

A Manufacture Driven Topology Optimisation of Synchronous Reluctance Machines

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Synchronous reluctance machines are receiving attention as they combine high efficiency with low material cost. The design of a high-performance synchronous reluctance rotors is complex, and benefits from using computationally intensive topology optimization. Significant discrepancy can occur between measured prototype performance and such FEA based simulation, attributed in part to the manufacturing processes. These factors can be large when stator and rotor core packs are fabricated by laser cutting. This paper presents a level set optimization approach with degradation modelling to adapt designs for manufacture during the optimization process. The results show topological changes and a reduction in torque deficit when manufacturing degradation is included. Further work will explore the effect of design parameters using a high-performance computing platform to accelerate the optimization process.

Index Terms—Level set, Degradation, Synchronous Reluctance, Manufacture, Laser cutting

I. INTRODUCTION

Synchronous reluctance (SyncRel) machines provide a rare earth permanent magnet free design, avoiding the associated cost and supply chain problems [1]. Such topologies however, have significant performance limitations. Common practice relies upon the dimensional optimization of complex and pre-determined geometries. Topology optimization is being explored to remove reliance on such prior topological constraints, allowing the computer algorithm the freedom to seek from “a clean sheet of paper” [2]. Such techniques rely on an iterative design process, often leading to long simulation times.

The permeability degradation of magnetic material during manufacture is widely reported however, rarely considered in the optimization process. Instead, build factors are applied to existing designs, to correct for performance losses. These factors are especially large when laser cutting machine core packs. Lazari, et al. [3] compares an idealized permanent magnet assisted SyncRel machine design to the physical laser cut machine, showing a torque reduction up to 10% depending on the load. Recent work has characterized the effect of permeability degradation on electrical steels from laser cutting, improving the accuracy of FEA modelling [4].

The work presented in this paper introduces a level set topology optimization, with material degradation and aims to show how changes in material permeability from the fabrication of rotor laminations can lead to significantly different topological designs. Such designs incorporate the influence of manufacture, instead of correcting for manufacture, after the design process. Early results, illustrated in Section III Fig. 2, can aid a designer to select a rotor topology to focus attention on, with future work researching the incorporation of physical and mechanical constraints to directly yield manufacturable designs.

II. OPTIMIZATION PROCESS

Topology optimization provides a priori free investigation of the design domain and has extensively been used in the optimization synchronous reluctance machines. Genetic algorithm, Solid Isotropic Microstructure with Penalization (SIMP) and

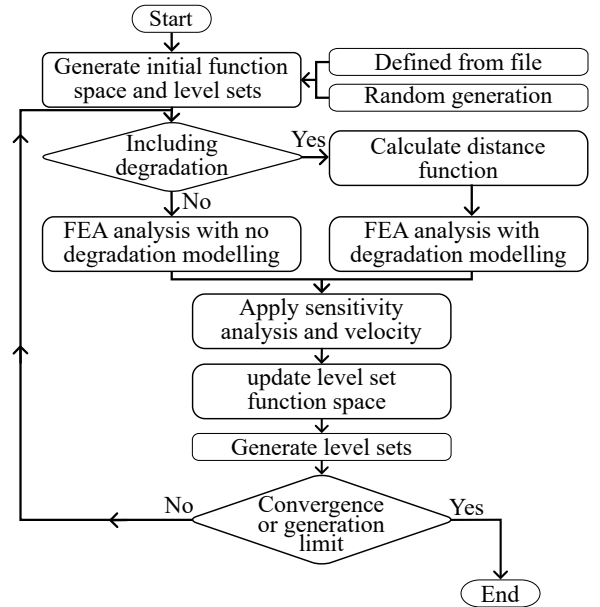


Fig. 1. Level set optimization process

level sets are all presented in the literature [2]. For example Lee, et al. [5] implements a SIMP optimization procedure achieving the desired torque with a 0.1% torque ripple and unconventional topology highlighting the potential benefit.

