PERFORMANCE ANALYSIS OF AN IPMSM WHEN APPLYING HEAVY RARE-EARTH-FREE NDFEB PMS

PAVEL OGRIZEK, MITJA GARMUT, MARTIN PETRUN
University of Maribor, Faculty of Electrical Engineering and Computer Science, Institute of Electrical Power Engineering, Maribor, Slovenia
pavel.ogrizek@um.si, mitja.garmut@um.si, martin.petrun@um.si

The pursuit of greener technologies has prompted research into alternatives to heavy rare-earth (HRE) permanent magnet (PM) materials in electric machines, notably Interior Permanent Magnet Synchronous Machines (IPMSMs). This study examines how an IPMSM performs with HRE-free PMs, aiming to reduce environmental impact and costs linked to HRE material use. Using a two-dimensional transient Finite Element Method (2D-FEM) IPMSM model in Ansys Maxwell 2D, torque and power characteristics across different speed ranges for IPMSM models with two HRE-free PM materials and traditional HRE PMs were compared. Scaling law was implemented on HRE-free PM models to maintain the maximum torque.

DOI
https://doi.org/10.18690/um.feri.4.2025.16

ISBN
978-961-286-986-1

Keywords:
interior permanent magnet synchronous machine (ipmsm),
permanent magnet (pm),
heavy rare earth free (HRE-free),
dy-free NdFeB,
torque-speed envelope

University of Maribor Press

I Introduction

The contemporary household electrical devices, cordless power tools, and electric or hybrid vehicles are equipped with Interior Permanent Magnet Synchronous Machines (IPMSM) incorporating rare-earth permanent magnets (PMs). High efficiency and high torque density IPMSM typically use rare-earth NdFeB magnets. Such rare-earth PMs include elements like dysprosium (Dy) and terbium (Tb) to reduce the risk of permanent demagnetization at elevated temperatures. Nd is a light rare-earth element, while Dy and Tb are heavy rare-earth (HRE) elements [1]. HRE PMs deposits are unevenly distributed, and recent production has been concentrated in specific countries. Additionally, there is a growing need to minimize the usage of HRE elements due to the associated risks and costs of working with such scarce resources [2].

The main goal of this study was to replace HRE with HRE-free PMs in an IPMSM, analyze the machine's electromagnetic performance, and compare it with the baseline configuration. Another important aspect was scaling (downscaling or upscaling) the HRE-free design to maintain maximum torque and operation range compared to the baseline design.

II Theoretical background

A. IPMSM d-q model

Voltage equations of an IPMSM in the *d-q* rotating reference frame where the *d*-axis of the rotating reference frame is aligned to PM flux-linkage Ψ_{PM} are defined by (1) and (2):

$$u_{\mathrm{d}} = Ri_{\mathrm{d}} - \omega_{\mathrm{e}}\Psi_{\mathrm{q}} = Ri_{\mathrm{d}} - \omega_{\mathrm{e}}L_{\mathrm{q}}i_{\mathrm{q}} \tag{1}$$

$$u_{\mathrm{q}} = Ri_{\mathrm{q}} + \omega_{\mathrm{e}}\Psi_{\mathrm{d}} = Ri_{\mathrm{q}} + \omega_{\mathrm{e}}(\Psi_{\mathrm{PM}} + L_{\mathrm{d}}i_{\mathrm{d}}) \tag{2}$$

where i_{d}, i_{q} and $u_{\mathrm{d}}, u_{\mathrm{q}}$ are the *d-q* reference frame voltages and currents, R is the phase resistance and ω_{e} is the electrical angular velocity. Flux linkage in the *q*-axis due to the current excitation is defined as $\Psi_{\mathrm{q}} = L_{\mathrm{q}}i_{\mathrm{q}}$, where L_{q} is incremental inductance in the *q*-axis. The total flux linkage in the *d*-axis is defined as $\Psi_{\mathrm{d}} = \Psi_{\mathrm{PM}} +$

$L_d i_d$, where Ψ_{PM} is the flux-linkage due to the PM, and product of current and incremental inductance L_d in d-axis is flux-linkage in the *d*-axis due to current excitation.

The model's parameter estimation was performed based on a finite element method (FEM) model of the IPMSM implemented in Ansys Maxwell 2D software. The analysed IPMSM has 4 poles, tangential interior PMs and 3-phase, 6-slot stator with double-layer fractional-slot concentrated windings. We evaluated 5 different operation points (OPs), i.e., 5 different i_d and i_q combinations with a 2D transient FEM analysis. To evaluate the steady state performance, currents i_d, i_q and the electrical angular velocity ω_e were defined as the inputs within the numerical analysis. From the results, non-linear dependences $\Psi_d(i_d, i_q)$, $\Psi_q(i_d, i_q)$ and $T_{em}(i_d, i_q)$ were obtained for all OPs. Obtained variables depended on current combinations and were average values with respect to rotor position. Ψ_{PM} was calculated from no-load. Detailed workflow for parameter estimation was presented in [3]. Based on the obtained variables torque- and power vs speed characteristics were calculated with equations for maximum torque per ampere (MTPA) and field-weakening (FW) control, as presented in [4].

