PERMANENT MAGNET SYNCHRONOUS MOTOR DESIGN OPTIMIZATION

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REZUMAT. În lucrarea de față se prezintă o metoda de optimizare, din punct de vedere electromagnetic, a construcției unei maşini sincrone cu magneți permanenți plasați direct în întrefier, fără perii. Scopul acestui studiu este, pornind de la o valoare impusa a cuplului de sarcină, identificarea valorii optime a razei exterioare de curbură a magneților permanenți, plasați pe rotorul maşinii electrice studiate, astfel încât atingerea valorii dorite a cuplului să se realizeze în condițiile utilizării unui volum minim de material magnetic şi la un curent statoric minim.

Cuvinte cheie: maşină sincronă cu magneți permanenți, rază de curbură exterioară, optimizare electromagnetică

ABSTRACT. The paper presents the rotor design of a brushless synchronous bread-loaf permanent magnet machine (PMSM), while the following restrictions are present: requested load torque, minimum current, minimum permanent magnet volume. The optimized parameter under study is the top curvature of the permanent magnets. The optimization is performed while monitoring related electromagnetic indicator quantities, such as the air-gap magnetic flux waveform, saturation and the amount of magnet material.

Keywords: PM machine drives, synchronous and reluctance machines, optimization

1. INTRODUCTION

The new global trend of minimizing the pollution has led to development of specific technologies applicable to electric vehicles.

As the employment of electric vehicles has proven to be a key challenge for the big manufacturers, i.e. lower autonomy when compared to conventional vehicles, these have turned their research interest to a more accessible area, namely the development of the hybrid electric vehicles (HEV).

The HEV concept is not a new one as the first patent, involving HEV technology, was filled in 1905 by the American H. Piper [1].

To remain competitive, HEV technology versus conventional vehicles requires the use of an electric motor featuring high power density, high efficiency and a wide constant power operating region as well as low manufacturing cost. It has been also appreciated the possibility of this type of motor to operate in a wide - constant power - speed range [2].

Both induction machine drives and permanent magnet synchronous machine (PMSM) drives are suitable for propulsion of electrical vehicles but only PMSM provide the necessary advantages (such as high torque/mass ratio, no windings, no sliding contact - simplicity in building of rotor-, better dynamic performance, higher power factor and therefore, an enhanced level of reliability) that lead to optimizing the cost, mass, autonomy and performance of the vehicle [3].

The recent developments of permanent magnet (PM) materials, solid-state devices and microelectronics made the permanent magnet synchronous motors to be also increasingly used in many other electric drive systems, in addition to electric vehicles [4], therefore it is not surprising that many current researches are taking into account PMSM optimization (both in terms of design and control method) [5], [6].

As we all know, the high price of PMSM is mainly due to the cost of permanent magnets material. So, in order to achieve minimum cost and volume for the motor, optimization of its PMs geometry is necessary.

An optimal design of a PMSM is presented in [7] and [8] in which some of the PMSM parameters and dimensions are selected as design variables. These variables (with the aim of getting maximum torque) are: magnet dimensions, motor stack length, flux barrier dimensions and number of phase winding. The main constant specifications in the design procedure are the rated torque, the pole pitch and the input voltage. Following the completion of the optimization process the amount of material required for permanent magnets is reduced by 8.8%.

Another paper which presents the design of a permanent magnet synchronous motor is [4]. Two rotor types were studied: the surface mounted PM (SPM) and inset PM configuration (IPM). The design study is based on an existing induction motor geometry and a PMSM prototype created with winding configuration identical to the one used in induction motor. The focus of the study has been only placed on the following three geometric parameters: size of the air gap, thickness of the magnet and magnet span/coverage. The final comparison in performance between SPM and IPM highlight that IPM has a higher rated torque, due to additional reluctance torque generated from the rotor saliency.

A novel structure for IPM synchronous machine used for traction applications is presented in [9]. In order to achieve low torque ripple, iron losses and cogging torque, an iteration method (based on a flowchart), using 3D-Finite Element Method, is described. This way an accurate volume for the permanent magnets, taking into account the magnetic circuit in which the PM material is inset, is possible. The main achievements of this iteration method (which leads to maximum flux density) are reaching of minimum volume, maximum torque per ampere and minimum value of cogging torque.

