

Nonlinear Hybrid Reluctance Network Applied to the Analysis of a Permanent Magnet Machine

João Vitor Gerevini Kasper^{1,2}, Christian Chillet¹, Thiago de Paula Machado Bazzo³, Laurent Gerbaud¹ *Member, IEEE* and Patrick Kuo-Peng²

¹ Univ. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, 38000 Grenoble, France

² GRUCAD, Universidade Federal de Santa Catarina, Florianópolis 88040-970, Brazil

³ PPGSE, Universidade Tecnológica Federal do Paraná (UTFPR), Curitiba 80230-901, Brazil

The paper presents a new fast hybrid reluctance network for the analysis of surface-mounted permanent magnet machines under load during the preliminary design step using optimization methods. The proposed hybrid reluctance network model takes into account the effects of magnetic saturation through equivalent current densities, expressed by Fourier series. It combines analytical methods and reluctance network to accurately predict the magnetic flux densities, the linked flux, the voltage under load condition and the torque waveform. The proposed hybrid reluctance network represents the field generated by the stator windings and the stator saturation effects taking into account the permanent magnet permeability. The results are validated against the finite element method, showing strong agreement with the numerical solution and more accurate results than those obtained with the methodologies available in the literature.

Index Terms—Analytical Model, Magnetic flux density, Reluctance Network, Saturation effect, Permanent magnet machines.

I. INTRODUCTION

SURFACE-MOUNTED PERMANENT MAGNET MACHINES (SMPMM) are applied in various engineering fields due to their torque density and efficiency. The permanent magnet (PM) mounted on the surface of the machine are influenced by the magnetic field produced by the stator windings. It is essential to know the state of the permanent magnets during the preliminary design phase to ensure their integrity and performances. Currently, the hybridization of analytical models (AM) and reluctance network (RN) has become a trend among electrical machine designers. AM provide accurate solutions for the magnetic flux densities calculated in the machine airgap, while reluctance networks deal with saturation effects. The coupling between the analytical models and the reluctance network is performed using equivalent current densities, which represent the saturation effects in the analytical solution of the airgap.

In [1], a SMPMM was analyzed by combining a conformal mapping and a RN. The Schwarz-Christoffel mapping transforms the slotted region with equivalent current sheets representing the magnets into a domain without slots. The field distribution, resulting from the winding current and the magnet equivalent currents placed at the newly mapped positions, is then calculated using Hague's solution. In [2], the subdomain method was combined with a reluctance network RN to analyze the field distribution the SMPMM. The subdomain method is a magnetic field calculation technique based on the separation of variables. The magnetic potential is obtained by solving a system of equations derived from Maxwell equations. However, the Schwarz-Christoffel transformation [1] and an equation system [2] must be solved for each rotor position, making its application challenging in an optimization process.

In contrast to the previous studies, paper [3] uses an analytical solution to calculate the field produced by the magnets [4] and represents the slot effects using a simplified conformal transformation: the complex permeance method (CPM) (see $\tilde{\lambda}_a(r, \theta)$ and $\tilde{\lambda}_b(r, \theta)$ in section II) [5]. The field

generated by the stator windings and the stator saturation effects are represented using an equivalent current expressed by a Fourier series. This model offers a good compromise between computational time and accuracy, making it an excellent model for the preliminary design of SMPMM.

However, the model does not take into account the PM permeability in calculating the field produced by the stator currents [3]. This underestimates the magnetic field generated by the stator windings, potentially leading to magnet demagnetization. In this way, here, a new formulation is proposed to represent the stator windings and the stator saturation effects by taking into account the PM permeability. The formulation was coupled with a hybrid reluctance network (HRN) to analyze the flux density in the PM of a SMPMM under load.

II. PROPOSED HYBRID RELUCTANCE NETWORK

Figure 1 presents the architecture of the proposed HRN. The upper section presents the models derived from the literature, while the lower section presents the models proposed in this paper. The complete information flow between the models will be provided in the full paper.

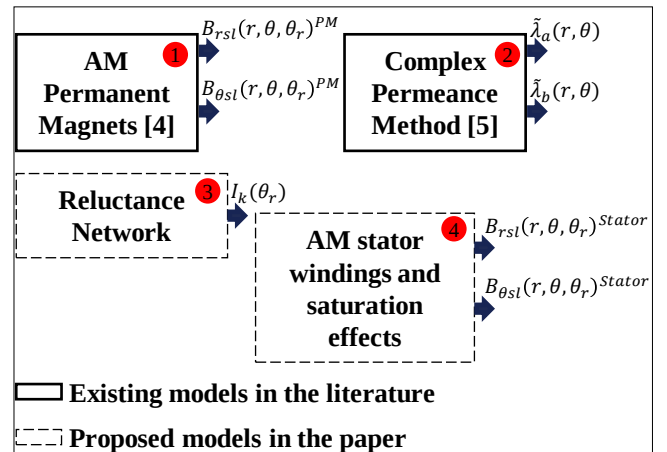


Fig. 1. Architecture of the proposed HRN.

The flux density is defined by $B_{jk}(r, \theta, \theta_r)^i$, where i represents the domain, j represents the radial or tangential component and k defines a slottless (sl) or slotted (s) domain. The AM in block 1 is defined in [4]. It allows to compute the magnetic flux densities produced by the PM $B_{rsl}(r, \theta, \theta_r)^{PM}$ and the $B_{\theta sl}(r, \theta, \theta_r)^{PM}$. The AM in block 2 is defined in [5]. By considering the slot effects, it allows to compute the real ($\tilde{\lambda}_a(r, \theta)$) and imaginary ($\tilde{\lambda}_b(r, \theta)$) components of the complex permeance.

