

A Simplified Approach for Modelling PMSG Using a Multi-Static Reluctance Network

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This paper presents a multi-static reluctance network (MRN) to carry out the modelling electromagnetic behavior of a surface Permanent Magnet Synchronous Generator (PMSG). The main objective of this work is to propose a model offering a good compromise between accuracy and simulation time. The rotational motion modelling is achieved by considering the displacement of the magnetomotive sources representing the permanent magnets of the machine. In this way, the reluctances of the air gap do not change during the rotational motion and eliminates the need of node reconnection techniques. The results obtained with the proposed methodology are compared with the Finite Element Method (FEM), and the results have strong agreement.

Index Terms— Permanent Magnet Synchronous Generator (PMSG), Multi-static Reluctance Network, induced voltage, Magnetic model nonlinear

I. INTRODUCTION

PERMANENT MAGNET SYNCHRONOUS GENERATORS (PMSG) are machines known for their high efficiency and torque density. Due to their widespread application in energy conversion systems based on renewable sources of energy, for instance in wind turbines, several academic works have proposed mathematical models capable of providing the magnetic flux density along the machine, to support the electromagnetic design stage.

Analytical approaches based on the solutions of Maxwell's equations can determine flux distributions and calculate torque ripple [1] – [2]. Nevertheless, these methodologies often neglect the nonlinear magnetic permeability of ferromagnetic materials, which limits their application to designs where the machine operates without saturation.

The coupling of analytical models with reluctance networks (RN) has emerged as a promising alternative. Whereas the analytical methods are able to calculate the flux distribution in the machine air gap, RN could take into account the nonlinearity of the soft ferromagnetic material in the machine yoke and teeth. The exact Schwarz-Christoffel transformation and subdomain analytical models have already been coupled with RN, yielding excellent results [3] – [4]. However, the hybridization of these models requires a coupling between the methodologies, which is not straightforward to implement. Furthermore, although these methods reduce computational time compared to finite element analysis, they remain time consuming and computationally expensive.

Methodologies utilizing multi-static reluctance networks have also been applied in the literature and have shown promising results validated by numerical simulations. When the machine's air gap is modelled using RN, the rotational motion has typically been represented in two possible ways: by adjusting the reluctance values that link the stator to the rotor [5], or by reconnecting the reluctance nodes of the air gap with the reluctance nodes of the rotor [6].

This work proposes a new methodology for a multi-static reluctance network that does not use element reconnection nor adjustments of the reluctances in the air gap. Motion modelling is implemented by varying the magnetomotive source values from the permanent magnets embedded in the rotor surface, which is the main contribution of this work.

II. METHODOLOGY AND RESULTS

The model proposed in this work is an extension of the static RN presented in [7], considering motion in a simple way and without using couplings or reconnections. Figure 1 presents one pole of the generator cross-section, superimposed with the corresponding RN model. The machine was designed following the methodology presented in [8], the proposed model was applied to a generator with an inner rotor with rare-earth permanent magnets mounted on its surface, but the methodology is flexible and can be adapted for different permanent magnet synchronous machines.

The simulation uses an algorithm that models the position of the permanent magnets with a high level of discretization (216 saturable iron reluctances, 144 air reluctances and 50 magnetomotive forces). The intensity of the MMF in each source depends on the remanent flux density (B_r) assigned to the respective element. The proposed method adjusts the B_r values proportionally to the amount of magnetic flux generated in each region. This approach ensures an accurate representation of the flux distribution within the machine and provides a robust framework for analyzing the interaction between the magnets and the surrounding magnetic circuit. When no permanent magnet is present, the magnetic flux density (B_r) is set to zero. The reluctance that represents this region remains the same and is computed with the assumption that the recoil permeability is equal to 1. When a reluctance is fully covered by a permanent magnet, its value is set to 1 (or -1 if the magnet polarization is reversed). Regions partially occupied by permanent magnets are calculated based on the

ratio of air to permanent magnet coverage, more details will be presented in the full paper.

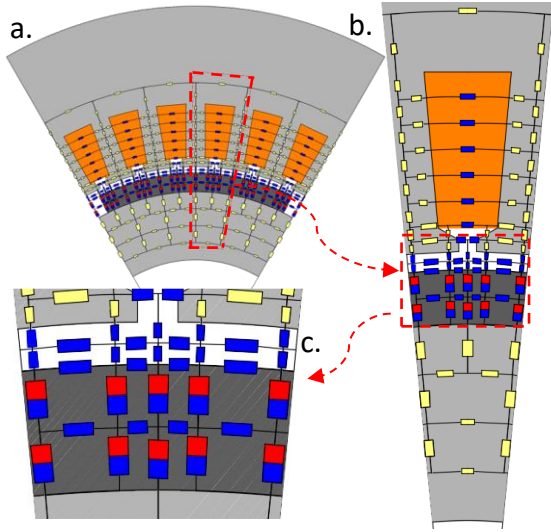


Fig. 1. Reluctance network overlaid on the structure of the PMSG. a. Cross-section of one pole. b. One tooth-pitch reluctance network. c. Air gap and permanent magnet reluctance network. The color of each element means yellow for non-linear iron, blue for air gaps, and blue/red for magnetomotive forces (magnets).

