Intermag 2023, May, 15-19, 2023, Sendai, Japan

Multiphysics modeling and optimization of PMSM for high speed operation

Thomas Marcand[1], Charles-Henri Bonnard [1], and Smail Mezani[1]

[1]GREEN, Université de Lorraine, F-54000, Nancy, France, thomas.marcand@univ-lorraine.fr

In many modern applications like aerospace and automotive, maximizing the power density of an actuator is required to ensure lighter systems. This can be achieved by increasing the rotational speed of electrical machines, which leads to face many constraints, particularly from a mechanical and thermal points of view. Developing multiphysics modeling tools associated to optimization methods is then necessary for sizing high speed machines. The paper presents electromagnetic, mechanical and thermal analytical models of surface mounted PMSMs to ensure pretty precise pre-sizing. Numerical simulations that use the finite element method (FEM) are conducted to validate the analytical findings.

***Index Terms*—High speed electrical machines, Multiphysics, Optimization, PMSM**

I. Introduction

Recently, high speed electrical machines have gained in interest since they allow for higher power densities than conventional machines. This advantage is particularly interesting for embedded applications like aeronautical or automotive transports in which PMSM are widely used thanks to high specific energy rare earth magnets. An optimized sizing with analytical multiphysics (electromagnetic, mechanic and thermal) models of surface mounted PMSMs is proposed in this paper.

II. Analytical Models

A 2D cross section view of the studied PMSM is shown in Figure 1. The surface mounted magnets are retained by a sleeve to withstand the centrifugal force.

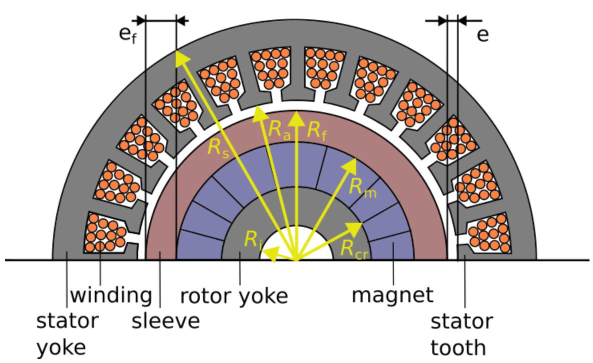

Fig. 1. 2D cross section view o PMSM (not to scale).

A. *Electromagnetic model*

The electromagnetic sizing of any electrical machine uses the concepts of magnetic and electric loading [1]-[2]. The starting point for the sizing is the expression of the electromagnetic power transmitted throughout the air-gap. For a machine rotating at the speed Ω in rad/s, the transmitted power is:

$$P_t = 2\Omega . k_w . \cos(\psi) . (BH) . \pi R_a^2 L \tag{1}$$

Where k_w is the winding factor (1st harmonic), ψ the phase shift between tangential field and normal flux density, R_a the armature bore radius, L the axial length, B the air-gap rms normal flux density (magnetic loading) and H the air-gap rms tangential magnetic field (electric loading).

The torque is therefore proportional to the product (BH) and the volume of the air-gap. For a surface mounted PMSM, the air-gap rms normal flux density is calculated analytically in 2D [3]. For radially magnetized magnets and $p > 1$, the value of B is calculated on the stator bore radius R_a by:

$$\mathrm{B} = \frac{4B_r}{\pi} . \sin\left(\frac{\beta\pi}{2}\right) . \frac{p}{1-p^2} . R_a^{-p-1} . \left(\frac{ \frac{2R_a^{2p}}{R_{cr}^{p-1}} - R_m^{p+1} . \left((1-p) + \frac{R_m^{-2p}}{R_a^{-2p}} . (1+p) \right) }{ \left(1 - \left(\frac{R_a}{R_{cr}} \right)^{2p} \right) } + (1-p) . R_m^{p+1} \right) \tag{2}$$

Where R_a, R_m and R_{cr} are respectively the stator bore radius, the magnet outer radius and the rotor yoke outer radius, B_r the remanent flux density, p the number of pole pairs and β, the angular opening of the magnets. The electric loading H is:

$$H = \frac{NI}{2\pi R_a} \tag{3}$$

Where N is the total number of conductors and I the rms current flowing in the conductor. Relations (1)-(3) allow the determination of R_a and L as well as the other stator and rotor dimensions by specifying a current density and a maximal saturation level in iron.