B. Evaluated PM materials

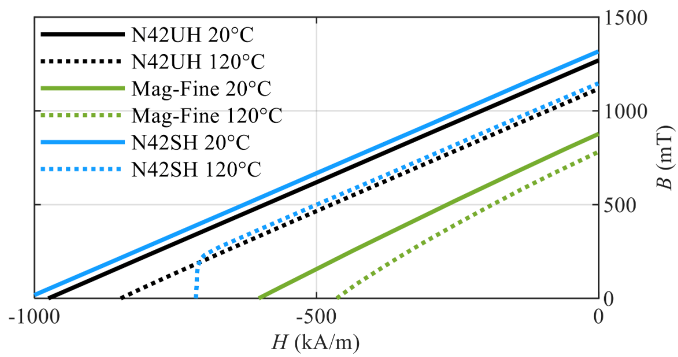

Figure 1: Demagnetization curves for evaluated PM materials at 20℃ and 120℃.

Magnetic properties of three commercially available PM grades are presented in Figure *1* at 20℃ and 120℃, respectively. The baseline design used HRE NdFeB (Arnold Magnetics N42UH). The applied HRE-free PMs for comparison were two compression-bonded NdFeB PMs: specifically, N42SH from JL MAG Rare-Earth Co. [5], and Mag-Fine MF18C from Aichi Corporation. Mag-Fine PMs use copper and aluminum for diffusion instead of Dy and Tb [6].

III Results

A comparison of obtained Torque- and power-versus-speed characteristic's for IPMSMs with the discussed PM materials are presented in Figure *2*. All characteristics were calculated with demagnetization curves for 120℃, which was assumed the steady state temperature of PMs. The analysis results showed that by replacing the N42UH PMs in the IPMSM model with HRE-free N42SH, the maximum torque in MTPA region is increased by 2%, meanwhile the use of Mag-Fine PMs decreases it by 28%. This is related to the remanent magnetic flux density and coercivity.

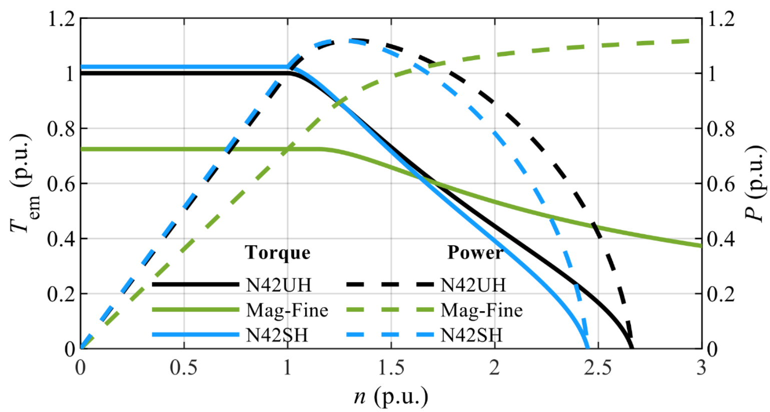

Figure 2: Comparison of torque- and power-vs-speed characteristic's for N42UH, Mag-Fine, and N42SH PMs in the IPMSM design at maximum current and temperature of PMs of 120℃.

It was observed that in FW region with Mag-Fine PMs in the model, significantly higher speeds and wide constant power range were achieved due to significantly lower remanent magnetic flux density. On the other hand, with N42SH and N42UH PMs, considerably lower speeds were reachable and the constant power ranges were significantly shorter. The obtained values of respective maximum speeds are collected in Table 1.

To maintain the baseline maximum torque with presented HRE-free PM materials, axial scaling was applied. Specifically, the IPMSM model featuring Mag-Fine PMs underwent upscaling through a 28% increment in stack length, while the variant employing N42SH PMs underwent downscaling via a 2% reduction in stack length. After scaling the targeted maximum torque was reached, as visible on Figure 3. In FW region the upscaled model with Mag-Fine PMs again reached significantly higher speeds compared to other two designs. Despite scaling, there has been a notable shift in the base speed of scaled model. In the case of Mag-Fine, the base speed point was shifted to the left and with a significant decrease in comparison to the baseline design. Conversely, for N42SH, the base speed was shifted slightly to the right with an increase relative to the baseline model. Base speed values for the all the designs are presented in Table 1.

