

Quasi 3D Open Circuit Magnetic Field Model of Slot-Less Axial Flux Permanent Magnet Motor Based on Mirroring Technique

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The sizing of Axial Flux Machines (AFM) remains a non-trivial task, as 3D approach is required. Generally, a 3D FEA software is used for a comprehensive analysis of such machines, which may require long calculation times. In the context of pre-sizing, the use of FEA software is not a relevant option. Simple analytical models are more suitable, due to shorter computation times which makes possible fast analysis of various motor geometries. This paper proposes a fully analytical model for calculating the open circuit magnetic field of a slot-less Axial Flux Permanent Magnet (AFPM) motor. Based on mirroring techniques, the combination of 2D equations in two normal planes to calculate the 3D magnetic field is the novelty proposed by this paper. A fair comparison with 3D FEA software (ANSYS Maxwell 3D) applied to motors identified from technical literature concluded in the relevancy of the proposed model regarding calculation speed and accuracy. Also, it can be easily parameterized which makes it perfectly suited to a pre-sizing phase. The limitations of this model are also shown and discussed.

Index Terms—Analytical models, Electric motors, Electromagnetic model.

I. INTRODUCTION

OVER the past years most of markets (e-mobility, transportation, factory automation, HVAC) have raised the need for more compact and performant power systems regarding efficiency, weight, and reliability. In conjunction with the massive adoption of Wide Band Gap (WBG) devices such as SiC or GaN for power converters, the demand for specialized motors is exponentially ramping up from e-mobility to consumer electronics. In the case of e-vehicle motors for example, Axial Flux Motors (AFM) are gradually becoming the high-end choice for electric vehicles, as it has a better torque density than their radial counterparts. AFM are now proposed by Infinium for HVAC (Heating, Ventilation, and Air-Conditioning) applications [1]. Smaller AFMs powered by GaN are also proposed by Tokgoz et al. [2]. For the sizing of these motors, 1D or 2D analytical models are proposed and then completed by a comprehensive 3D FEA analysis.

To size slot-less Axial Flux Permanent Magnet (AFPM) motors from small to high torques, a pre-sizing procedure such as [3] is considered. The backbone of the pre-sizing procedure is an accurate, fast, and adaptive open circuit magnetic field model. As slot-less motors are being modelled, the torque can be calculated with the Lorentz force. In this case, the geometric parameters of the stator allows to calculate the torque with an open circuit magnetic field model [4].

This article is divided into two parts: first is the presentation of the analytical model. Then the second part is dedicated to its benchmark based on salient case studies.

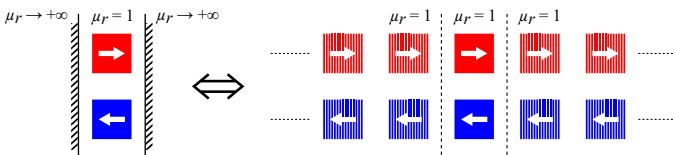


Fig. 1. Mirroring technique with two magnets and two boundary conditions.

II. OPEN CIRCUIT MAGNETIC FIELD MODEL DEVELOPMENT

A. Mirroring technique

The Mirroring technique is used to model magnetic field based on real and fictitious sources defined by boundary conditions (Fig. 1). The magnets are represented by coils (Amperian approach) and the total magnetic field can be analytically derived. An elegant demonstration is given by Di Gerlando A. & Ricca C. [5]. To represent the motor's pole pairs, several magnets are modeled, and the superposition theorem is applied. The magnetic field produced by the n_{th} magnet is given in (1).

$$B_n(\mathbf{z}) = \frac{\mu_0 H_c}{2\pi} \left[\ln \left(\frac{\sinh \left(\frac{\pi(\bar{\mathbf{z}} - \bar{\mathbf{z}}_n^+)}{2g} \right)}{\sinh \left(\frac{\pi(\bar{\mathbf{z}} - \mathbf{z}_n^+)}{2g} \right)} \right) - \ln \left(\frac{\sinh \left(\frac{\pi(\bar{\mathbf{z}} - \bar{\mathbf{z}}_n^-)}{2g} \right)}{\sinh \left(\frac{\pi(\bar{\mathbf{z}} - \mathbf{z}_n^-)}{2g} \right)} \right) \right] \quad (1)$$

