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## ► To cite this version:

Olivier Brun, Laurent Gerbaud, Olivier Chadebec, Nicolas Abdelnour, Thomas Lehmann, et al.. Topology Optimization of the Magnetic Force Harmonic Content in the Air Gap of Permanent Magnet Synchronous Machines. 25th International Conference on the Computation of Electromagnetic Fields (COMPUMAG'2025), Jun 2025, Napoli, Italy. <hal-05135365>

**HAL Id: hal-05135365**

**<https://hal.science/hal-05135365v1>**

Submitted on 30 Jun 2025

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# Topology Optimization of the Magnetic Force Harmonic Content in the Air Gap of Permanent Magnet Synchronous Machines

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**In this work, a magneto-mechanical topology optimization method applied to the reduction of the harmonic content of magnetic forces in the air-gap of a Permanent Magnet Synchronous Machine (PMSM) is proposed. This can help building innovative machines with reduced noise and vibrations. The Virtual Work Method is used to compute the magnetic torque, the airgap force harmonics and the sensitivity analysis needed in the optimization process. The novelty of this work is the use of non-linear mechanical constraints in the optimization process that take into account the air gap around magnets, and help getting more realistic results.**

*Index Terms*—Magneto-mechanical topology optimization, Permanent magnet synchronous machines. Noise and Vibration reduction.

## I. INTRODUCTION

**T**OPOLOGY optimization (TO) of electrical machines is a popular topic with numerous recent publications [1]. With a low *a priori* knowledge on the desired structure, devices with significant improvements in terms of performance, efficiency, and mass can be found.

Previous studies have shown that purely magnetic optimizations lead to non-connected structures, highlighting the need for coupled magneto-mechanical optimizations to get manufacturable results. In [2], the authors consider magneto-mechanical TO of a PMSM rotor, with a standard linear elastic mechanical analysis under centrifugal load. However, the contacts between magnets and the ferromagnetic core makes this analysis unrealistic for high rotation speeds. Therefore, in this work, the authors propose the new use of a more sophisticated non-linear mechanical model to find more realistic designs.

Most TO methods for electrical machines focus on objectives related to torque, such as average torque, torque ripple, and torque harmonics [1], [3]. In this work, the harmonic content of magnetic forces in the air-gap is also considered, which significantly contributes to noise and vibrations [1]. The Virtual Work Method (VWM) [4] is used to compute in a unified way the magnetic torque, forces harmonics, along with the sensitivity analysis needed for the TO process. The VWM is also known to be more accurate than the Maxwell Tensor Method for the computation of the torque and airgap magnetic forces [4].

## II. OPTIMIZATION METHODOLOGY

### A. Magneto-mechanical topology optimization

The topology optimization method used is based on the Level-Set method described in [5]. The design is implicitly defined through a function  $\Phi(x)$  for all  $x$  in the design space, such that  $\Phi$  is positive inside the design, negative in air and the boundary of the design is given by  $\{x \text{ such that } \Phi(x) = 0\}$ . Therefore, the function  $\Phi$  is used as the optimization variable, and the optimization is performed using a gradient-based

method. The magnetic and mechanical optimization targets are evaluated using the Finite Element Method (FEM). The Level-Set function  $\Phi$  is defined on the finite element mesh of the design space. In order to combine magnetic and mechanical targets in the optimization, the principle proposed in [2] is used. The same mesh is used for both magnetic and mechanical analysis, such that the optimization variables and sensitivity analysis can be unified for both physics.

### B. Sensitivity analysis

The VWM [4] is used to compute the average torque of the machine for several rotor positions, but also the magnetic force harmonics in the air-gap that have to be considered in the optimization. Since a gradient-based method is used, their sensitivity analysis is necessary. To do so, an adjoint method [2] is used. The case of the torque has been addressed in one of our previous work. The force harmonic computation and sensitivity analysis process using the VWM is proposed in [3]. More details about force and harmonics computation will be given in the full paper. The optimization algorithm along with the finite element and sensitivity analysis rely on Altair<sup>TM</sup> OptiStruct and a development version of Altair<sup>TM</sup> Flux [5].

## III. EXAMPLE OF OPTIMIZATION

### A. Motor of application

The methodology has been applied to the rotor of a Tesla Model 3 PMSM machine studied under non-linear transient magnetic assumptions. The rotor mechanical analysis is performed under the centrifugal load generated by a rotation speed of 18500 rpm. The magnetic force computation is conducted in the airgap, resulting in a periodic signal in both space and time. One period correspond to a full rotation of the rotor. Thus, the complete force information  $\mathbf{f}(x, t)$  is computed in a  $(x, t) \in [0, 360 \text{ deg}] \times [0, 360 \text{ deg}]$  space/time domain (time is identified to an angular position of the rotor). Finally, the force harmonics  $\hat{\mathbf{f}}(u, v)$  are evaluated using a 2D discrete Fourier Transform on  $\mathbf{f}(x, t)$ . This process is illustrated in Figure 1.

