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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,  $\nu$  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  $\rho_{opt}$  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  $\rho$  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

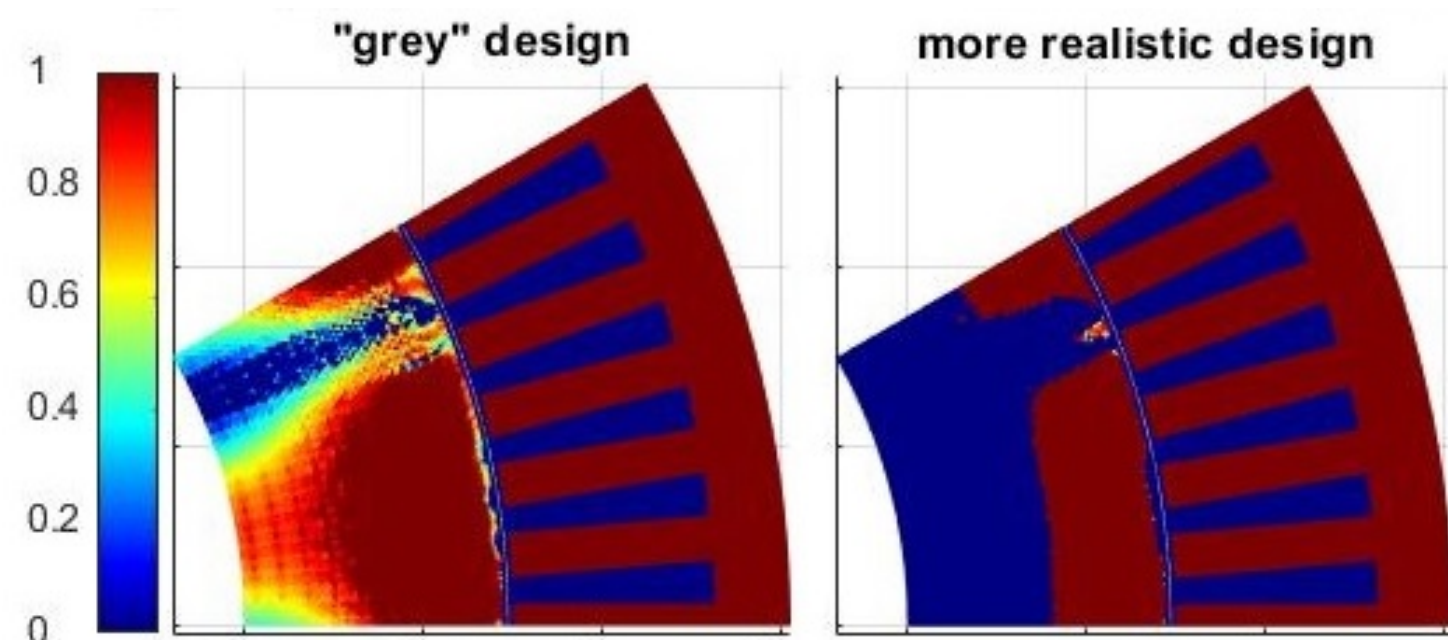
### Adjoint system

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

