COMPUTATION OF IRON LOSSES USING FEM MODEL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

LOVRENC GAŠPARIN,[1] KLEMEN DROBNIČ,[2] RASTKO FIŠER[2]

[1] MAHLE Electric Drives Slovenia d.o.o., Šempeter pri Gorici, Slovenia
lovrenc.gasparin@si.mahle.com
[2] University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia
klemen.drobnic@fe.uni-lj.si, rastko.fiser@fe.uni-lj.si

Accurate computation of iron losses in permanent magnet synchronous motors is a challenging task due to their nonlinear dependency on a motor's instantaneous loading condition. In the proposed computational procedure, a finite element method (FEM) is used for calculations of magnetic flux density in each particular mesh element. Applying a fast Fourier transform (FFT), its harmonic content is determined, followed by iron loss density calculation independently for several significant harmonics in all mesh elements over the entire stator iron core of PMSM. The proposed procedure predicts iron losses significantly better than classic approach where sinusoidal magnetic flux density is assumed.

DOI
https://doi.org/10.18690/um.feri.4.2025.32

ISBN
978-961-286-986-1

Keywords:
permanent magnet synchronous machine,
magnetic field density,
iron losses,
finite element model,
harmonic components

University of Maribor Press

I Introduction

Modern traction drivetrain must satisfy number of specific requirements such as high dynamic performance, high torque density, high efficiency, low noise, and a wide speed range. In recent years, interior permanent magnet synchronous motors (PMSMs) have become the most popular motor traction topology for fast growing field of hybrid and electric vehicles. In order to achieve highest possible machine efficiency, the precise determination of losses is of the utmost importance and must be properly addressed already during machine design. Next to copper losses in windings, the iron losses in core lamination are the main contributor to the total losses in PMSM. Since iron losses vary strongly due to instantaneous operating condition (e.g. rated flux vs. field weakening operation) as well as on material/geometry, their accurate determination becomes a challenging task [1]. Therefore, an adequate simulation model should take into consideration lamination geometry, nonlinear material properties, different saturation levels, magnetic flux higher harmonics, etc. [2]. To take into account most of the aforementioned phenomena, FEM analysis is widely used and has become an industrial standard [3]. It ensures an accurate magnetic field computation, which is an excellent basis for further simulation of machines static and dynamic characteristics.

II Magnetic Field and Iron Loss Computation

Majority of methods for iron losses calculation are based on variation of magnetic field density B in a small mesh (volume) element of an iron core, whereupon total losses are decomposed into eddy current, hysteresis and excess losses, respectively. Two simplifying assumptions are commonly adopted, i.e. B is varying sinusoidally in time and the mesh element has an uniform distribution of B pointing in just one direction [4]. However, due to iron saturation and a specific lamination design, B also contains several prominent higher harmonics, suggesting an increase of total iron losses. Therefore, the conventional approach is not accurate enough and should be improved [5].

PMSM under consideration has 3-phase, fractional-slot winding, placed in 36 stator slots. Eight permanent magnets are buried in the rotor lamination in stamped holes. The motor is designed for mild hybrid drivetrain and features rated torque 60 Nm and maximum speed 21000 min^{-1}. For stator lamination, a soft magnetic material denoted as M270-35A is used, lamination thickness is 0.35 mm. Due to simplicity and computational efficiency, the analysis of the magnetic field density is limited to the smallest symmetrical part of a stator geometry, i.e. one stator tooth and corresponding back-iron sector. Cross-section of the stator core with designated calculation area and *x-y* coordinate system is shown in Fig. 1.

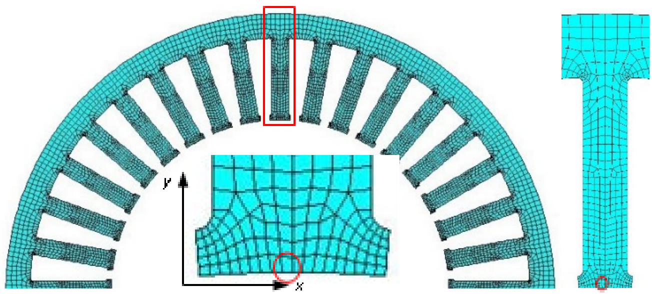

Figure 1: Selected symmetrical domain of FEM calculation, a tooth mesh of finite elements with selected single element, and defined coordinate system.