Reference [10] presents a methodology for the design of a permanent magnet generator used in wind power turbines. The technique comprises a preliminary design stage by means of standard formulas and an optimization stage, involving a two dimensional finite element model (in which the magnet main dimensions are varied), for the permanent magnet shape. The process involves torque maximization for a given PM volume. An application of the proposed method is given concerning the design of a 20 kW multi-pole generator.

The paper presents the design optimization of a permanent magnet synchronous motor regarding the top side curvature of the bread-loaf permanent magnets in order to fulfill the designing input data, i.e. the torque and the speed. During the optimization, the saturation, stator current and permanent magnet volume are also monitored, so that the final solution features high efficiency material usage, i.e. high energy density for a reduced quantity of permanent magnet material.

2. MOTOR SPECIFICATIONS

The motor under design is a permanent magnet synchronous motor with bread-loaf shaped magnets. The main data of the motor to be designed are shown in Table 1. The presented data correspond to the load required by a small-size electric transportation vehicle prototype.

Table 1

PMSM main design data

Quantity	Value	Unit
Speed	3000	rev/min
Torque	1	Nm

3. OPTIMIZING METHOD

In order to get the optimized geometry several parameters have to be monitored. The main goal is to get the highest torque, the highest torque density for the given geometry of the machine to be more specifically. The quantity that influences the torque is the magnetic flux inside the machine and so this is a crucial factor to be optimized. While the stator magnetic flux is generated by the stator magneto-motive force, i.e. phase stator currents, the rotor magnetic flux is obtained using permanent magnets. Thus, the rotor magnetic flux depends on the permanent magnets' parameters, such as magnetic remanence, coercivity or maximum magnetic density. In this case these properties are already known, so the only constraint is to exploit those as best as possible.

A. Air-gap magnetic field analysis:

This means that in the air-gap the magnetic field should be maximized. For various top curvatures the air-gap magnetic field has been computed, i.e. radial component of the magnetic flux density along the air-gap periphery. The analyzed geometries are presented in Fig. 1 to Fig. 5. The curvature is described by the center of the arc describing the top side of the PMs with respect to the coordinates (0,0) meaning the center of the machine (i.e. shaft center in radial direction).

Table 2

Permanent magnets top side arc center

Case	x [mm]	y [mm]
C1	0	-18.1
C2	0	-9.05
C3	0	0
C4	0	1
C5	0	2.5

In Table 2 are presented the coordinates of the arcs' centers for each case. The height and length of the rectangular bottom part of PMs has been considered fixed. In Fig. 6, the waveforms for the radial component of the air-gap magnetic flux density are presented, cases C1 to C5.

The depicted waveforms represent the air-gap magnetic waves generated by the permanent magnets when different top side curvatures have been considered. Due to the magnetic symmetry of the machine only one pole-pair is presented. As the machine has six magnetic poles, the mechanical degree corresponding to one pole pair is 120º, angle denoted with α.

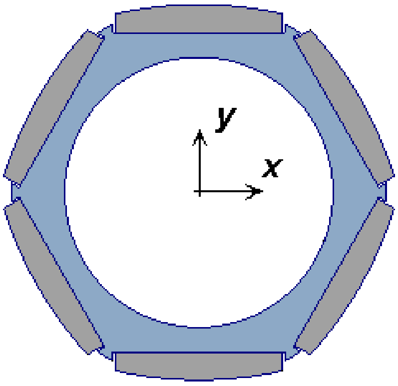

Fig. 1. Permanent Magnets Geometry - Case 1 (C1).

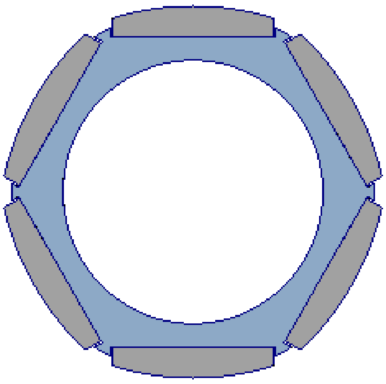

Fig. 2. Permanent Magnets Geometry - Case 2 (C2).

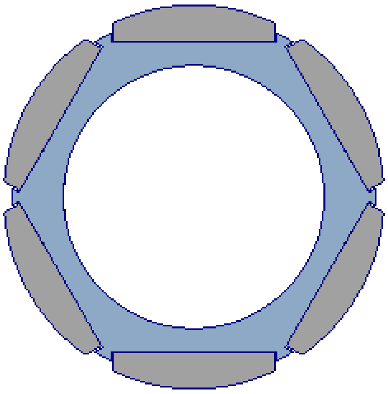

Fig. 3. Permanent Magnets Geometry - Case 3 (C3).

