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MULTI-MATERIAL TOPOLOGY OPTIMIZATION OF A ROTATING ELECTRICAL MACHINE WITH A DENSITY-BASED METHOD

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Context and motivations

Topology optimization has become a popular tool especially in mechanical engineering. Many interesting methods have been developed [1].

Density methods like SIMP have been introduced in electrical engineering by [2], and are now widely used to design electrical actuators. **Multi-materials** problems involving source distribution have been addressed [3,4]. However, most of the work focuses only on single parts of the machine (rotor, stator teeth), and a few papers such as [5] deal with the coil distribution within the stator.

This work presents a **density-based method** which could be used to separately optimize the rotor and the stator of a rotating machine, with the future objective to optimize both from scratch.

Magnetostatics equation

2D vector potential local formulation

$$-\nabla \cdot [\nu(a_z) \nabla a_z] = j_z + \nabla \cdot \left(\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \cdot \mathbf{M} \right) \quad (1)$$

a_z is the unknown z -component of vector potential, ν the magnetic reluctivity which depends on a_z within ferromagnetic materials, j_z the z -component of current density and \mathbf{M} the magnetization of permanent magnets. $\nu = H/B$ is defined by material law (B-H curves).

Anti-periodic boundary conditions are used to model a single pole of the machine.

Problem formulation

The aim of the optimization is to find the discrete density vector ρ_{opt} which maximizes the average torque

Optimization problem

$$\text{find } \rho_{opt} = \arg \max \langle C(\mathbf{a}(\rho)) \rangle \\ \text{subjected to } 0 \leq \rho_i \leq 1 \\ \forall i \in \llbracket 0, n-1 \rrbracket$$

With n the total number of densities. The torque C is computed with Arkkio's method [6]. It depends **implicitly** on ρ through the discretization of equation (1) by finite elements method :

Finite element system

$$K(\mathbf{a}, \rho) \cdot \mathbf{a} = \mathbf{b}(\rho) \quad (2)$$

Adjoint variable method

The **adjoint variable method** was used [3] to compute efficiently the derivatives of the objective function with respect to the density :

Sensitivity expression

$$\frac{\partial C}{\partial \rho_i} = \mathbf{p}^T \left(\frac{\partial \mathbf{b}}{\partial \rho_i} - \frac{\partial K}{\partial \rho_i} \mathbf{a} \right)$$

\mathbf{p} is the so-called **adjoint state**, solution of the following linear system

