Uncertainty Analysis of an Additively Manufactured Rotor for Flux-Intensifying Permanent Magnet-Assisted Synchronous Reluctance Machine with Surface-Inset Ferrite Magnets

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Introduction

Based on our literature review, the **flux-intensifying permanent magnet-assisted synchronous reluctance machine (FI-PMaSynRM) type** [1] - which is a rarely covered topic in the literature - is a possible alternative to conventional permanent magnet-assisted synchronous reluctance machines considering circular economy aspects, mainly disassembling the machine and using a low amount of non-rare-earth element-based permanent magnets [2]. The basis of our research is **remanufacturing** a low-power surface-mounted permanent magnet synchronous machine to a flux-intensifying permanent magnet-assisted synchronous reluctance machine with surface-inset ferrite magnets by redesigning and **3D printing** the rotor. This study investigates the optimisation process and **sensitivity of the average torque, torque ripple, cogging torque and total harmonic distortion** of the surface inset magnets and the magnet pockets using **NSGA-II. and Taguchi method** [3], plus the effects of **magnet shifting.**

Methodology

The objective function of the NSGA-II. optimisation was

$$max\, T_{avg}(x_i)$$
$$min\, T_{rip}(x_i),\ T_{cog}(x_i),\ T_{thd}(x_i) \quad i \in \mathbb{Z},\ i = 1,..,4$$
$$x_1 \in \mathbb{Z},\ x_1 = 10,..,15$$
$$x_2 \in \mathbb{Z},\ x_2 = 10,..,18$$
$$x_3 \in \mathbb{Z},\ 2x_3 = -16,..,16$$
$$x_4 \in \mathbb{Z},\ 2x_4 = -16,..,16$$

with the contraint of

$$s.t.\ if\, x_2 + x_4 > 26:\ x_2 = 18 - \frac{x_4}{2}$$
$$if\, x_1 > x2:\ x_1 = x_2,\ x_3 = x_4$$
$$if\, x_3 > (x_2 - x_1) * 2 + x_4:\ x_3 = (x_2 - x_1) * 2 + x_4$$
$$if\, x_+ < -(x_2 - x_1) * 2 + x_4:\ x_3 = -(x_2 - x_1) * 2 + x_4$$

with the goal to ensure a design that does not behave as a permanent magnet synchronous machine (PMSM), in other words **limiting the amount of magnets** and the size of the pocket.