The magnetic field density B in each mesh element of the lamination segment (denoted with red square) is decomposed in tangential (B_x) and radial (B_y) component. However, the ratio between two components strongly depends on the location of the element: in elements near tooth center the B_y strongly prevails, while in back-iron elements dominates B_x. In lamination regions, where flux lines are crossing from tooth center into the back-iron and in tooth-end elements near the air-gap, both components are similarly pronounced. Additionally, saturation effect in each particular element is pronounced differently, which leads to a variety of higher harmonic components. For correct iron losses calculation, all these effects require a precise and exact examination of the magnetic field density in each mesh element by *x*- and *y*-components for several harmonic components, instead of assuming only fundamental value of B as usually adopted [6]. In a particular case of presented PMSM, the first seven harmonic components prove to be influential enough to substantially contribute to iron losses.

Magnetic field density $B_\theta = f(\theta, I_d, I_q)$ in each mesh element changes with instantaneous rotor angle θ and is also dependent on I_d and I_q current components (defined in rotor coordinates). With operating point fixed at (I_d, I_q), a number of static FEM calculations are performed, where instantaneous rotor angle θ sweeps exactly one electric period. Then, B_θ is decomposed into radial $B_{y,\theta}(I_d, I_q)$ and tangential $B_{x,\theta}(I_d, I_q)$ component. It is important to note, that $B_{x,\theta}$ and $B_{y,\theta}$ are periodic in electric angle. To determine the corresponding harmonic spectra for each component, a FFT is employed. In this way, amplitudes of $B_{x,i}(I_d, I_q)$ and $B_{y,i}(I_d, I_q)$ for i^{th} harmonic component in each particular mesh element are obtained. Consequently, it can be ascertained, how particular harmonic contributes to the final value of iron losses P_{Fe}. The described computational procedure combining FEM (Ansys) and Matlab domain is presented in Fig. 2 for a single operating point.

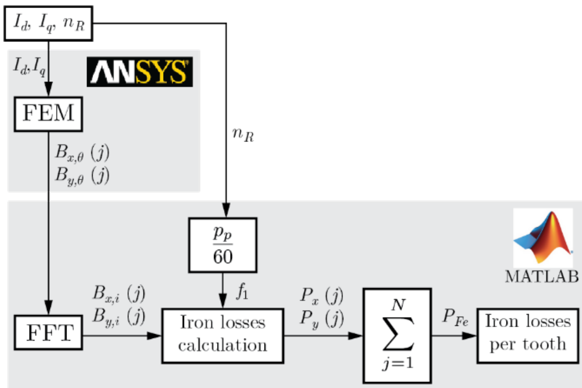

Figure 2: Flow chart of iron loss density calculation in one stator tooth for a chosen rotor speed and a single load operating point.

III Simulation and Experimental Results

Three chosen representative positions in a stator lamination segment regarding magnetic field density orientation are shown in Fig. 3: (a) a tooth end near the air-gap, where $B_{x,i}$ and $B_{y,i}$ are of a similar extent; (b) a tooth center position with dominant y direction; (c) a back-iron position with dominant x direction. A close study of Fig. 4 reveals the most influential components of iron loss density p_{Fe} in terms of direction and higher harmonics in these three positions for the specific operating point (I_d = –463 A, I_q = 624 A). Each of these three cases gives a completely different arrangement of components, however the sum of all individual components corresponds well to the expected values of loss density in the iron regions.

Measurements of iron losses were performed at no-load with no current in stator windings to exclude cooper losses, while driving the tested motor with external drive at constant speed, and subtracting previously identified friction losses afterwards. Fig. 5 presents a comparison among both calculated iron losses and measured ones, where obvious improvement of the proposed procedure can be observed. If in addition to the fundamental component also 3rd, 5th, and 7th harmonics are considered, predicted iron losses for a speed range from 0 to 12000 min^{-1} are increased up to 10 % and correspond much better to measurements. Once the improved calculation of p_{Fe} is verified by measurements at no-load, any other operating point of the loaded PMSM can be predicted in terms of P_{Fe}.