With $\mathbf{z} = x + jy$ a complex number, $\mathbf{z}_n = x_n + jh$ and $\vec{B}_n(\mathbf{z}) = \text{Re}(\vec{B}_n(\mathbf{z})) \cdot \vec{e}_x + \text{Im}(\vec{B}_n(\mathbf{z})) \cdot \vec{e}_y$. Notations are in Figure 2.

B. Modelling in the (θ, z) and (r, z) planes

The slot-less AFPM motor is modelled in the (θ, z) plane by a constant radius r section as in Figure 2. Periodicity conditions are applied to the boundary of a pair pole p . These periodicity conditions can be emulated by other magnets wisely placed. The magnetic field produced by the magnet column n (Fig. 2) is given by (1). As all the workplaces considered are linear, the total magnetic field is obtained by superposition (2). The main advantage of this formulation is to be applicable to any types of AFPM motor topology, as 1 Rotor 1 Stator (1R1S), 1 Rotor 2 Stators (1R2S), and 2 Rotors 1 Stator (2R1S) (Fig. 2).

For the modelling in the (r, z) plane, the (r, z) area is taken at a constant angle allowing the plane to pass through a magnet. The magnetic field in this plane is directly derived from equation (1), but with $n = 1$ and (x^-, x^+) respectively being the internal R_{int} and external R_{ext} radii of the magnets.

$$B_{tot}(\mathbf{z}) = \sum_{n \in \mathbb{Z}} (-1)^n B_n(\mathbf{z}) \quad (2)$$

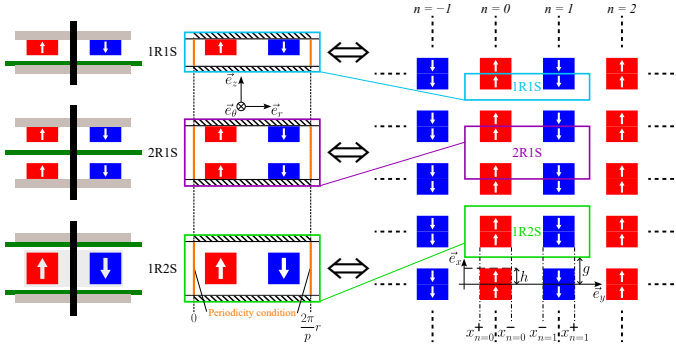


Fig. 2. Mirroring technique modelling AFPM motor topologies in (θ, z) plane (slot-less with ferromagnetic core (1R1S & 1R2S) and core-less stator (2R1S)).

C. Double 2D Model for 3D modelling

A 3D modelling of the magnet field can be achieved by combining both (θ, z) and (r, z) 2D equations. The values of the magnetic field calculated in one of the two planes are normalized depending on the magnet's form factor. For example, if the magnet is longer (along r) than wider (along θ), the field in the (r, z) plane is then normalized at the mean radius R_m (3). With B^{RZ} the magnetic field in the (r, z) plane and $B^{\theta Z}$ that in (θ, z) .

$$B_z(r, \theta, z) = \frac{\text{Im}(B^{RZ}(r + jz)) \text{Im}(B^{\theta Z}(\theta r + jz))}{\delta} \quad (3)$$

$$\text{with } \delta = \begin{cases} \text{Im}(B^{RZ}(R_m + jz)) & \text{if magnet longer than wider} \\ \text{Im}(B^{\theta Z}(\frac{\pi}{2p} R_m + jz)) & \text{otherwise} \end{cases}$$

III. VALIDATION BY 3D FEA

The numerical simulation consists of a pie-shaped air box enclosing the magnets. Periodicity conditions are applied to the planes normal to θ . A normal field condition is applied to the planes normal to z and the magnetic field is set to zero on the plane normal to r (Fig. 3).