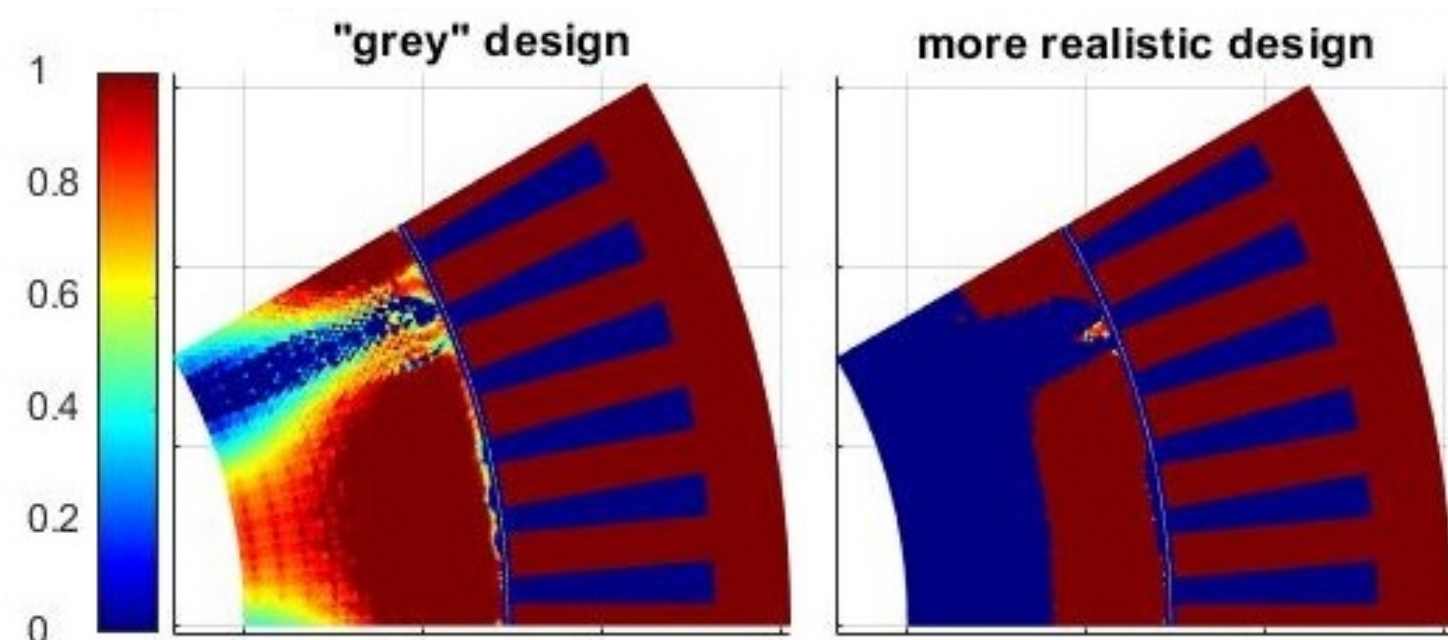
Adjoint system

$$(K')^T \mathbf{p} = \frac{\partial C}{\partial \mathbf{a}} \\ \text{with } K'_{ij} = K_{ij} + \sum_k \frac{\partial K_{ik}}{\partial a_j} a_k$$

K' is the **tangent operator** of (2).

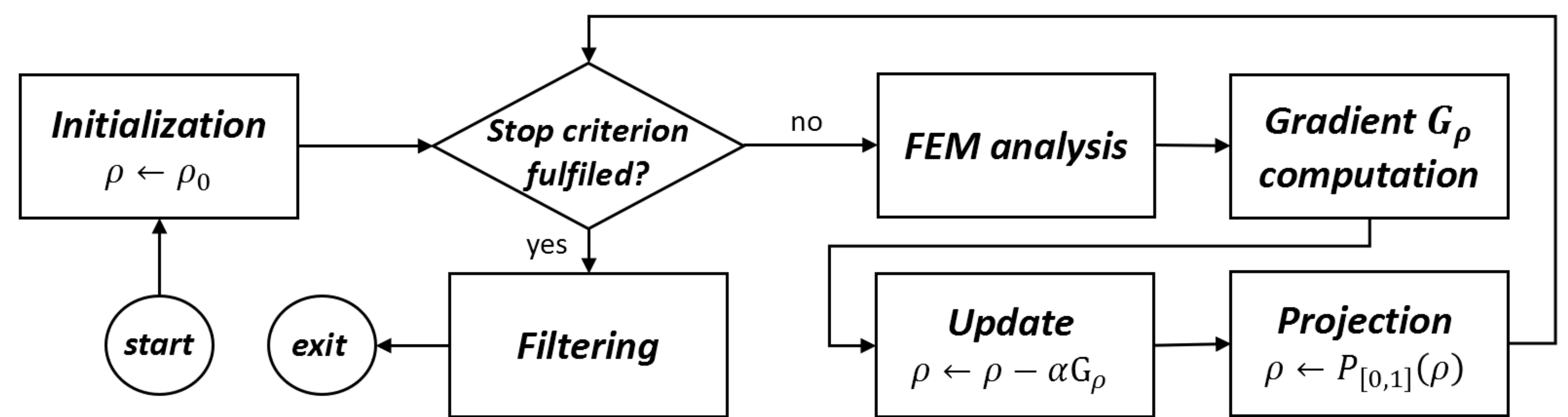
Principles of density methods

Density methods rely on a bounded spatial field $\rho : x \mapsto \rho(x)$ which supports **differentiable** interpolations between material properties and allow to define a differentiable optimization problem.