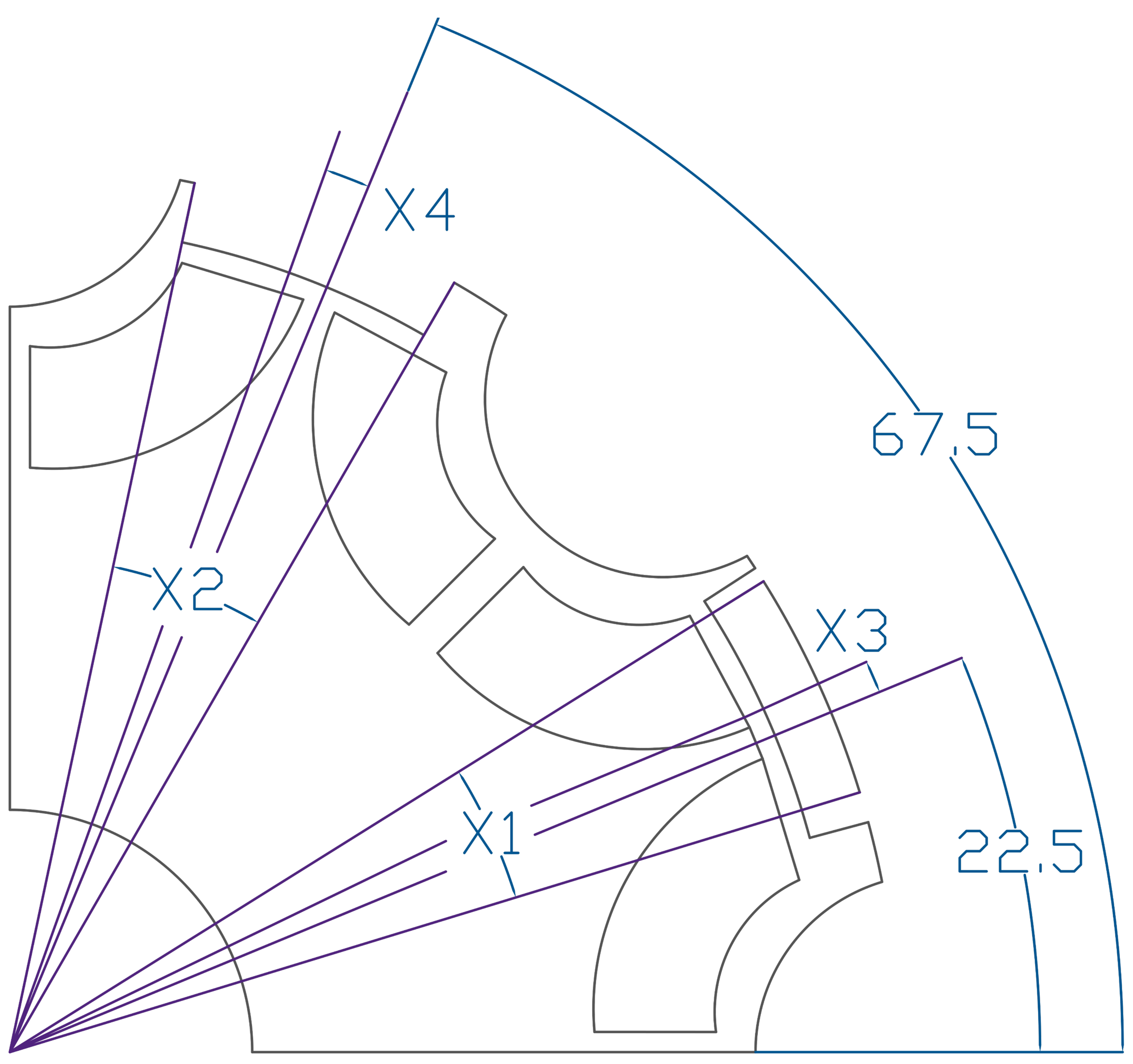
The sensitivity analysis was carried out using Taguchi method **L25 orthogonal array** excluding the last two columns resulting in **four parameters and five levels**. In the case of minimizing the performance characteristics:

$$SN_i = -10\log\left(\frac{\sum_{u=1}^{N_i} y_u^2}{N_i}\right)$$

In the case of maximizing the performance characteristics:

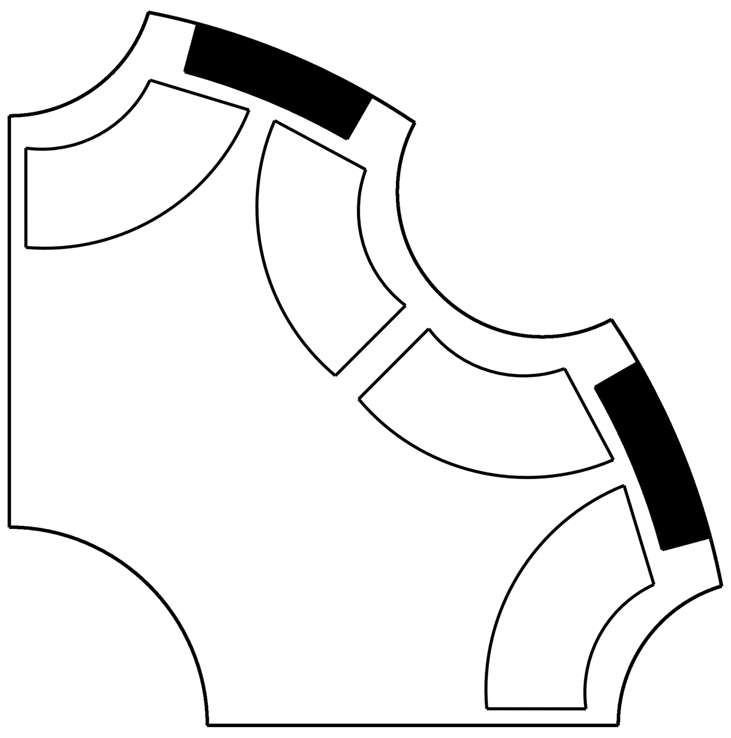
$$SN_i = -10\log\left[\frac{1}{N_i}\sum_{u=1}^{N_i}\frac{1}{y_u^2}\right]$$