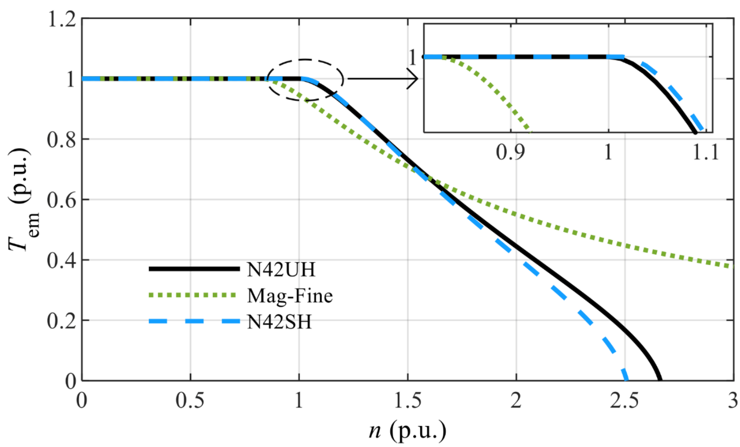

Figure 3: Comparison of torque-vs-speed characteristics for N42UH (baseline), upscaled Mag-Fine and downscaled N42SH based IPMSM designs at maximum current and temperature of PMs of 120℃.

Table 1: Comparison of base speed, maximum speed, and maximum torque.

IPMSM model	PM type	Base speed (p.u.)	Maximum speed (p.u.)	Maximum torque (p.u.)
Baseline	N42UH	1	2.66	1
	Mag-Fine	1.15	≫3	0.72
	N42SH	0.99	2.45	1.02
Axial scaled	Mag-Fine	0.83	≫3	1
	N42SH	1.02	2.51	1

IV Conclusion

Utilizing two HRE-free NdFeB, N42SH and Mag-Fine (MF18C) PMs as alternatives to the standard HRE NdFeB (N42UH) demonstrates the potential for enhancing or compromising IPMSM performance, contingent on the chosen PM material. A straightforward substitution with N42SH PMs led to increase in maximum torque within the MTPA region, with reduction of maximal operating speed. Conversely, the adoption of Mag-Fine PMs resulted in a torque reduction, albeit enabling significantly higher operational speeds suitable for high-speed applications. The results of axial scaling of the HRE-free NdFeB PM IPMSM models were:

- maintaining the same maximum torque as the baseline design,
- shifting the base speed, i.e. upscaling shifts the base speed point to the left side (a decrease), meanwhile downscaling shifts to the right (an increase) compared to the baseline base speed.

Moreover, there is a room for further optimization of IPMSM geometry with HRE-free PMs to maximize the maximum torque or speed. In the full paper a detailed analysis of back electromotive force, torque components versus load angle, and demagnetization risks will be presented.

References

[1] A. Al-Qarni and A. E.-. Refaie, "On Eliminating Heavy Rare-Earth PM Elements for High Power Density Traction Application Motors," in *2021 IEEE International Electric Machines & Drives Conference (IEMDC)*, 17-20 May 2021 2021, pp. 1-8, doi: 10.1109/IEMDC47953.2021.9449542.

[2] S. Soma, H. shimizu, E. Shirado, and S. Fujishiro, "Magnetic Form of Heavy Rare-Earth Free Motor for Hybrid Electric Vehicle," *SAE International Journal of Alternative Powertrains,* vol. 6, no. 2, pp. 290-297, 2017, doi: 10.4271/2017-01-1221.

[3] M. Garmut, S. Steentjes, and M. Petrun, "Parameter identification for MTPA control based on a nonlinear d-q dynamic IPMSM model," *COMPEL - The international journal for computation and mathematics in electrical and electronic engineering,* 2022-12-12 2022, doi: 10.1108/compel-09-2022-0331.

[4] S. Morimoto, M. Sanada, and Y. Takeda, "Wide-speed operation of interior permanent magnet synchronous motors with high-performance current regulator," *IEEE Transactions on Industry Applications,* vol. 30, no. 4, pp. 920-926, 1994-01-01 1994, doi: 10.1109/28.297908.

[5] L. JL MAG Rare-Earth Co. *Demagnetization curves, Heavy rare earth free technology*. [Online]. Available: https://www.jlmag.com.cn/en/about.php?cid=70

[6] A. S. Corporation. *Magfine technical datasheet*. [Online]. Available: https://www.aichi-steel.co.jp/_assets/dl/products_development/products/magFine_catalog.pdf