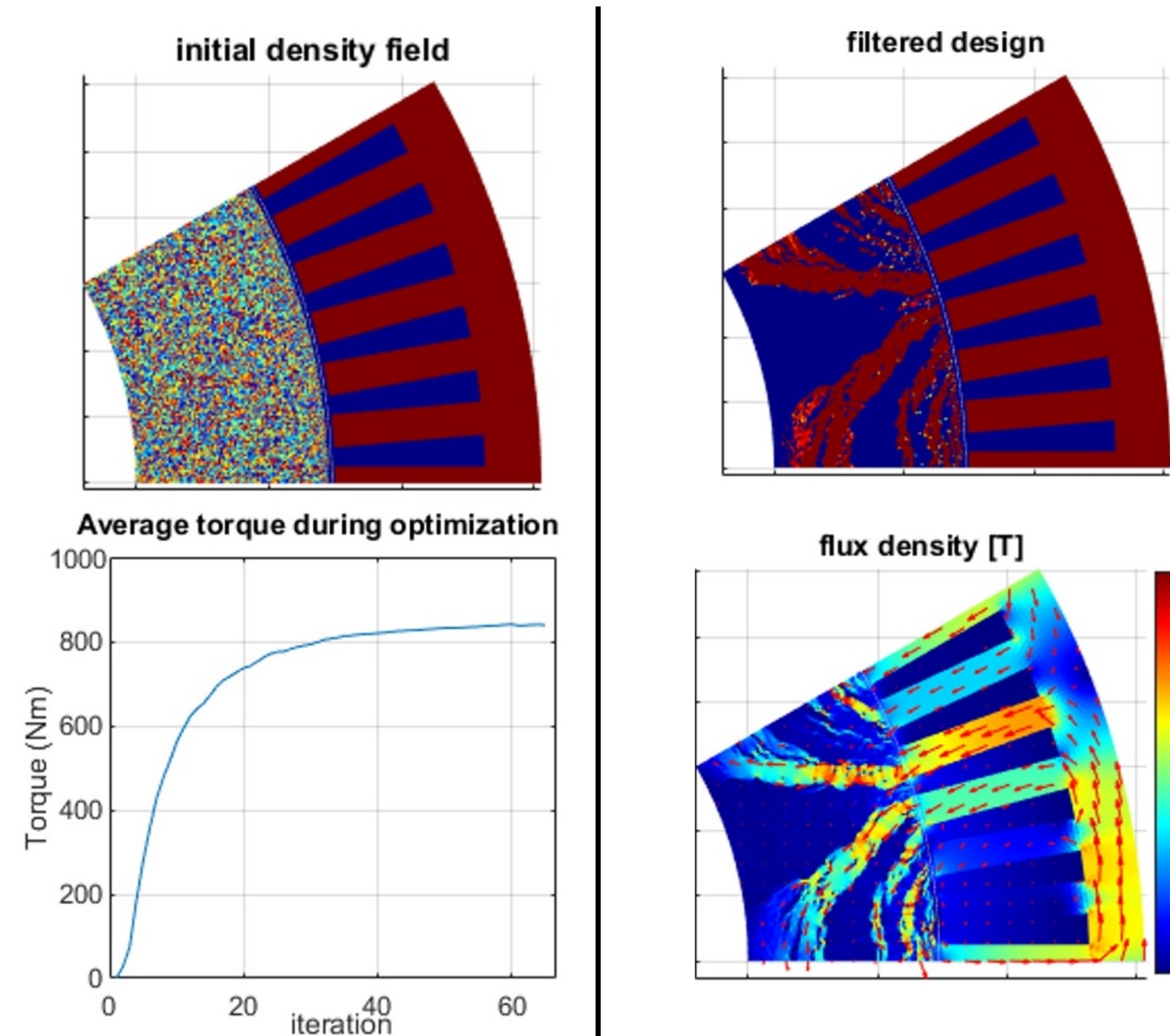


Intermediate materials should be eliminated during the optimization process, by the use of penalization (SIMP, RAMP [1]), thresholding, constraints, etc.