The optimal design were selected by comparing multiple Multi-Criteria Decision Methods as **TOPSIS, MABAC, COMET, SPOTIS**.

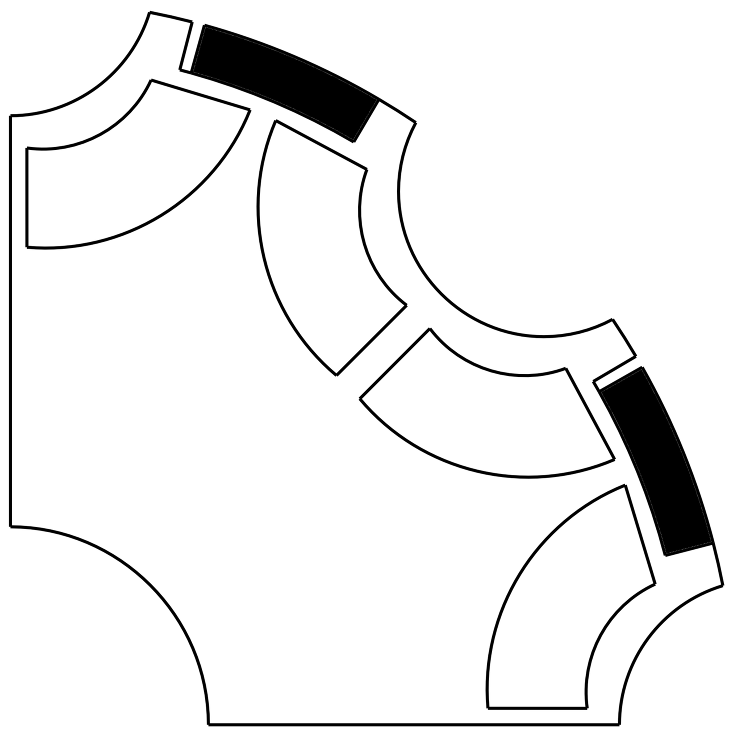


6. Fig: Design parameters on the surface inset magnets

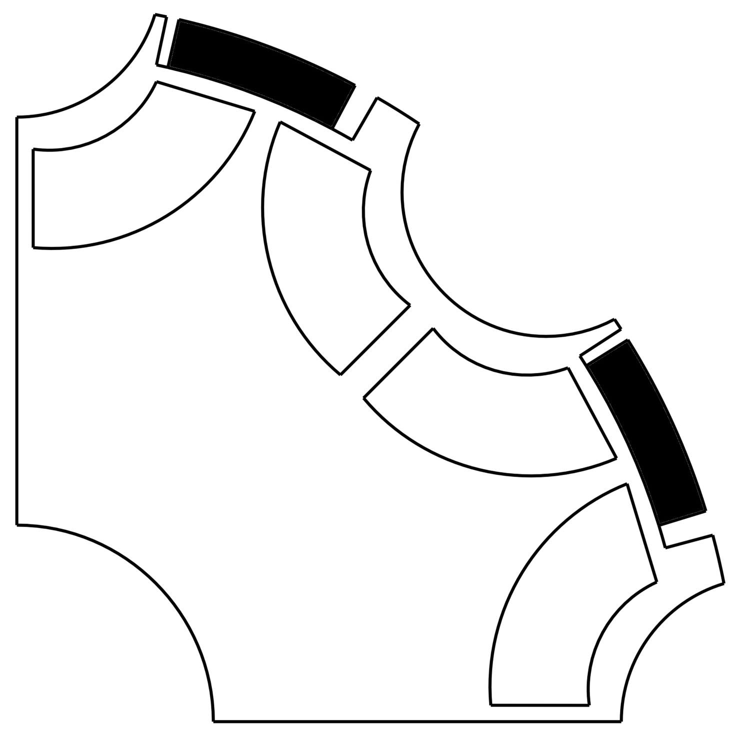
Rotor Designs



1. Fig: Base FI-PMaSynRM design



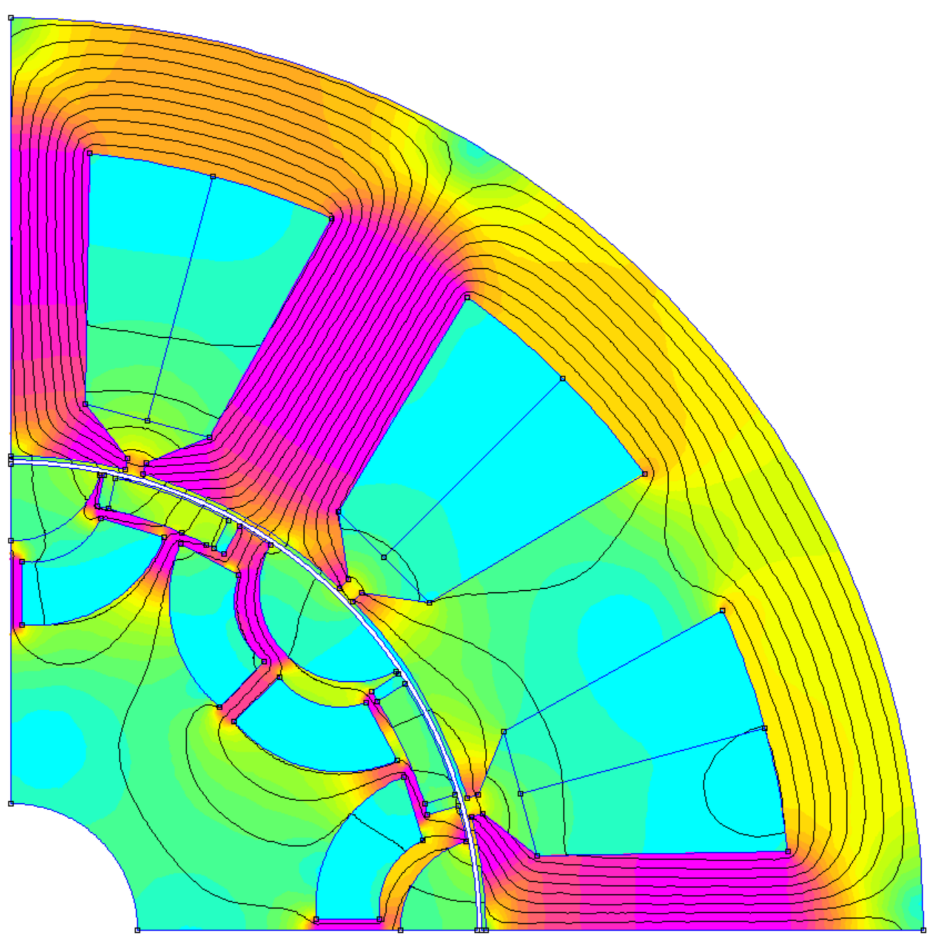
2. Fig: Shifted FI-PMaSynRM design