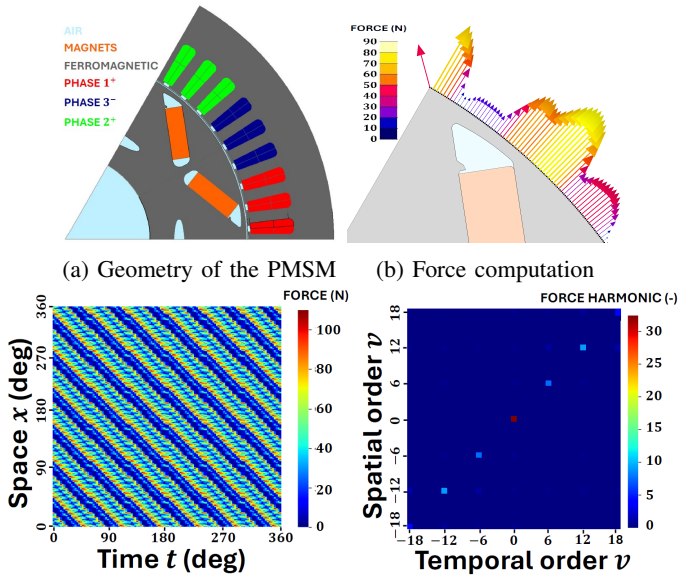


Fig. 1: Force harmonics evaluation process

### B. Optimization problems

The optimization aims to find the ferromagnetic structure of the rotor that minimizes the arbitrary harmonic  $\mathcal{H}$  of coordinates (6, 6) in the space/time Fourier domain of Figure 1d. This is an academic example, but it is possible to target any harmonic of interest in a context of noise and vibration reduction. Moreover, a constraint on the average torque  $\mathcal{T}_{avg}$  is enforced, such that the torque from the original machine is preserved. In order to highlight the importance of considering mechanical constraints, results obtained in the three following cases are compared:

- **Case 1:** No mechanical constraints are added.
- **Case 2:** Constraint on the maximum Von Mises stress in the rotor, computed with a traditional linear elastic model.
- **Case 3:** Same stress constraint as in case 2, but computed with a non-linear elastic study that takes into account the gap between magnets and the ferromagnetic structure. This allows to consider the motion of magnets inside their slots, and therefore to get more a realistic mechanical analysis [6]. This model is the main novelty of this work and will be detailed in the full paper.

### C. Conclusion

The optimization is performed on a ferromagnetic subpart of the rotor, as shown in Figure 2. The results obtained for the three cases and the comparison of the magnetic performances of different machines are shown in Figure 3 and Table I.

The targeted harmonic  $\mathcal{H}$  is significantly reduced in all cases, showing the interest of the optimization methodology. However, cases 1 and 2 lack mechanical realism, as the magnets are not stopped in translation. Case 3 offers a better balance between magnetic improvement, mechanical strength and realism of the solution, demonstrating the contribution of the nonlinear mechanical model.

TABLE I: Comparison of resulting magnetic performances

Case	Initial machine	Case 1	Case 2	Case 3
$\mathcal{H}$ [-]	10.9	5.87 (-46%)	5.93 (-45%)	7.63 (-30%)
$\mathcal{T}_{avg}$ [N.m]	448	449	447	446

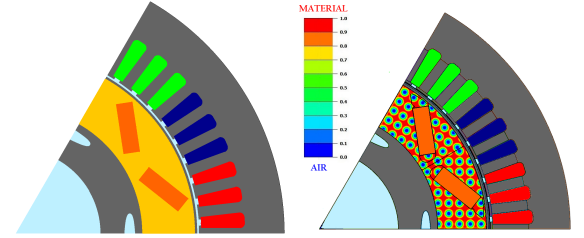


Fig. 2: Overview of the optimization configuration

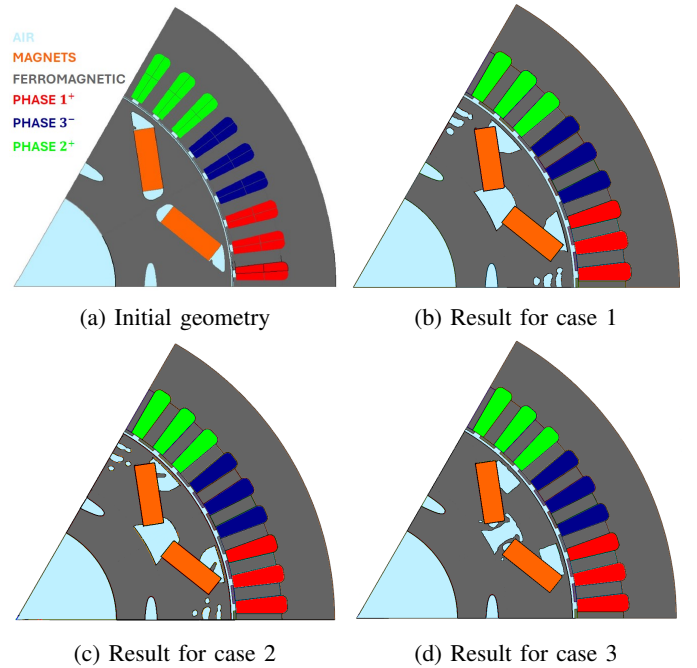


Fig. 3: Optimization results

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