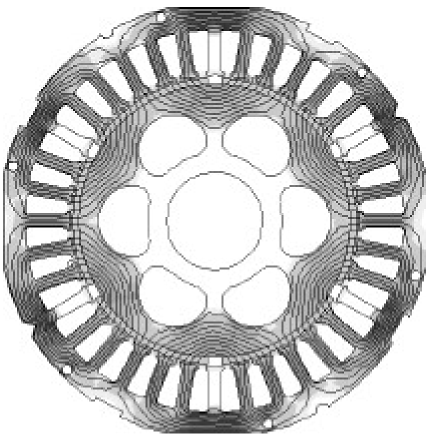

Fig. 7. RFM magnetic field distribution at no load

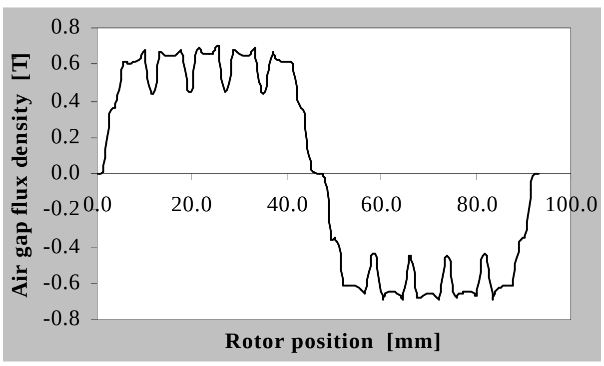

Fig. 8. RFM air gap flux density distribution at no load

In Fig. 9, Fig. 10 and Fig. 11 a magnetic field distribution at no load for the axial field motor is presented for the 1st, 3rd and 5th segment, respectively. On the other hand the air gap flux density for the same no load condition for the three segments is presented in Fig. 12, Fig. 13 and Fig.14, respectively. Although the magnetic field calculation is performed for all five segments the field distribution in this paper is presented only for the 1^{st}, 3^{rd} and 5^{th} segment because they are more interesting for the magnetic field analysis.