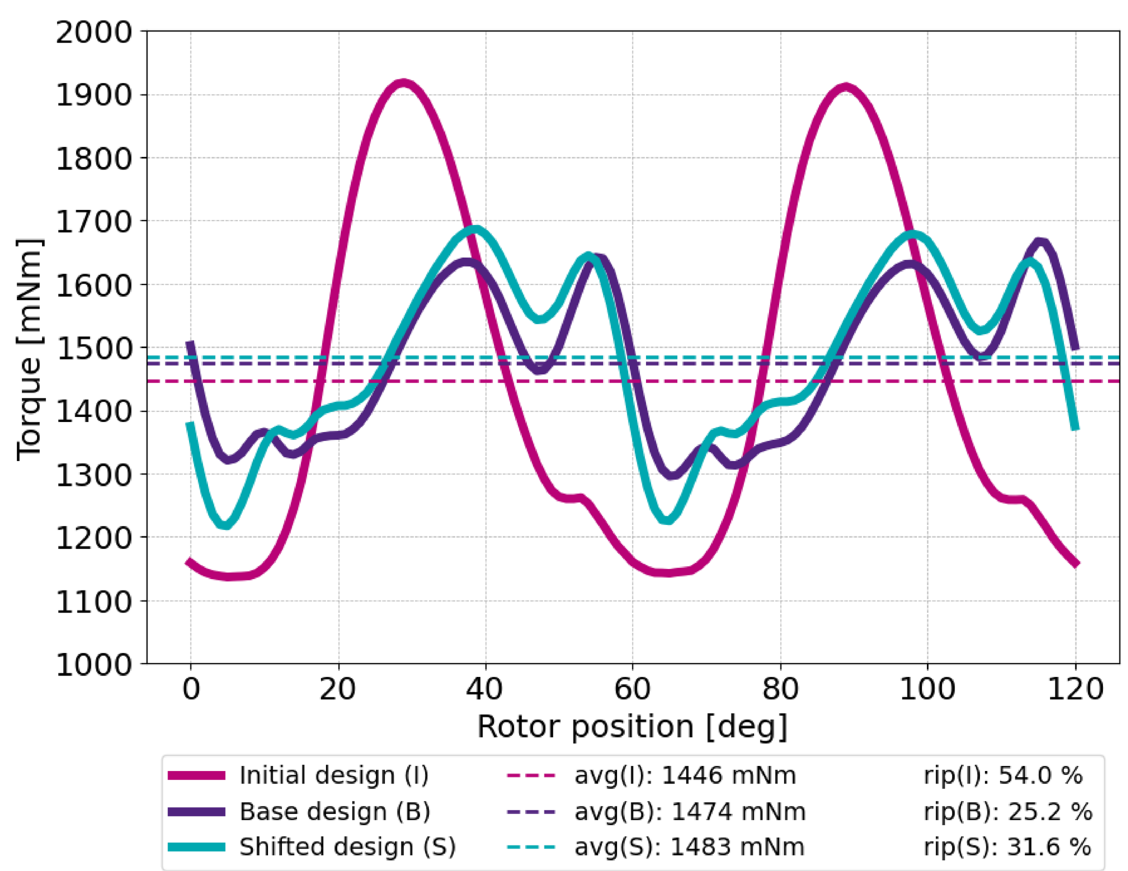
3. Fig: False FI-PMaSynRM design

First a rescaled model of [4] was created for the dimension of the investigated scrap stator. Liu et al. introduced the definition of **Repeating Unit** considering surface inset permanent magnet shifting. A Repeating Unit (RU) is a group of poles producing torque in a consistent waveform and phase but was **considered a similar shifting direction** [5]. Du et al. considered the presence of **air pockets** next to the magnets **on one side** [6]. The main problem is that with the standard objective functions, **the algorithm tends to create a traditional PMSM**. Solving that geometrical constraints are introduced as constraining based on additional FEM calculations is computationally expensive.

