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Toward topology optimization of hybrid-excited electrical machines using recursive material interpolation

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Introduction

Topology optimization is a promising tool for designing innovative electromagnetic actuators, overcoming engineers' preconceptions [1]. A common approach relies on a so-called **density field** $\rho \in \mathcal{L}^\infty(\Omega)$, defining the material properties in each point of the design domain Ω through a differentiable interpolation as illustrated in Figure 1. The problem to solve is

$$\begin{aligned} &\text{Minimize} && f(a(\rho)) \\ &\text{Subject to} && \rho : \Omega \rightarrow \mathcal{D}, \end{aligned} \quad (1)$$

with f the cost function that depends explicitly on the physical state $a \in \mathcal{H}_0^1(\Omega)$, which itself depends implicitly on the design variable ρ by solving the 2D magnetostatic equation [2]:

$$\forall a^* \in \mathcal{H}_0^1(\Omega), \quad \int_{\Omega} \nu_0 \nabla a^* \cdot (\nabla a + R_{-\pi/2} \tilde{m}(R_{-\pi/2} \nabla a, \rho)) = \int_{\Omega} a^* \tilde{j}(\rho). \quad (2)$$

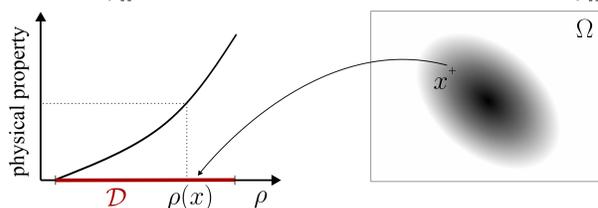


FIGURE 1: Principle of the density-based approaches: material property mapping.

This approach can handle multiple materials by **extending the dimension** of the interpolation domain \mathcal{D} . Available domains in the literature are **hypercubes** of any dimension [3], and **convex polytopes** up to dimension 3 that are necessary to optimize multiphased stators [4]. This dimension limit comes from the difficulty of imposing **box-type constraints** on non-rectangular domains. It prevents considering additional material natures as in **hybrid-excited electrical machines**, that aim to combine the flexibility of wound-field (WF) excitation with the efficiency of permanent magnets (PM) for traction applications [5].

Interpolation scheme

Each material i is associated with one of the n_m vertices of \mathcal{D} . The interpolations of the current density j and the field-dependent magnetic polarization m are built using **generalized barycentric coordinates** ω_i [4], verifying the partition of unity and linear completeness:

$$\tilde{j}(\rho) = \sum_{i=1}^{n_m} \omega_i(\rho) j_i, \quad (3a) \quad \left| \quad \tilde{m}(\rho, b) = \sum_{i=1}^{n_m} \omega_i(\rho) m_i(b). \quad (3b)$$

This formalism can be extended to consider an *interpolation of interpolations*, i.e., to define a **hierarchy** of interpolation domains. The **projection** on such a structure comes down to the *projection on each subdomain*, which is easy to handle in a **projected gradient** scheme. From the computation side, this structure is a **rooted tree** \mathcal{T} , the branches being **products** by the shape functions and the nodes being **sums**. Using Neveu's labeling [6] as illustrated in Figure 2, we define $\mathcal{C}(l) = \{[l, n], n \in \mathbb{N}, [l, n] \in \mathcal{T}\}$ the set of the children of node l .

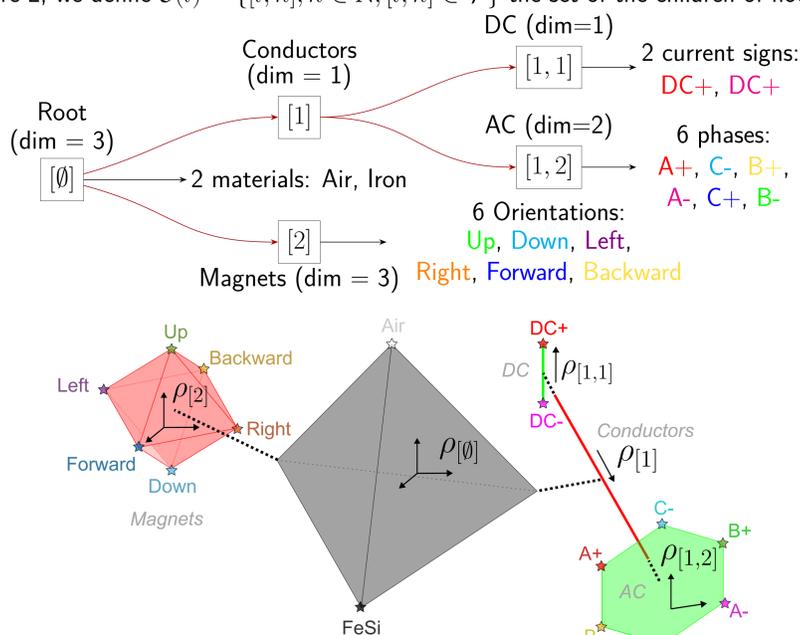


FIGURE 2: Example of a 10-D and 3-level interpolation domain between 16 materials.