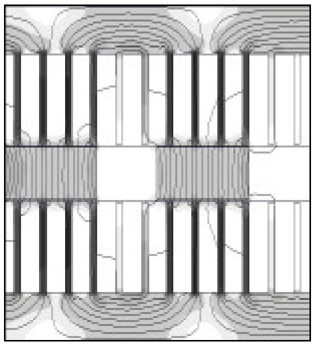

Fig. 9. AFM magnetic field distribution at no load for the 1^{st} segment

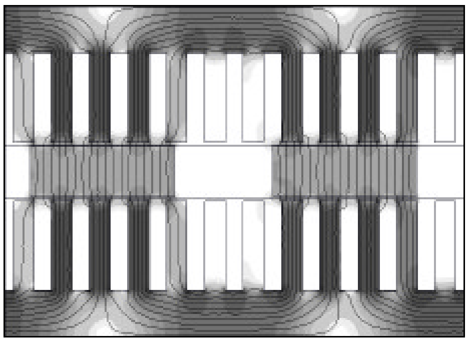

Fig. 10. AFM magnetic field distribution at no load for the 3^{rd} segment

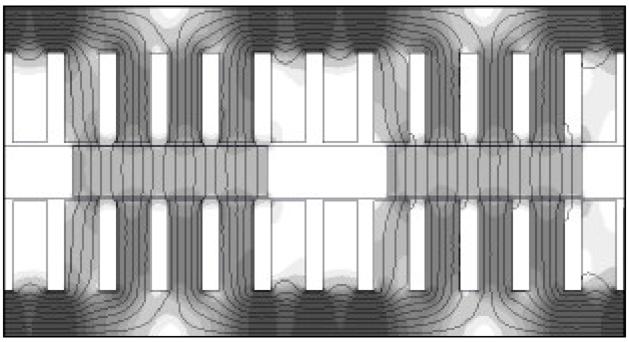

Fig. 11. AFM magnetic field distribution at no load for the 5^{th} segment

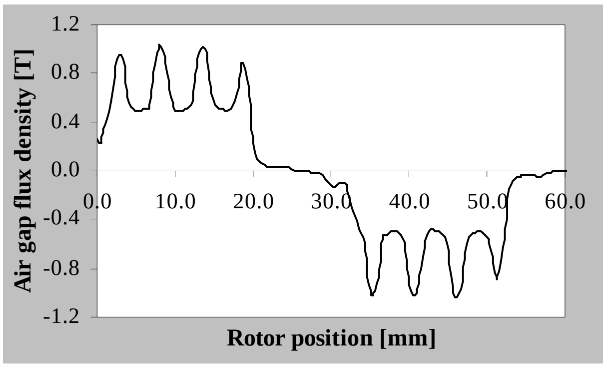

Fig. 12. AFM air gap flux density distribution at no load for the 1st segment

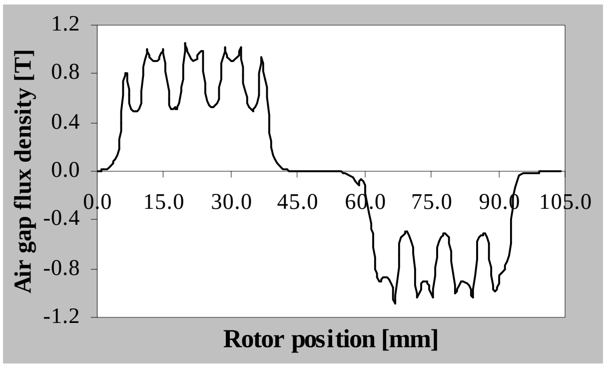

Fig. 13. AFM air gap flux density distribution at no load for the 3rd segment

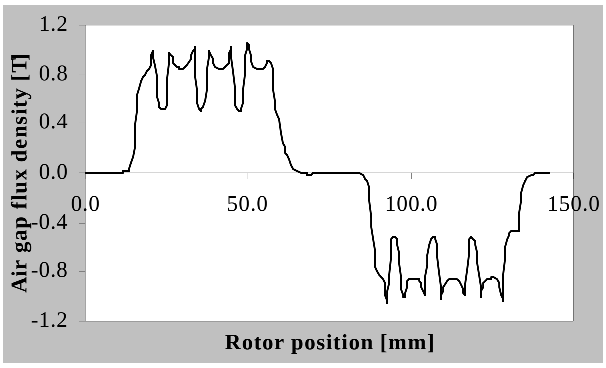

Fig. 14. AFM air gap flux density distribution at no load for the 5th segment

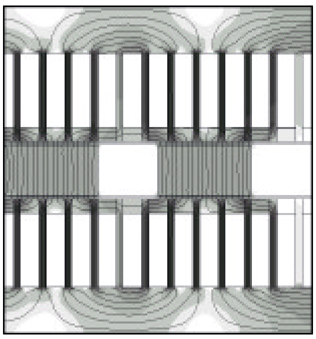

Fig. 15. AFM magnetic field distribution at no load for the 1st segment with SMC closure

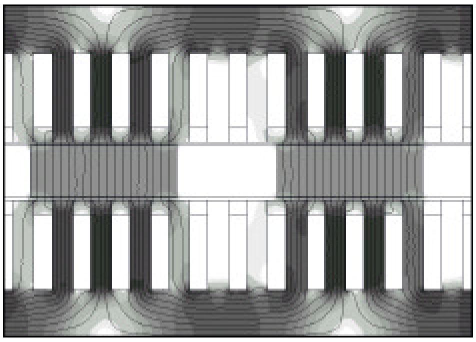

Fig. 16. AFM magnetic field distribution at no load for the 3rd segment with SMC closure

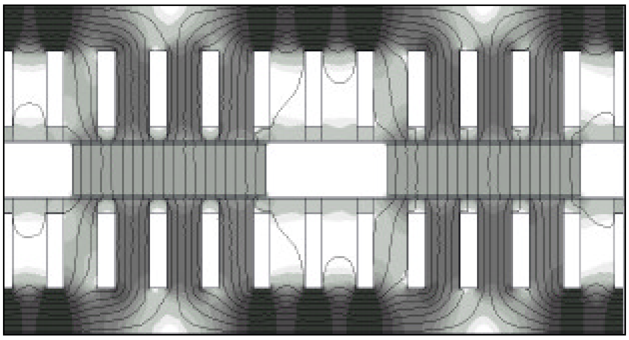

Fig. 17. AFM magnetic field distribution at no load for the 5th segment with SMC closure