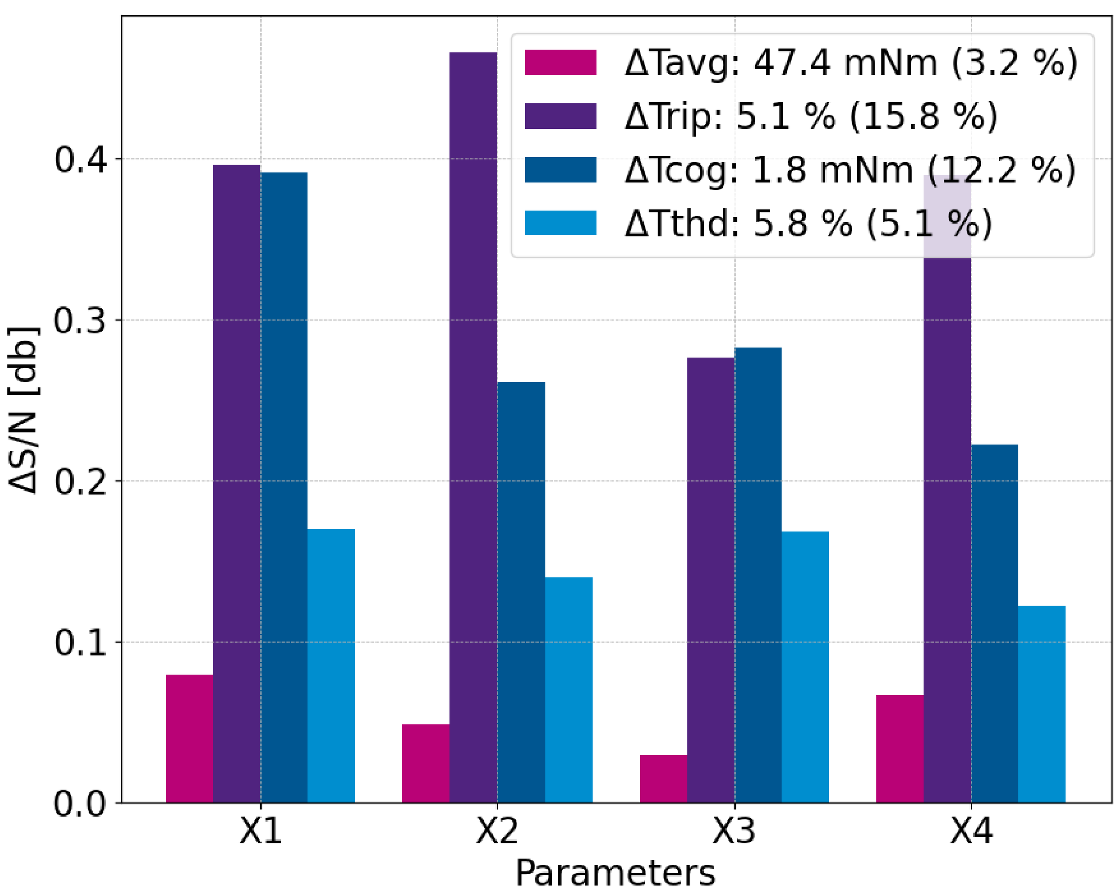
Results



4. Fig: Flux density of the false design



5. Fig: Comparison of average torque for different machines



6. Fig: Sensitivity of design parameters by Taguchi method

The uncertainty of the design parameters were set to

$$x_{1j} = x_1 - j \cdot 0.1, \quad x_{2j} = x_2 + j \cdot 0.1$$
$$x_{3j} = x_3 + j \cdot 0.1, \quad x_{4j} = x_4 + j \cdot 0.1$$
$$j \in \mathbb{Z},\ j = 0,..,4$$

Conclusion

- The analysis showed that magnet shifting is an appropriate method for lowering the cogging torque. However, the **0.4° uncertainty** in the design variables results in a considerable **12.2% relative error** to the optimum outcome.
- Using objective functions used for traditional permanent magnet synchronous machines leads to an algorithm that tends to create false designs even with geometrical constraints. The machine is highly sensitive to the position of the magnets and magnet pockets changing from FI-PMaSynRM to PMSM. **Introducing one pole pair as a repeating unit and counter directional shifting** is a possible solution for further investigation.

References

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