B. *Mechanical model*

At high speed, the surface-mounted magnets are held on the rotor yoke by a sleeve. Continuum mechanics allows to express the stresses as a tensor of order 2.

$$\left[\underline{\sigma}\right] = \begin{bmatrix} \sigma_{rr} & \sigma_{r\theta} & \sigma_{rz} \\ \sigma_{\theta r} & \sigma_{\theta\theta} & \sigma_{\theta z} \\ \sigma_{zr} & \sigma_{z\theta} & \sigma_{zz} \end{bmatrix} \tag{4}$$

The rotor is considered sufficiently long to use a 2D model, so only σ_{rr} and $\sigma_{\theta\theta}$ remain in (4). The rotor model includes 3 coaxial rings (rotor yoke, magnet and sleeve) as shown in Figure 1. The sleeve being pressed onto the magnet, a pressure p_s is applied at the interface between magnet and sleeve.

The displacement method [4] allows the calculation of the maximum stress located at the inner radius of the sleeve:

$$\begin{cases} \sigma_{rr} = -p_s \\ \sigma_{\theta\theta} = \dfrac{\rho\Omega^2(3+\vartheta)}{8}\left[\dfrac{-(1+3\vartheta)}{(3+\vartheta)}R_m^2 + 2R_f^2\right] \\ +p_s\left[-1 - \dfrac{2R_f^2}{(R_m^2 - R_f^2)}\right] \end{cases} \quad (5)$$

Where ϑ and ρ are respectively the Poisson's coefficient and the density of the sleeve, Ω is the angular speed.

It is necessary to define a plasticity's criteria to compare the mechanical stresses with the material yield strength. The Von Mises's stress criteria is used here.

C. Thermal model

Owing its good accuracy and low CPU time, a lumped parameter thermal model (LPTM) of the machine is built [5]. Each part of the machine consists of an elementary block composed of a number of independent unidirectional lumped thermal circuits. Figure 2 shows a unidirectional thermal circuit in cartesian coordinates considering a thermal conductivity λ in $\mathrm{W/(m.K)}$, a power source P in W and a thermal capacitance C in $\mathrm{J/(m.K)}$. Three thermal resistances constitute the lumped model and allow to determine the average temperature. A similar circuit can be built for radial heat flow [5]. In the multidimensional case, the model is obtained by connecting each unidirectional lumped circuit to the average temperature node of the elementary blocks.

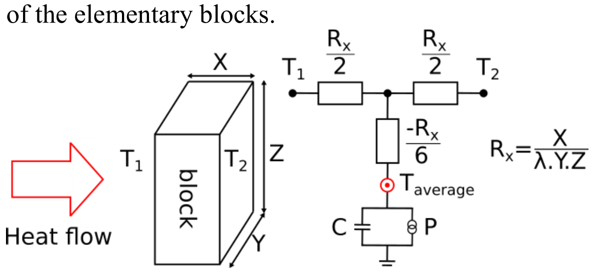

Fig. 2. Elementary block and its equivalent 1D thermal circuit.

In elaborating the LPTM of the machine, we assume a 2D model by considering a zero heat flow along the orthoradial direction. It is worth mentioning that we only consider steady state temperature in this work, i.e. the capacitance is not used. It has been implemented in the LPTM model for further work. The values of the thermal resistances and the sources are calculated using the dimensions and the losses issued from the electromagnetic model. To have the thermal network of the overall machine, the thermal circuit of a given block is connected to its neighboring ones at their contact surface.

