Topology Optimization Of Magnet Shape For Synchronous Machines

R. Khlissa[1], F. Gillon[1], and N. Takorabet[2]
[1] radhouane_enis@yahoo.fr , frederic.gillon@ec-lille.fr
Univ Lille Nord de France, F-59000 Lille, France
ECLille, L2EP, F-59650 Villeneuve d'Ascq, France
[2] noureddine.takorabet@ensem.inpl-nancy.fr
Institut National Polytechnique de Lorraine, Nancy, France

Abstract — A part of the torque ripples in the permanent magnet synchronous machines is due to the harmonics of back-electromotive force which depend on the flux density waveform in the air-gap. The shape of the air gap directly affects the quality of the torque generated by the motor. Topology optimization is a technique used to find the optimal geometry of a given structure. It is widely used in mechanical structures design. This technique is a promising approach to solve the problem of torque ripples due to the air gap shape. In this paper, topology optimization of the magnet with the homogenization method is presented and explained. The implementation and tests are performed by using finite element method (FEM). Homogenization method is implemented with some constraints imposed by the FE software limits. Optimization is realized under Matlab environment using SQP algorithm.

I. INTRODUCTION

Topology Optimization (TO) is used to determine the basic structure of a new design during the design phase of a device. It can be considered as a special case of shape optimization which includes parameters and geometry optimization [1]. TO seeks, without restrictions, the best possible shape even if topology changes.

In this article, this tool is used to determine the optimal shape of the surface mounted magnets in a synchronous machine. This tool can be used to justify some techniques previously defined by different authors and may improve some of them. TO is used to determine the optimal topology to reduce torque ripple in the PMSM. Reducing torque ripple passes by reducing the unwanted harmonics in the magnetic flux density in the air gap.

II. TOPOLOGY OPTIMIZATION

1) *Topology optimization problem:*

Solving a TO problem needs to fix three main components:

- *The model*: used to evaluate the physical quantities.
- *The optimization domain*: domain fixed to choose where to put material or void.
- *The objective function*: function that characterizes optimization criteria and constraints.

TO problems are mainly written in terms of minimum weight formulations with nonlinear constraints, which may have several objectives, which will increase, obviously, the complexity of the problem so the computation time and quality results such as a convergence to a local minimum. [2]

$$\begin{array}{ll} \min f & f\colon \mathbb{R}^n \rightarrow \mathbb{R} \\ x \in \Omega & \\ c_i \leq 0 & i \in \{0, 1, 2 \ldots n\} \end{array} \qquad (1)$$

where x is the domain variable, Ω is the optimization domain, f is our objective function and c_i is the constraint number i.

2) *Methods:*

Solving TO problems consists in finding where to put material and void in the précised domain Ω. Two main ways are followed to do that: [3]

First, domain is discredited to elementary regions in a fixed resolution. The more the resolution is high, the better are the results. Discrete and homogenization methods of TO are using this technique.

Second, the level set method for TO tries to determine the optimal shape of the borders between material and the void. It is a different way of TO, the optimization domain is not discredited.

The homogenization is the method used in this work and is applied to reduce the torque ripple in the PMSM.

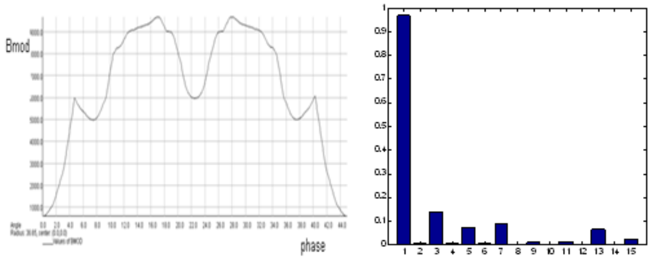
III. MINIMIZATION OF TORQUE RIPPLE IN PM MOTORS

PMSM are widely used in industrial applications. The improvement of the magnetic material led to the spread of this kind of motors.

A. *Torque ripple in PMSM*

Used as a motor, the torque provided by the synchronous machine is often affected by unwanted harmonics, this problem is highly affecting the performance when it is the case of an application that requires precise movement control. The difficulty for the case of synchronous machines is that the fluctuations have three sources which are: [4]

- Interaction torque: the scalar product of electromotive forces and currents.
- Reluctance torque: due to the saliency of the rotor
- Cogging torque: due to the saliency of the stator in presence of magnets (slotting effect)



Magnetic field wave form in the air gap

Magnetic field harmonics

Fig1: *Magnetic flux density and harmonic*

All of these origins have an oscillatory component but only the first and second origin have a non null average value. In smooth rotor motors, the second origin disappears. The torque ripples are due to the harmonics of air-gap flux density.
The air-gap flux density along a pole and spectral components are shown in figure 1.