A. Level set Methodology

A level set topology optimization method is implemented here, along with a linear regression update scheme to investigate the design space. The level set process is applied on a single rotor pole of a 4 pole, 3 phase, 36 slot machine, which makes up the bulk of the design parameters. During the FEA program the rotor is rotated 90 degrees electrically, simulating the machine when aligned with the d and q axes [6]. By considering the energy in mesh elements between the two axes the rotor design is optimized to maximize the saliency ratio, and hence torque. A brief flow chart of the process is

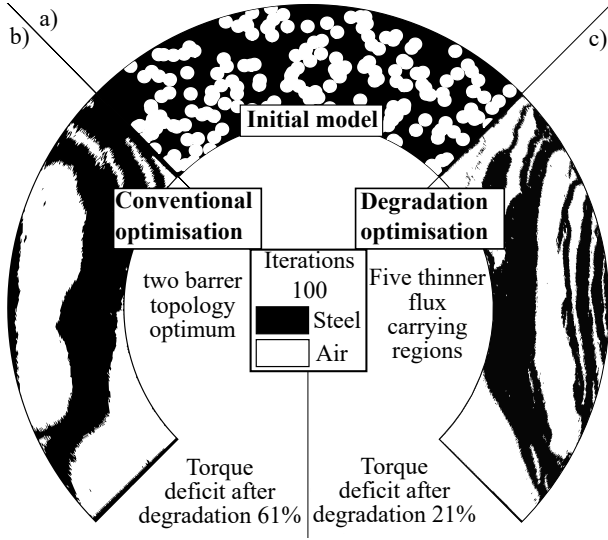


Fig. 2. Level set optimization results, a) initial clean sheet starting point, b) conventional topology optimization indicating two barrier topology, c) topology optimization with degradation indicating a multi barrier topology.

seen in Fig. 1. GMSH and GetDP are lightweight open source platforms which are used to mesh (GMSH) and carryout the FEA (GetDP) on designs [7], [8].

B. Degradation implementation

To implement the degradation model a distance function is required, to describe the distance from cut edges to mesh elements [9]. This is done using a built in post processing tool in GMSH. The degradation is implemented using a modified weak equation form of Amperes law in the rotor steel.

$$\nabla \times \left(\frac{1}{\mu(\nabla \times A) \cdot \text{Deg}(d, H)} \cdot \nabla \times A \right) = J \quad (1)$$

In (1), A is the magnetic vector potential [wb/m], μ is the permeability [H/m], d is the distance to a cut edge [m], H is the magnetic field strength [A/m] and J is the current density [A/m²]. In implementing distance into the problem domain, the variables in the problem increase, resulting in a greater computational burden. Assuming NO20 steel cut with 100 W 1064 nm 10 m/min laser cutting parameters with a 12 bar N₂ assist gas, $D(H)$ is implemented in the degradation function (Deg).

$$\text{Deg} = 1 - 0.9e^{D(H) \cdot d} \quad (2)$$

$$D(H) = 1.7e^{-6} \cdot H^2 - 8.3e^{-4} \cdot H + 0.24 - 0.24 \cdot e^{-H \cdot 70} \quad (3)$$

The parameters used in (2), (3) are based on the results from Epstein frame testing.

III. RESULTS

Two level set implementations are set up with a constant initial problem seen in Fig. 2 and 100 iterations are performed. Modeling the degradation doubles the simulation time to 280 seconds here however, this will vary with the selected parameter set. This computation burden can be broken down into 7.4% to generate a distance function and 92.6% to run

magnetic FEA simulations. The increase in simulation time highlights the need for initial testing on a reduced order magnetic model, before implementation into a full magneto-mechanical optimization procedure. No design restrictions have been applied, thus the results in Fig. 2 are not guaranteed to be feasible mechanically, instead they highlight the influence of incorporating degradation. A constant initial result ensures deviations in results are from degradation only and not from initial conditions or model set up.

IV. DISCUSSION, CONCLUSION AND FURTHER WORK

The results in Fig. 2 show an increase in flux barriers when degradation is included. The magnetic steel permeability in the zones close to the cut edges significantly degrades from laser cutting. This has a negative impact on the motor torque (saliency ratio) by acting to increase the q-axis reluctance, although the effect is offset by a reduction in d-axis leakage fluxes. The trade-off between the q- and d-axis effects may explain that when the degradation is included in the topology optimization, the results point towards a higher number of flux barriers being optimal. However, by increasing the number of flux barriers more cuts are required thus, increasing the zone of degradation, and the implications of this will be expanded on in the full paper.

The full paper will expand upon the level set topology optimization with manufacturing degradation shown here. Further implementation of a high performance computing platform will accelerate testing enabling the exploration of optimization parameters on results and further improve simulation speed.

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