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

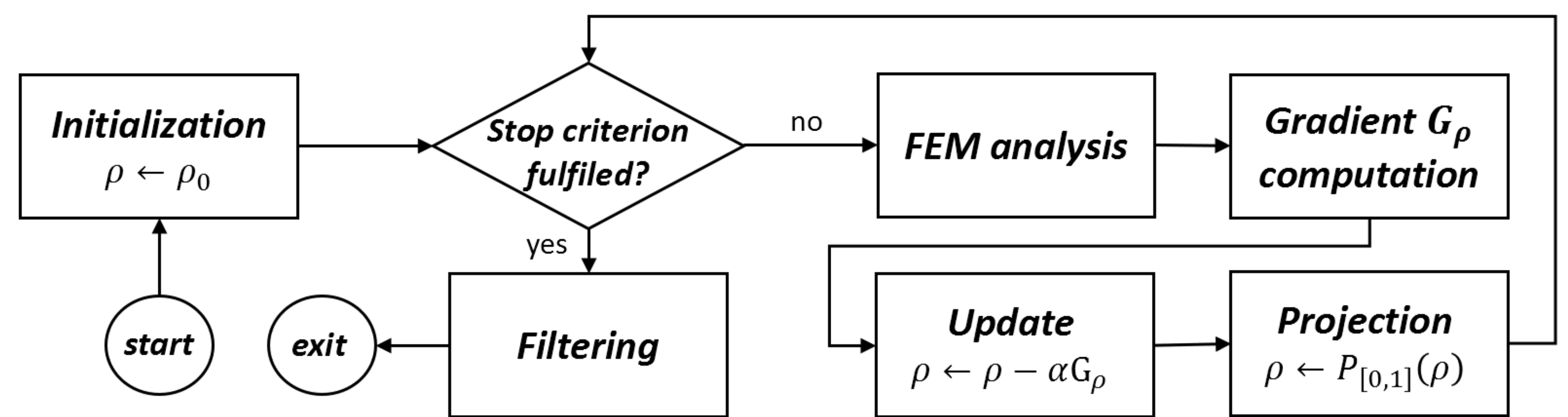
## Principles of density methods

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.

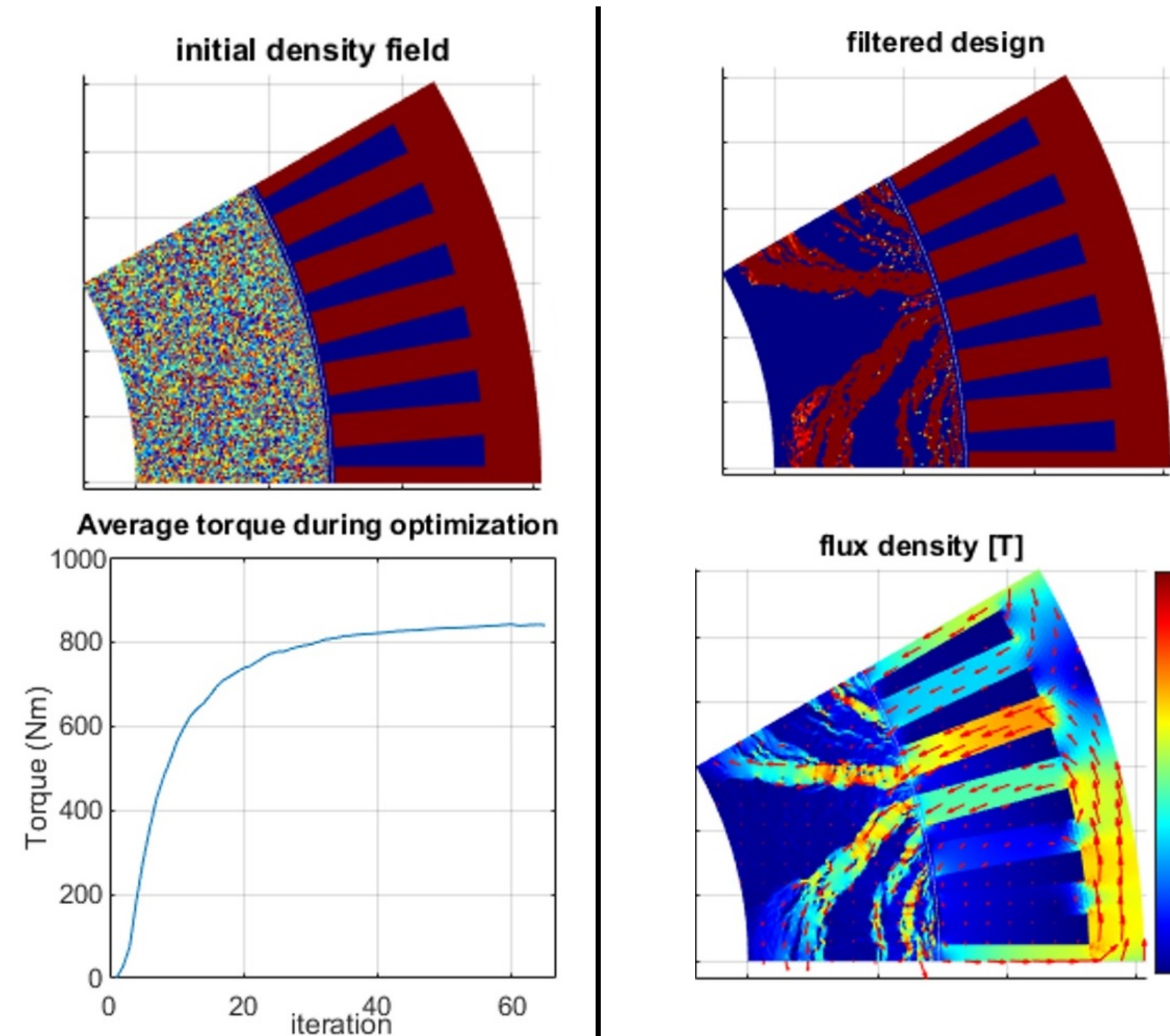


Intermediate materials should be eliminated during the optimization process, by the use of penalization (SIMP, RAMP [1]), thresholding, constraints, etc.