Optimization process



Optimization of SRM rotor

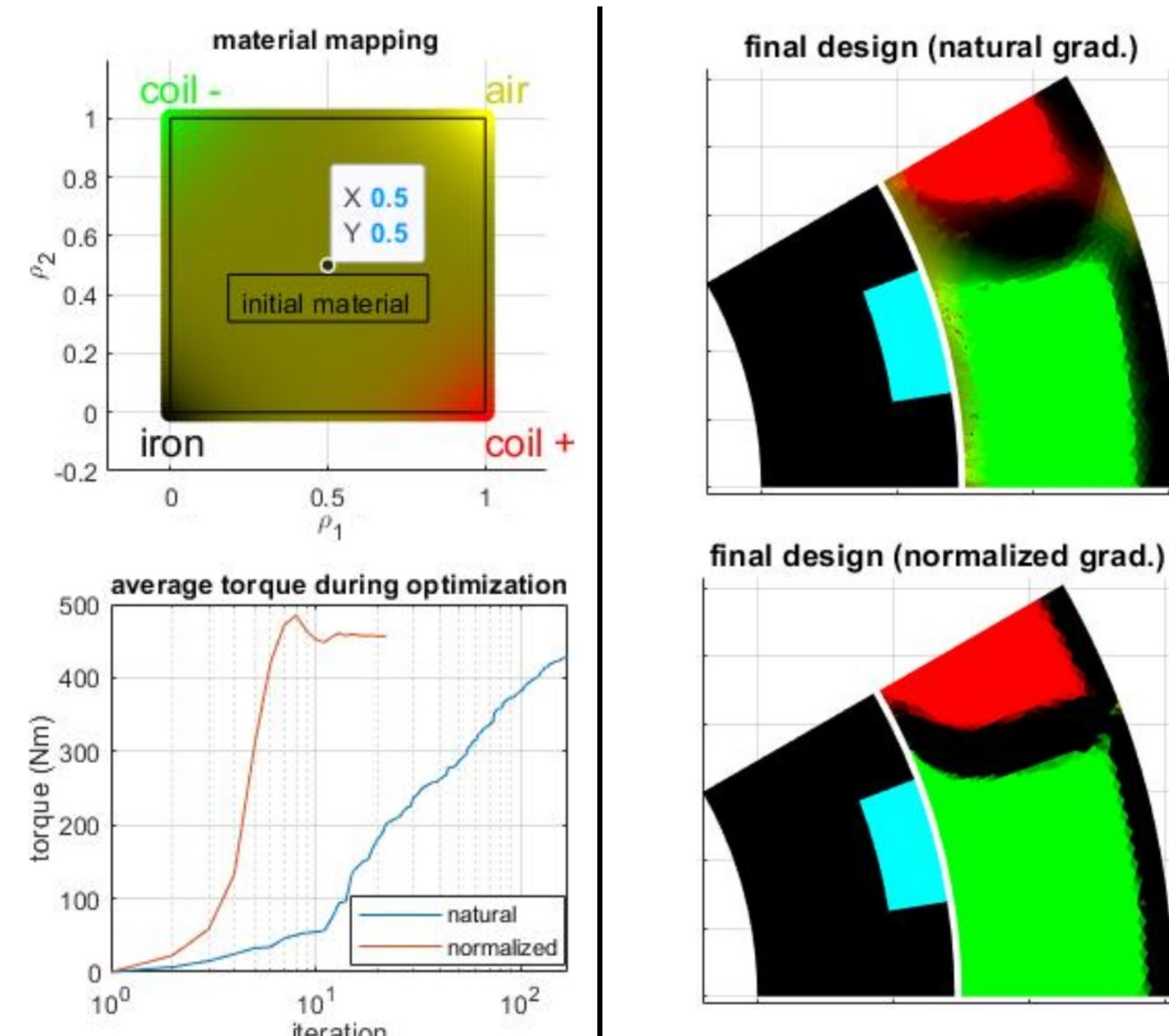


Filtering inspired by ESO procedure [7] was applied : materials which carried few flux was replaced by air. Then, **flux barriers** [8] appear clearly and correspond to industrial design like ABB[®] SRM :



ABB[®] SRM

Optimization of PMSM stator



4-materials topology optimization [4] was performed on a one-phase PMSM stator with **uniform initialization**. Two densities per element were used. The convergence is slow near the airgap, so each gradient pair of elementary terms was **normalized**. As it is multiplied by a symmetric definite matrix, it remains a descent direction and leads to an **asymmetrical** design.

Conclusion and outlook

Encouraging results with **flux barriers** were obtained for the SRM rotor optimization. The multimaterial PMSM stator optimization of the stator leads to intriguing **asymmetrical design**, which is maybe a local optimum. Further research is needed to compare this topology with established ones. It is also necessary to improve the robustness of the method especially for high **current density**, before optimizing both the rotor and the stator. **Multiphysics** considerations will be taken into account in future work.

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References

- [1] Ole Sigmund and Kurt Maute. Topology optimization approaches: A comparative review. *Structural and Multidisciplinary Optimization*, 48(6):1031–1055, 2013.
- [2] D.N. Dyck and D.A. Lowther. Automated design of magnetic devices by optimizing material distribution. *IEEE Transactions on Magnetics*, 32(3):1188–1192, 1996.
- [3] J.S. Choi and J. Yoo. Structural optimization of ferromagnetic materials based on the magnetic reluctivity for magnetic field problems. *Comp. Meth. in Appl. Mech. and Eng.*, 197:4193–4206, September 2008.
- [4] Y. Jung and S. Min. Material Interpolation in Multi-Material Topology Optimization for Magnetic Device Design. *IEEE Transactions on Magnetics*, 55(11):2019–2022, 2019.
- [5] T. Labbé and B. Dehez. Convexity-Oriented Mapping Method for the Topology Optimization of Electromagnetic Devices Composed of Iron and Coils. *IEEE Transactions on Magnetics*, 46(5):1177–1185, 2010.
- [6] A. Arkkios. Time-stepping finite element analysis of induction motors. In *Proceedings of ICEM*. IEEE, 1988.
- [7] Y.M. Xie and G.P. Steven. A simple evolutionary procedure for structural optimization. *Computers & Structures*, 49(5):885–896, 1993.
- [8] M. Martinovic, S. Stipetic, D. Zarko, and M. Klanac. Comparison of synchronous reluctance machines using topology optimization. In *SPEEDAM*, pages 472–477, 2020.