The static solution is considered because it is similar to a time instant during the operation of the machine. In steady state operation the rotor has the same angular speed as the stator's rotating magnetic field. Thus, when the rotor frame is considered the problem is a static one. The solved equation is:

$$\nabla \times \left(\frac{1}{\mu} \cdot \nabla \times \boldsymbol{A} \right) = 0 \qquad (1)$$

where the unknown is $\boldsymbol{A}$ the vector potential and μ is the magnetic permeability, known from the magnetizing curve of each medium.

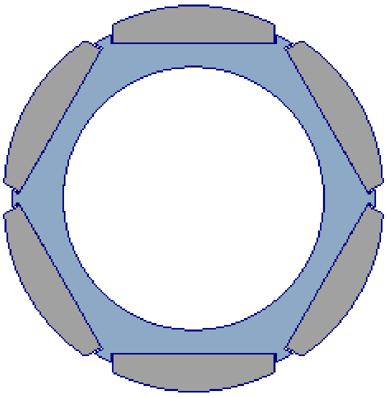

Fig. 4. Permanent Magnets Geometry - Case 4 (C4).

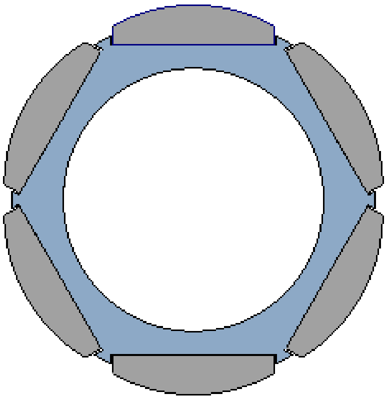

Fig. 5. Permanent Magnets Geometry - Case 5 (C5).

The magnetic flux density $\boldsymbol{B}$ is then computed using the following equation:

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \qquad (2)$$

Moreover, the computations are performed by taking into account the non-linear magnetizing characteristic of the magnetic cores, both stator and rotor.

The maximum peak value is obtained in case C5 but this can not be yet stated as the optimal one because there are other factors that should be considered, as it will be shown in the following sections.

B. Harmonic analysis:

By looking at the obtained waveforms in time domain it is possible to see which one has the greatest amplitude. Time domain results are not so intuitive to estimate in great detail which case is better because it is not the waveform's amplitude regarded but the waveform's fundamental which is the quantity that contributes to the machine's useful torque. Thus, in order to better decide which curvature provides the best magnetic flux density distribution in the air-gap, the Fast Fourier Transform is applied. In such way the waveforms are transformed from time domain to frequency domain where the harmonics weights are observed in a simple manner. Harmonics are an important issue because they generate additional losses (i.e. lower efficiencies) and do not contribute to an increased torque density. On the contrary, when high harmonic content is present then the torque might be affected, and not only.

In Fig. 7 to Fig. 11 the harmonic spectrum for each waveform of the radial component air-gap magnetic flux density are presented. The waveforms for C1 and C2 show a low fundamental of 0.58T and 0.55T respectively, while C3, C4 and C5 have a fundamental greater than 0.8T, these are possible candidates for the optimal scenario.

Comparing C3 and C5 one can see that based on spectrum analysis point of view, C5 is better because it has higher fundamental amplitude and lower third, fifth and twelfth harmonics, while the others are equal.

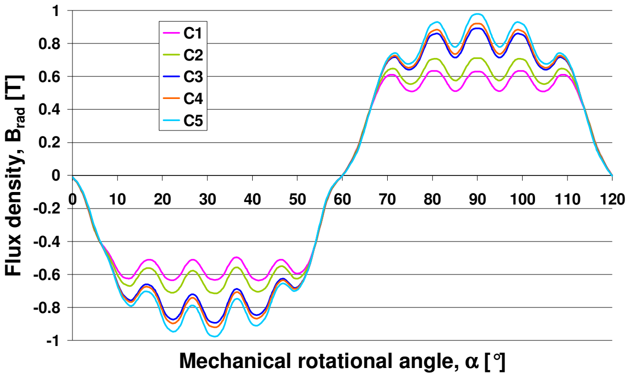

Fig. 6. Radial component of the magnetic flux density along the air-gap periphery for different geometries (case C1 - case C5).