## Optimization process



## Optimization of SRM rotor

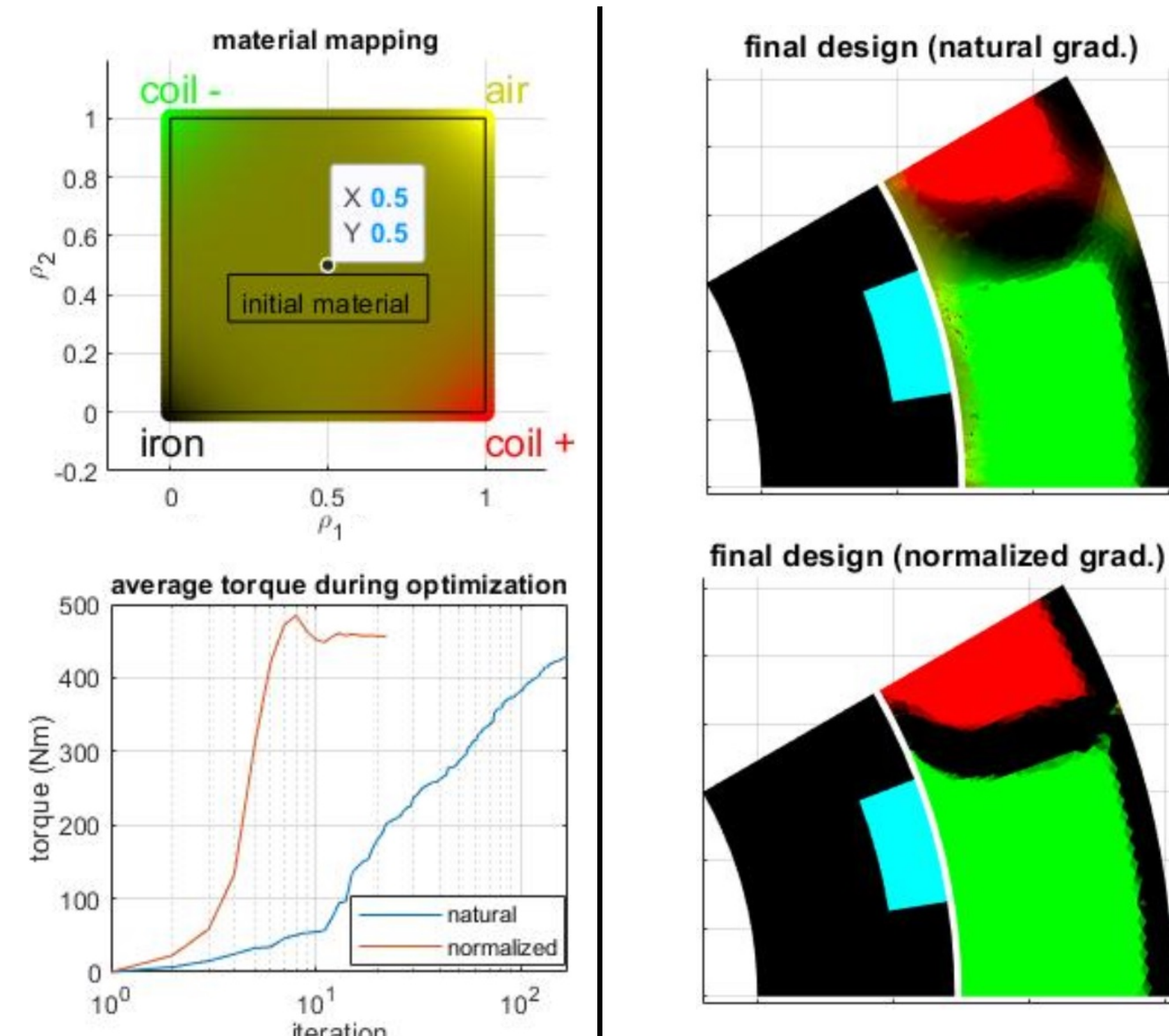


**Filtering** inspired by ESO procedure [7] was applied : materials which carried few flux was replaced by air. Then, **flux barriers** [8] appear clearly and correspond to industrial design like ABB<sup>®</sup> SRM :



ABB<sup>®</sup> 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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