TO is applied to reduce shape related harmonics of the PMSM torque, the reduction of torque ripple is related to the reduction of harmonics of the magnetic flux density is the air gap:

B. Homogenization method for torque ripple reduction

Homogenization is a discredited domain TO method. Combinatorial resolution leads to an exponential increase of number of material distribution possibilities. Homogenization permits a lower coast solution by according to each elementary domain a magnetic material density $\rho \in [0,1]$ where $\rho=1$ for magnetic material and $\rho=0$ for void [5]. The value of ρ permits to change the magnetic material's characteristic by continuously varying its permanent magnetization.

$$B_r = B_{r_{max}}.\rho \qquad (2)$$

Optimization problem becomes to find the optimal values of magnetic densities to get the lowest magnetic flux density harmonics.

A FE model has been used to calculate the flux magnetic density in the air gap. Optimization domain is the area located between the air gap and the rotor, it is segmented in identical regions for each is affected a magnetic material density ρ, this region is shown in Fig 2.

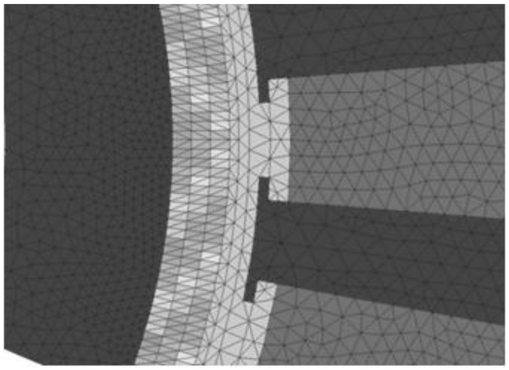


Fig 2*: Mesh display of the segmented zone*

The flux density values calculated by the FEM in the air gap are used to determine the harmonics. Optimization process uses values of harmonics to determine the optimal density values:

$$\min_{\rho_i \in [0,1]} f(\rho) = \frac{B_3(\rho)^2 + B_5(\rho)^2 + ... + B_{2k+1}(\rho)^2}{B_1(\rho)^2} \qquad (3)$$

$$B_1(\rho) > B_{ref}$$

$\rho = [\rho_1, \rho_2, ..\rho_n]$ is the densities vector, *n* is the size of ρ .

$B_k(\rho)$ is the value of harmonic number *k*.

The optimization solution gives a non discrete solution, the values of densities given are used to determine a discrete solution by a penalization process: The value of density is raised to a fixer power *n* which permits to obtain easily density values nearer to 0 or 1.

Variation of density values is shown in Fig3: A represents material distribution in the initial shape, B shows the homogenized solution and C represents the discrete solution.

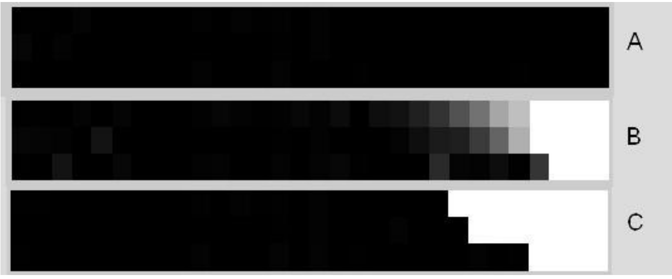


Fig3: *Variations of magnetic material density along optimization process*.

The gray level on the figure 3 represents the magnetic material density as Black is for magnet and white is for void.

IV. RESULTS

The machine on which the TO has been tested is a permanent magnet synchronous machine with 4 pairs of poles and 3 slots per pole. The magnetic flux density harmonics of this machine are given in Fig1. Optimal topology of the magnet shape was searched using this method. Basic results of magnet shape to eliminate a harmonic have been tested and found: Topology optimization succeeded to find the optimal magnet shape to eliminate the harmonic of *p* order. Fig3 shows the shape found to eliminate the harmonic of order 5 of the magnetic flux density. Other results will be presented in the full paper.

Algorithm has been tested with different resolutions of discretization: 10, 12, 45, 90 and 180 elements. Calculation time depends on resolution. Implementation has been realized by Matlab coupled to a FEM software.

V. CONCLUSION

TO is an efficient method to explore the space design. This approach permits to discover new topologies and to improve used ones. Applied on the optimization of permanent magnet shape successfully, this technique is able to discover original solutions of electromagnetic actuators design. Optimization execution time is an important factor for the choice of the method and the resolution of discretization.

VI. REFERENCES

[1] A Kimouche, M R Mekideche 'Optimization of Magnetic Pole Shifting to Reduce Cogging Torque in Solid-Rotor Permanent-Magnet Synchronous Motors' IEEE Trans Mag vol n

[2] MP. Bendsoe, O. Sigmund Topology Optimization: Theory, Methods and Applications . ISBN: 3-540-42992-1

[3] G. Allaire, *Topology optimization with the homogenization and the level-set method*, in Nonlinear Homogenization and its Applications to Composites, Polycrystals and Smart Materials, P. Ponte Castaneda et al. eds., pp.1-13, Kluwer (2004)

[4] S. Chaithongsuk: Comparison of different methods achieving sinusoidal air-gap flux density of PM Motors, IEEE CEFC, Athens, Greece May 11,14 2008, VOL 45

[5] MP. Bendsoe, Optimal shape design as a material distribution problem, Structural Optimization, Springer 1989