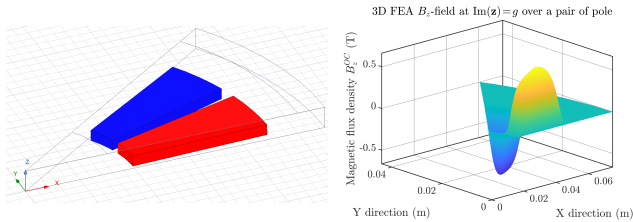


Fig. 3. 3D FEA modelling of a pole pairs and its B_z -field at $\text{Im}(\mathbf{z})=g$.

Two motors (respectively Mot_1 and Mot_2) are simulated on ANSYS Maxwell 3D, the one designed by Tokgoz et al. [2] and the Infinitum motor [1]. Figure 4 defines the lines where the magnetic field is plotted in Figure 5 for both motors.

The mean relative error between the magnetic field calculated by the model and that calculated by ANSYS Maxwell 3D at $\text{Im}(\mathbf{z}) = g$ is 4.84% for Mot_1 and 3.36% for Mot_2 . The FEA 3D software took 1min 36s (Mot_1) and 3min 58s (Mot_2) of CPU time for 147388 and 283952 mesh elements respectively. The proposed model took 0.17s and 0.93s of CPU time respectively. Gain ratio: 565 and 256 respectively.

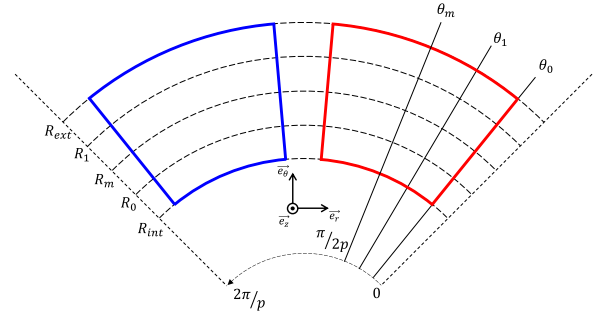


Fig. 4. Line where magnetic field is plotted on Fig. 5.

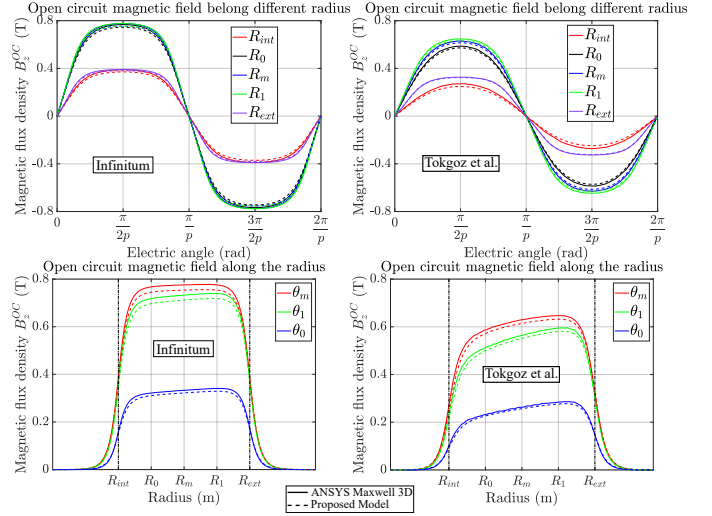


Fig. 5. 3D FEA vs. proposed model at the stator bore (height at $\text{Im}(\mathbf{z})=g$).

IV. CONCLUSION

For pre-sizing purpose of slot-less AFPM motors, an analytical model is proposed for calculating the open circuit magnetic field, in the case of tile-shaped magnets. This model provides a high degree of accuracy, speed and versatility. The errors are mainly related to the relative permeability of the magnets, which was assumed to be unitary. In order to highlight the relevance and the limitations of the proposed approach, the final paper will include a fair comparative study based on thirty motors from literature, extension to non-tile-shaped magnets and flux calculation for validation purpose.

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