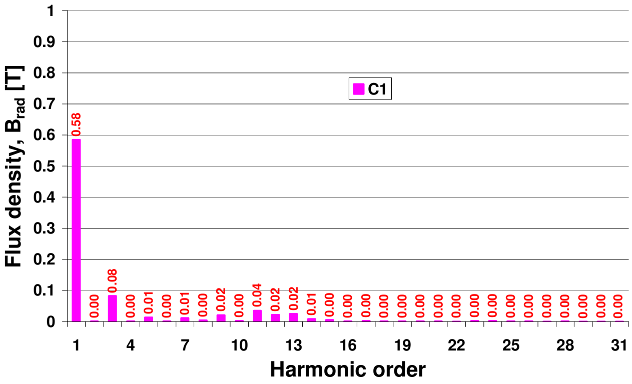

Fig. 7. Spectrum for the radial component of the magnetic flux density - C1.

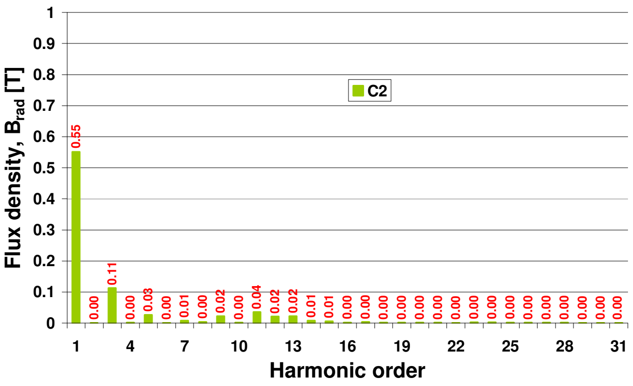

Fig. 8. Spectrum for the radial component of the magnetic flux density – C2.

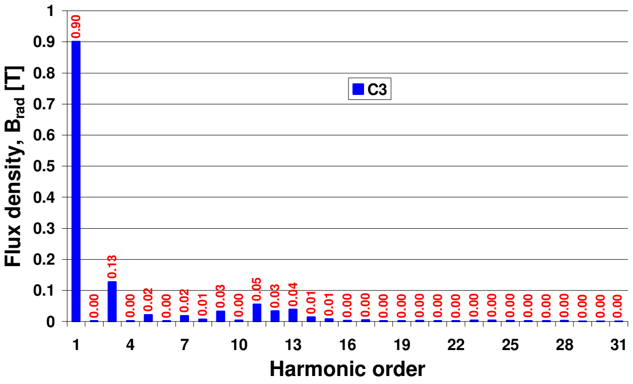

Fig. 9. Spectrum for the radial component of the magnetic flux density – C3.

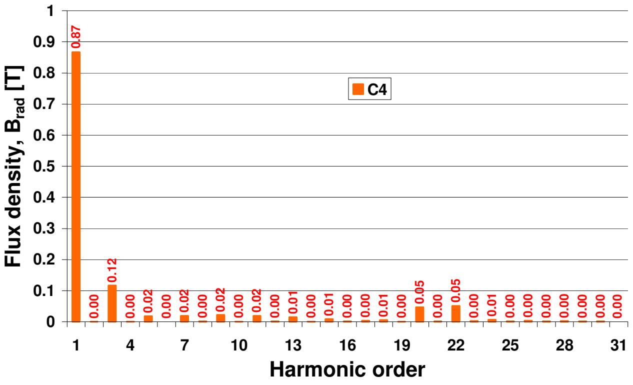

Fig. 10. Spectrum for the radial component of the magnetic flux density – C4.

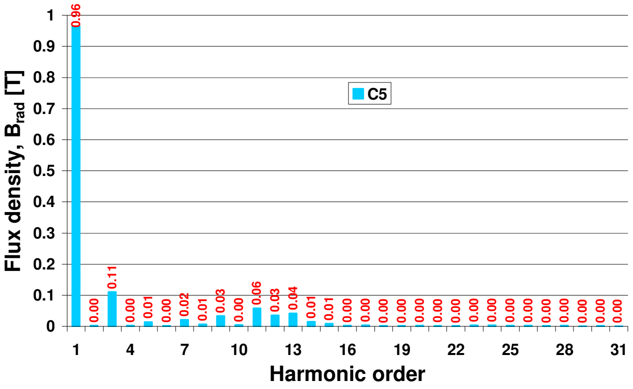

Fig. 11. Spectrum for the radial component of the magnetic flux density – C5.