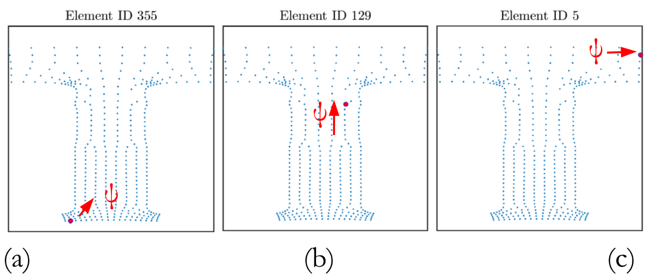

Figure 3: Selected mesh elements under investigations in three representative positions: (a) tooth end, (b) tooth center, (c) back-iron.

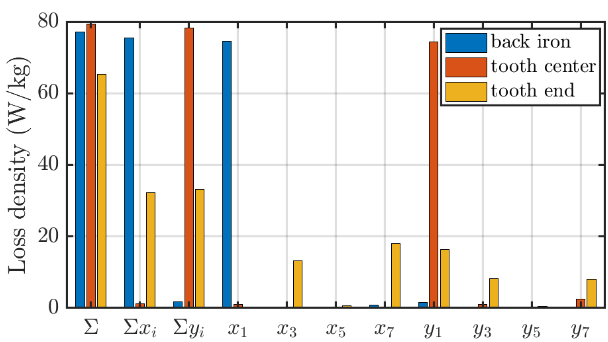

Figure 4: Components of iron loss density arranged by direction and higher harmonic components in three representative mesh elements for operating point (I_d = –463 A, I_q = 624 A).

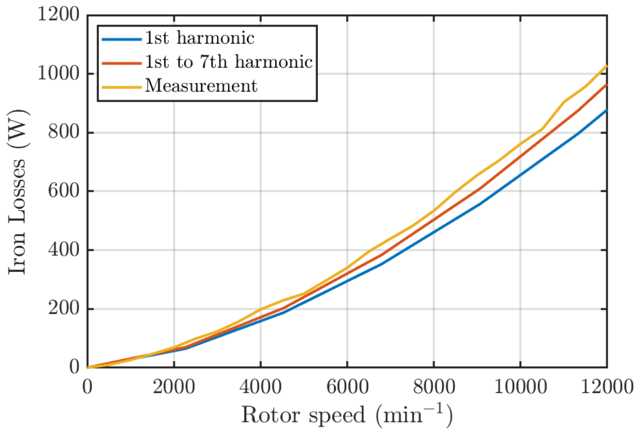

Figure 5: Improved calculation of PMSM iron losses taking into account also corresponding higher harmonics of B_x and B_y for a wide speed range.

References

[1] P. H. Mellor, R. Wrobel, D. Holliday, "A computationally efficient iron loss model for brushless AC machines that caters for rated flux and field weakened operation," *2009 IEEE IEMDC*, 3-6 May 2009, Miami, FL, USA, pp. 490-494.

[2] A. Krings, M. Cossale, A. Tenconi, J. Soulard, A. Cavagnino, and A. Boglietti, "Magnetic materials used in electrical machines," *IEEE Ind. Applicat. Mag.*, pp. 21-28, Nov./Dec. 2017.

[3] X. Chen, J. Wang, B. Sen, P. Lazari, and T. Sun, "A high-fidelity and computationally efficient model for interior permanent-magnet machines considering the magnetic saturation, spatial harmonics, and iron loss effect," *IEEE Trans. Ind. Electron.*, vol. 62, no. 7, pp. 4044-4055, Jul. 2015.

[4] N. Yogal, C. Lehrmann, M. Henke, and H. Zheng, "Measurement, simulation and calculation using Fourier transformation of iron losses for electrical steel sheets with higher frequency and temperature effects," in *22nd IEEE ICEM*, 4-7 Sept. 2016, Lousanne, Switzerland, pp. 2655-2661.

[5] V. C. do Nascimento, S. D. Sudhoff, "Continuous time formulation for magnetic relaxation using the Steinmetz equation," *IEEE Trans. Ener. Conv.*, vol. 33, no. 3, pp. 1098-1107, Sept. 2018.

[6] K. Yamazaki and Y. Seto, "Iron loss analysis of interior permanent magnet synchronous motors - variation of main loss factors due to driving condition," *IEEE Trans. Ind. Applicat.*, vol. 42, no. 4, pp. 1045-1052, July/Aug. 2006.