III. Results and Conclusion

Simulation studies are conducted on a PMSM whose parameters (see Fig. 1) are: $p = 2$ pole pairs, $R_m = 63.7$ mm, $e = 2$ mm, $e_f = 3$ mm, $R_{cr} = 56.7$ mm, $R_i = 0$ mm. Figure 3 shows the no-load (magnets alone) radial flux density computed on a circle of radius R_a. The remanent flux density of the radially magnetized PMs is 1.1 T. The analytical and the FE results are similar although slotting effect is not considered in the analytical model. The fundamental flux density rms value given by (2) is $B = 0.57$ T, while the numerical calculation gives $B = 0.52$ T. Figure 4 shows the evolution of the VM stress vs. sleeve thickness. The sleeve material is glass fiber. The rotor speed is set to 30.000 rpm. The analytical and the FE results are in good agreement. It can also be seen that the sleeve thickness $e_f = 3$ mm is enough to ensure the mechanical integrity of the rotor under maximal centrifugal stress. In the full paper, more results will be presented regarding the coupled multiphysics optimization of a PMSM.

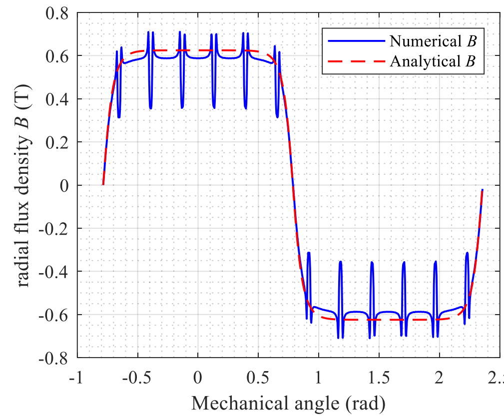

Fig. 3. Radial flux density waveform on a circle of radius R_a.

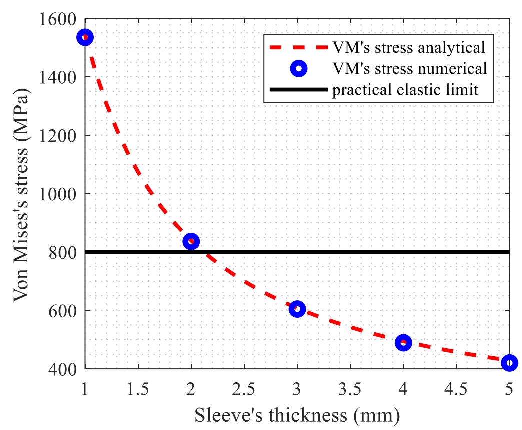

Fig. 4. Von Mises's Stress at the inner radius of the sleeve vs its thickness.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875006 IMOTHEP

References

[1] J. Pyrhönen, T. Jokinen, and V. Hrabovcova, 2008 *Design of rotating electrical machines, 1st edition*, John Wiley & Sons, 512 p.
[2] B. Laporte, 2007, *Machines électriques tournantes – Conception, dimensionnement, fonctionnement*, 1st Edition, Ellipses-Technosup, 370 p.
[3] Z. Q. Zhu, D. Howe, E. Bolte and B. Ackermann, "Instantaneous magnetic field distribution in brushless permanent magnet DC motors. I. Open-circuit field," *IEEE Transactions on Magnetics*, vol. 29, no. 1, pp. 124-135, Jan. 1993
[4] G. Burnand, D. M. Araujo, et Y. Perriard, « Very-high-speed permanent magnet motors: Mechanical rotor stresses analytical model », in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, Miami, FL, USA, mai 2017, p. 1-7.
[5] P. H. Mellor, D. Roberts, and D. R. Turner, 1991, "Lumped parameter thermal model for electrical machines of TEFC design," *IEE Proceedings-B*, vol. 138, no. 5, pp. 205-218.