C. Magnetic Saturation:

Other phenomenon that has to be taken into account is the magnetic saturation of the machine. The assessment of the magnetic core saturation is important just for the stator armature because the rotor armature does not suffer variable magnetic field. Determination of magnetic field is performed using a virtual probe, marked with a red dot in Fig 12, positioned in the middle of the bottom tooth on the stator yoke.

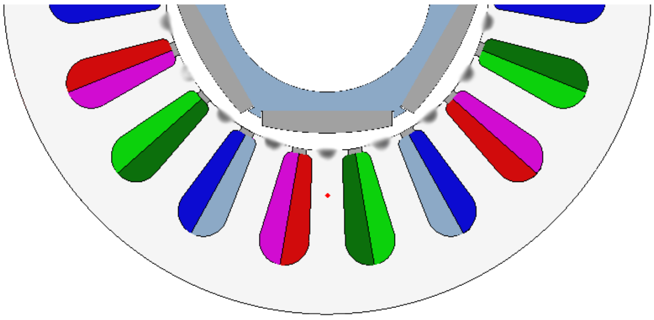

Fig. 12. The magnetic field probe set in the middle of a stator tooth.

During the revolution of the rotor, permanent magnets generate in any point of the stator armature a periodic change of the magnetic field. The values of the B-H couple determined by the depicted virtual magnetic probe during one period are shown for each case in Fig. 13 to Fig. 17.

Cases C1 and C2 are dropped again because the working point is situated on the linear range of the magnetizing characteristic. Thus, the magnetic core is not fully used because it is capable to store more magnetic energy.

Regarding the other cases C3, C4 and C5 respectively the working point is placed at the knee zone so the magnetic core is fully used.

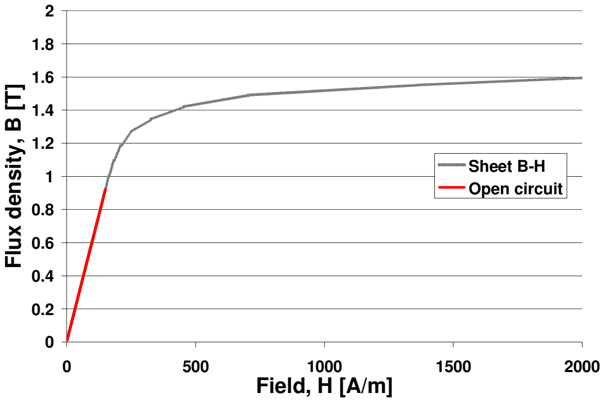

Fig. 13. The B-H curve for PMSM open-circuit test - C1.

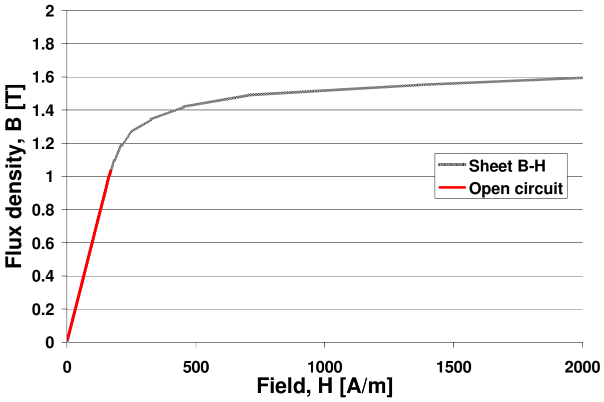

Fig. 14. The B-H curve for PMSM open-circuit test – C2.

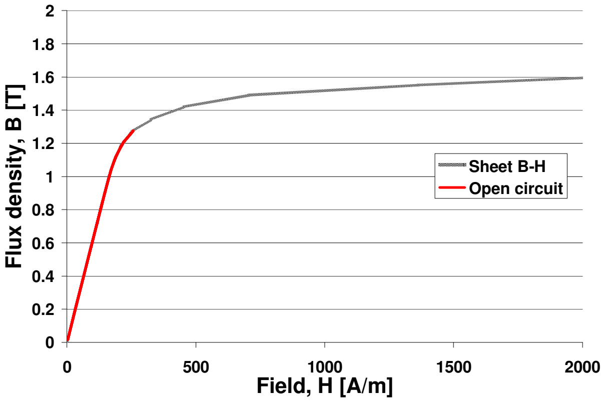

Fig. 15. The B-H curve for PMSM open-circuit test – C3.