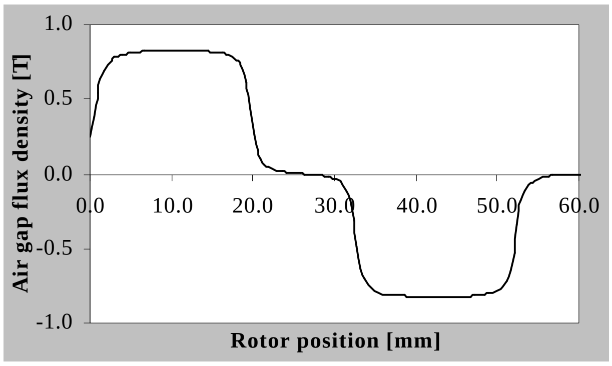

Fig. 18. AFM air gap flux density distribution at no load for the 1st segment with SMC closure

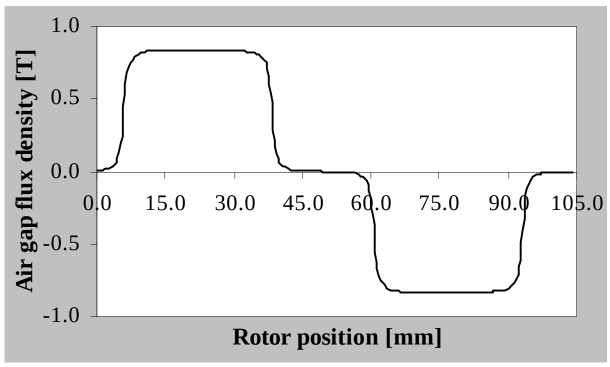

Fig. 19. AFM air gap flux density distribution at no load for the 3rd segment with SMC closure

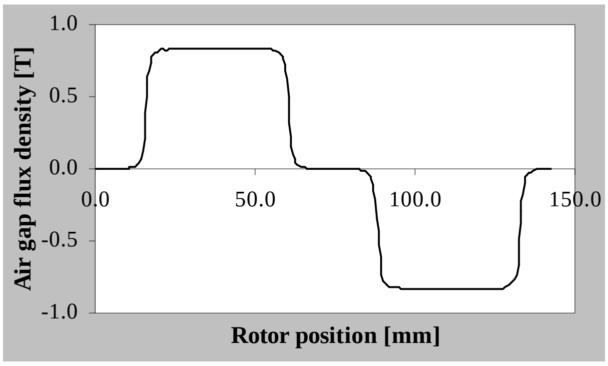

Fig. 20. AFM air gap flux density distribution at no load for the 5th segment with SMC closure

It should be noted that the disc topology gives the possibility of inserting a slot closure made of soft magnetic composite (SMC) material, which quite improves the magnetic field distribution in the motor as it is presented in the Fig. 15, Fig. 16 and Fig. 17. The improvement of the air gap flux density distribution is presented in Fig. 18, Fig. 19 and Fig.20. The implementation of the SMC material as a stator slot closure not only improves the magnetic field distribution but also improves the motor parameters and characteristics [3-4].

5 Comparative Analysis of the Motor Models

The calculated data form the FEM magnetic field analysis in the postprocessor mode could be also used to determine some other magnetic and electric parameters [5] necessary for the complete and complex analysis of the two PM motors topologies. The comparative values of some RFM and AFM parameters are presented in Table 8.

Table 8. RFM and AFM parameters

Parameter	RFM	AFM
I [A]	17.6	8.183
g [m]	0.00082	0.0005161
W_s [turns/coil]	9	8
d_w [mm]	1.878	2.00
$R_{ph75°}$ [Ω]	0.2548	0.161
P_{Cu} [W]	115.42	32.35
P_{Fe} [W]	50.58	20.93
V_m [m^3]	0.0000432	0.00007937
V_{Fe} [m^3]	0.0007449	0.0004485
B_{gav} [T]	0.5178	0.54997
$F_{g\,av}$ [Wb]	0.002176	0.0009827
efficiency	0.8479	0.9351

From previously presented data it is obvious that the axial field motor has overall better parameters, both geometric and electromagnetic. This makes the AFM very attractive for applications where there is lack of space (planes, ships, vehicles, PC etc.) or in applications where there is a need of a motor with high efficiency and high energy/volume ratio.

6 Conclusion

In this paper a geometrical comparison of axial and radial flux permanent magnet motors is presented. An introduction of the genetic algorithm as optimisation tool is also performed. The axial field motor is designed using genetic algorithm based optimisation programme proceeding from input data of the radial flux prototype motor. For the comparison analysis of the two motor topologies, a 2D FEM magnetic field calculation is performed. At the end a comparative analysis of RFM and AFM, based on geometrical and FEM calculated parameters, is presented.

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