Block 3 contains the reluctance network of the stator considering saturation effects, the airgap and rotor in short-circuit. It will be presented in the full paper. Block 4 contains the analytical model to obtain the components $B_{rsl}(r, \theta, \theta_r)^{stator}$ and $B_{\theta sl}(r, \theta, \theta_r)^{stator}$ of the magnetic flux density produced by the stator windings and saturation effects, represented by the equivalent current I_k . Figure 2 shows the considered study domain.

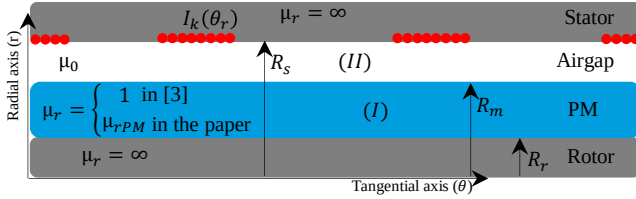


Fig. 2. Study Domain Considered for the Model of Flux Density Produced by the Equivalent Current (I_k).

The solution of Laplace's equation for regions (I) and (II) provides the magnetic flux density produced by the equivalent current (I_k), without considering the slot effects. This specific model considers the domain presented in Fig 2, where μ_{rPM} is the real PM permeability contrary of paper [3] where $\mu_{rPM} = 1$. This is one of the contributions of the work. The completed formulation will be developed in the full paper.

Thus, $B_{rs}(r, \theta, \theta_r)^{stator}$ and $B_{\theta s}(r, \theta, \theta_r)^{stator}$ are obtained by accounting the PM permeability. This consideration introduces two boundary conditions to the problem solved in [3], defined by the equality of the radial flux density and tangential magnetic field between regions I and II when the radius equals the magnet radius (R_m). Finally, the magnetic flux densities in the machine airgap ($B_{rs}(r, \theta, \theta_r)$) and ($B_{\theta s}(r, \theta, \theta_r)$), considering the slot effects, are determined by equations (1) and (2).

$$B_{rs}(r, \theta, \theta_r) = B_{rsl}(r, \theta, \theta_r) \cdot \tilde{\lambda}_a(r, \theta) + B_{\theta sl}(r, \theta, \theta_r) \cdot \tilde{\lambda}_b(r, \theta) \quad (1)$$

$$B_{\theta s}(r, \theta, \theta_r) = B_{\theta sl}(r, \theta, \theta_r) \cdot \tilde{\lambda}_a(r, \theta) - B_{rsl}(r, \theta, \theta_r) \cdot \tilde{\lambda}_b(r, \theta) \quad (2)$$

using equations (3) and (4)

$$B_{rsl}(r, \theta, \theta_r) = B_{rsl}(r, \theta, \theta_r)^{PM} + B_{rsl}(r, \theta, \theta_r)^{stator} \quad (3)$$

$$B_{\theta sl}(r, \theta, \theta_r) = B_{\theta sl}(r, \theta, \theta_r)^{PM} + B_{\theta sl}(r, \theta, \theta_r)^{stator} \quad (4)$$

III. RESULTS

Figures 3 and 4 present the radial and tangential flux density of a SMPMM in saturated operating point with $\mu_{rPM} = 1.15$, for the model proposed in [3], FEM [6] and the proposed model. The proposed model is closer to FEM than [3]. This comparison reveals that [3] underestimates the magnetic flux density in the permanent magnet regions which may lead to the demagnetization of the PM at some positions if the machine design is based in [3]. Table I shows the root mean square for the flux densities comparing [3] and the proposed model.

TABLE I
THE ROOT MEAN SQUARE FOR THE MAGNETIC FLUX DENSITY

Method	$B_{rs}(T)$	$B_{\theta s}(T)$
[3]	0,004	0,0838
Proposed	0,0008	0,0458

IV. CONCLUSION

The HRN method effectively represents the magnetic flux distributions within the permanent magnets. The solution presented in this work offers an alternative approach to determine the magnetic flux density in PM region when the PM permeability cannot be neglected.

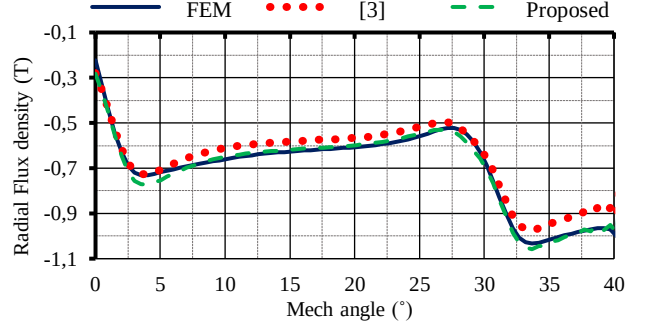


Fig. 3. Validation of the Radial Component at $r = 0.99 \cdot R_m$.

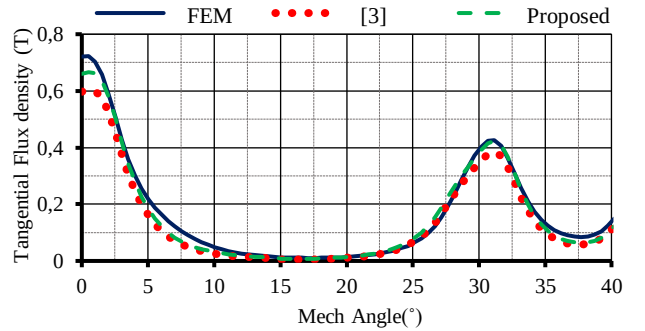


Fig. 4. Validation of the Tangential Component at $r = 0.99 \cdot R_m$.

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