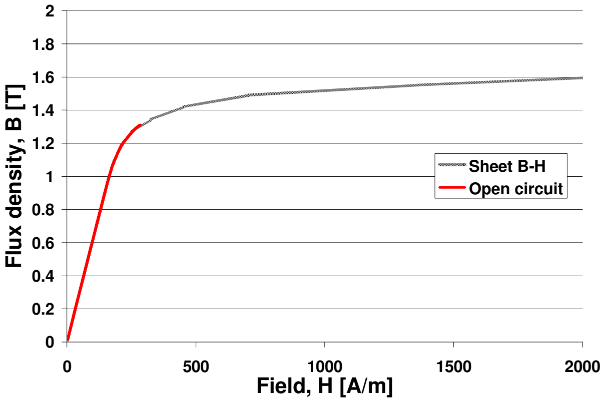

Fig. 16. The B-H curve for PMSM open-circuit test – C4.

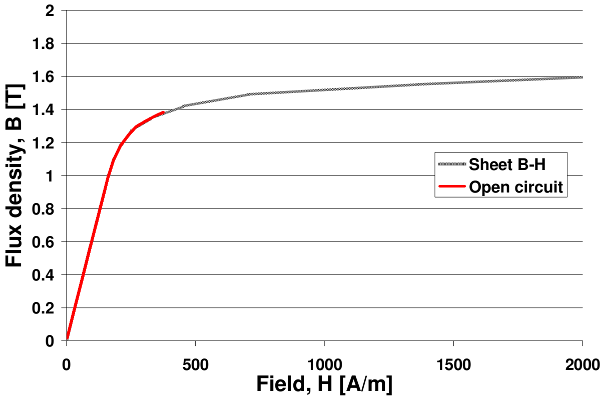

Fig. 17. The B-H curve for PMSM open-circuit test – C5.

Still, there is another factor that has to be analyzed in order to decide the optimal configuration for the permanent magnets, which is the required torque.

For each case the stator current is ranged from 0A to 10A and the torque generated by the motor is determined. The stator currents are the RMS phase values. The results are shown in Fig. 18. Based on this data it is possible to extract the stator current RMS value corresponding to the requested torque, i.e. 1Nm. The values obtained for each case are shown in Table 3. For cases C1 and C2, corresponding to -18.1mm and -9.05mm respectively the current is greater than 3A while for the other cases this is less than 3A. So, in the last three cases fewer losses are generated and thus they have to be further analyzed in order to decide the optimal solution.

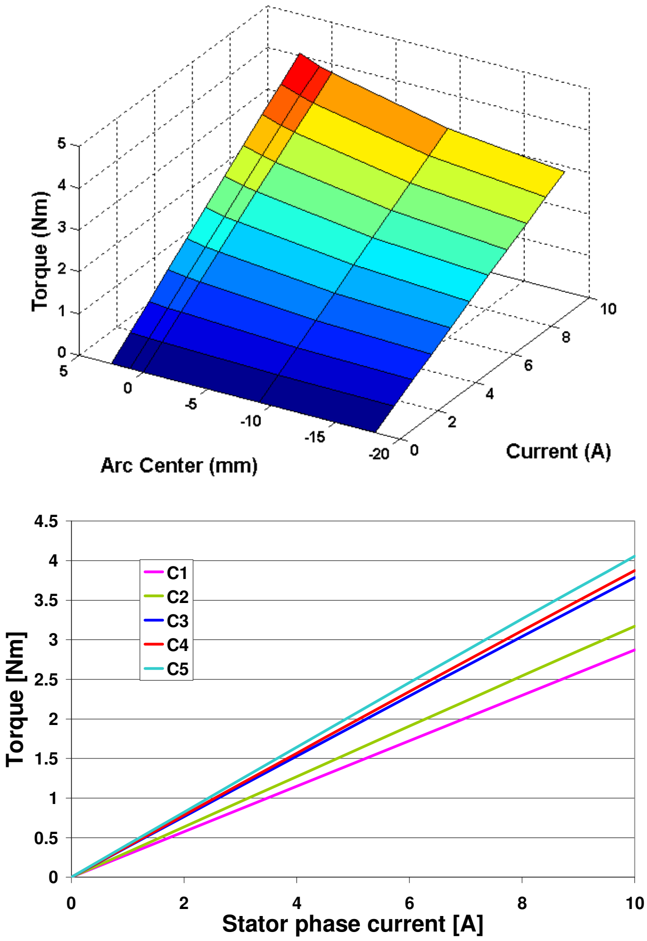

Fig. 18. Torque dependence with the PM top side curvature's arc center and the stator's current.