Evaluating the interpolation \tilde{m}_i can be done **recursively** [7], initializing l to \emptyset and k to 1:

$$(\partial_b) \tilde{m}_i(b, \rho) = \begin{cases} (\partial_b) m_i(b) & \text{if } \mathcal{C}(l) = \emptyset \\ \sum_{i \in \mathcal{C}(l)} \omega_i(\rho) (\partial_b) \tilde{m}_i(b, \rho) & \text{else.} \end{cases} \quad (4a)$$

$$\partial_{\rho} \tilde{m}_i(b, \rho, k) = \left\{ \underbrace{k \sum_{i \in \mathcal{C}(l)} \tilde{m}_i(b, \rho) \frac{d\omega_i(\rho)}{d\rho}}_{\text{derivative with respect to } \rho_i}, \left\{ \forall i \in \mathcal{C}(l), \partial_{\rho} \tilde{m}_i(b, \rho, k \omega_i(\rho_i)) \right\} \right\} \quad (4b)$$

Numerical Experiments

The design region is **one magnetic pole** of the rotor. We consider 16 candidate materials: iron, air, positive and negative DC conductors, and 12 orientations of PM. Since hybrid excitation is a combination of PM and WF, we solve the following optimization problem:

$$\text{Find } \rho^* = \max_{\rho \in \mathcal{D}} \frac{\gamma+1}{2} \phi^+(a(\rho)) - \frac{\gamma-1}{2} \phi^-(a(\rho)), \quad (5)$$

with $\gamma \in [-1, 1]$ a **hybridization ratio**, ϕ^+ and ϕ^- the **outward fluxes** produced by the rotor pole when the feeding current is positive and negative, respectively. The amplitude of the current is set to 10 A/mm^2 and the remanence of the PM to 1 T. The optimizations are performed for several γ and 3 different interpolation domains represented in Figure 3.

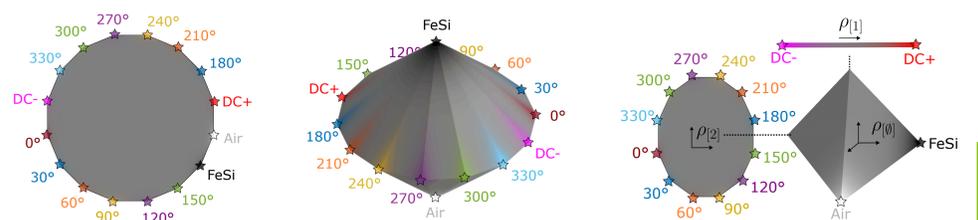


FIGURE 3: Different types of interpolation domains and their color scale: hexadecagon (left), diamond (center) and hierarchical domain (right).

As shown in Figure 4, the flux is maximized in only one direction when $\gamma = \pm 1$, leading to PM **Halbach arrays** [8]. When $\gamma = 0$, the flux is inverted with the DC current, so a **wound rotor** is obtained. Intermediate γ values lead to **parallel hybrid-excited** topologies. The normalized signed distance sd_0 to $|\phi^+| = |\phi^-|$ is used to assess the designs.

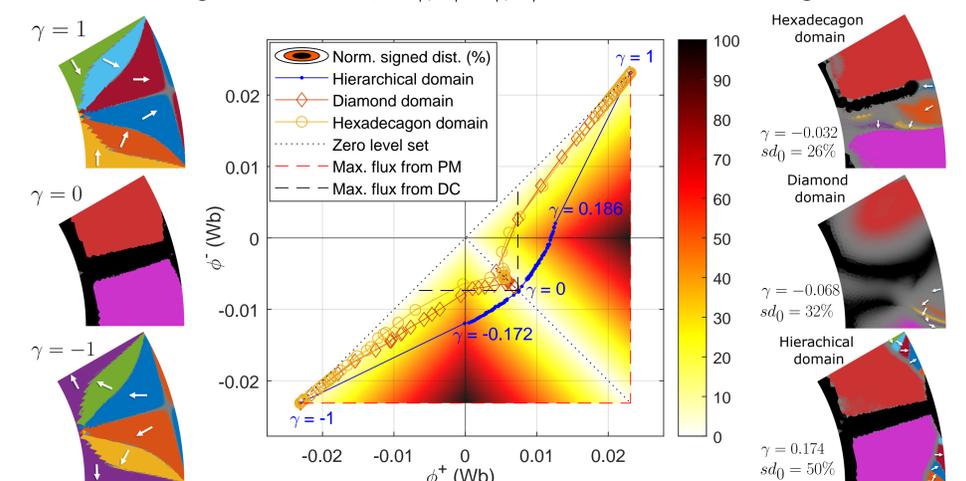


FIGURE 4: Optimized designs and performances: non-hybrid designs (left), Pareto front obtained for equally distributed γ (center), most hybridized designs with higher sd_0 (right).

The **hierarchical domain is more appropriate** since its optimized results perform better according to sd_0 , and contain fewer intermediate materials.

Conclusion and outlooks

The proposed recursive domain provides **more flexibility** than the currently available domains in the literature and can be adapted to a wide variety of problems. Further research will consider the **mechanical integrity** of the rotor, as well as including **additional AC conductors** for applications such as hybrid-excited **flux-switching machines** [9].

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