The decision regarding the optimal solution is done based on the working point on the magnetizing characteristic and the volume of the permanent magnets.

Table 3

RMS value of the stator current for a torque of 1Nm

Case	Current (A)
C1	3.48
C2	3.14
C3	2.61
C4	2.55
C5	2.43

In Fig. 19 are presented the working points corresponding to a torque of 1Nm, the values of the stator currents being the one previous shown in Table 3.

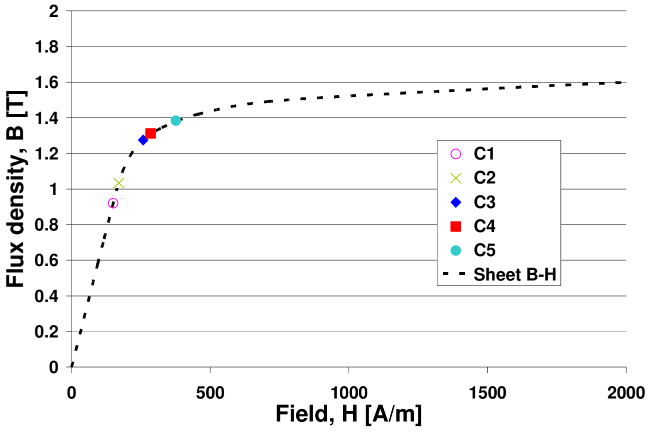

Fig. 19. Working points of the motor for 1 Nm obtained for cases C1 to C5.

In Fig. 20 is depicted the volume of one permanent magnet.

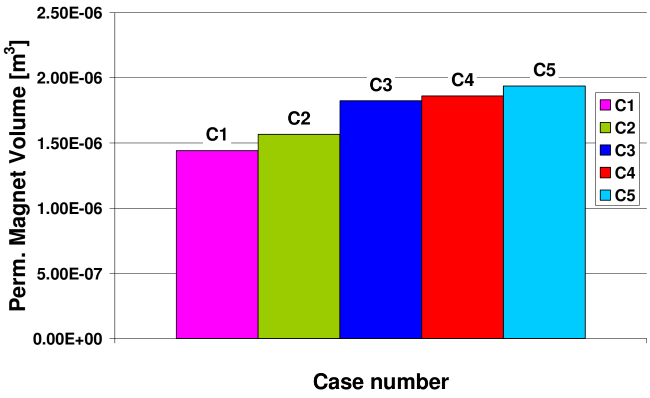

Fig. 20. Permanent magnet volume for cases C1 to C5.

Case C5 compared to C3 and C4 has a higher saturation and a higher permanent magnet volume. Thus, the motor has higher iron losses and lower efficiency.

Comparing cases C3 and C4 they are close (in C4 current increases with 2.35% with respect to C3 while the volume increases with 2%). Based on these figures it can be concluded that case C3 is the optimal configuration because lower magnetic flux density generate lower iron losses and so higher efficiency is achieved for small loads or dynamic loads also (as it is the case of the transportation vehicle). Moreover, smaller weight of the permanent magnets entails smaller total weight and so smaller energy consumption, that it is very important especially when dynamic regimes are often encountered.

4. CONCLUSIONS

The paper presents an approach on the optimal design of the rotor bread-loaf permanent magnet type of a synchronous machine. The objective was to obtain the best curvature for the top side of the bread-loaf permanent magnets, such that the required torque is obtained while the minimum stator current is required. For the achievement of such objective the designer has to consider a few factors such as: harmonic content, working point on the B-H curve and the permanent magnet volume.

The waveforms in time domain are just an idea for the starting point of the designing process. Nevertheless, the harmonic analysis requires the time-domain waveform.

The presented approach is also useful in situations where the stator armature is already given and a specific torque is required.

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