The reluctance network was developed using the CADES software tool [9]. Although the RN is static, it simulates the machine rotation and is used to predict the terminal voltage curve. The saturation curve of the iron core was implemented in the software tool, and it was considered during the analysis. The RN performance was subsequently analyzed using a finite element analysis (FEA) tool [10]. Results from the FEA model were compared with those obtained from the RN of the proposed methodology to evaluate its reliability. The induced electromotive force is obtained from the flux linkage through Faraday's law by discrete derivative.

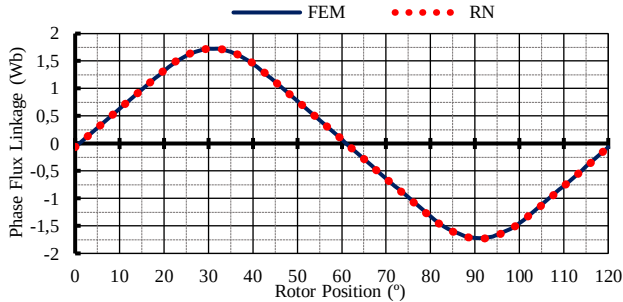


Fig. 2. Linked flux over one phase winding: comparison between RN and FEM methods.

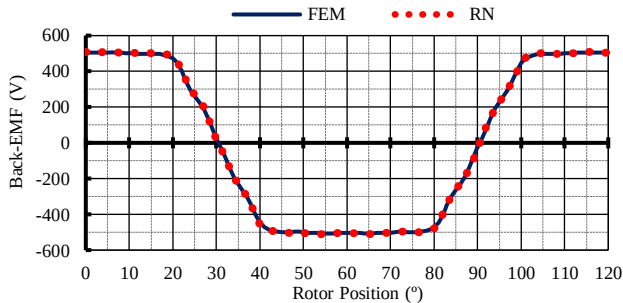


Fig. 3. No-load phase voltage: comparison between RN and FEM methods.

Figure 2 presents the obtained flux linkage whereas Fig 3 presents the no-load induced electromotive force, as determined by the RN and FEA approaches. Results obtained exhibit a very good agreement, with a no-load RMS phase voltage difference of less than 1%. The RMS values were 435.5 V (FEM) and 439.5 V (RN). The analysis was processed using a computer with an Intel core i7-10750H 32 Gb RAM and the computational time with the FEM model was about 407 seconds and with the RN model was less than 7 seconds. The mesh in FEM contains 30000 elements, while the RN contains 410 elements. It represents a considerable timesaving in processing, mainly when an iterative process of optimization is running.

III. CONCLUSION

The multi-static reluctance network proposed in this work satisfactorily models the magnetic flux linked by the coil and accurately estimates the induced voltage of the machine. The results are highly satisfactory, with the simulated and reference curves showing strong agreement, and the RMS no-load voltage differing by less than 1%. Future works will further elaborate on the development of the proposed methodology and present results for the generator under load condition on these findings, including terminal voltage and torque curves, harmonic distortion analysis, and machine reactance evaluation.

REFERENCES

- [1] D. Zarko, D. Ban and T. Lipo, "Analytical Solution for Cogging Torque in Surface Permanent-Magnet Motors Using Conformal Mapping," *IEEE Transactions On Magnetics*, pp. 52 - 65, 2008.
- [2] L. Wu, Z. Q. Zhu, D. Staton, M. Popescu and D. Hawkins, "Subdomain Model for Predicting Armature Reaction Field of Surface-Mounted Permanent-Magnet Machines Accounting for Tooth-Tips," *IEEE Transactions On Magnetics*, pp. 812 - 822, 2011.
- [3] A. Hanic, D. Zarko, D. Kuhinek and Z. Hanic, "On-Load Analysis of Saturated Surface Permanent Magnet Machines Using Conformal Mapping and Magnetic Equivalent Circuits," *IEEE Transactions On Energy Conversion*, pp. 915 - 924, 2018.
- [4] L. Wu, H. Yin, D. Wang and Y. Fang, "On-Load Field Prediction in SPM Machines by a Subdomain and Magnetic Circuit Hybrid Model," *IEEE Transactions On Industrial Electronics*, pp. 7190 - 7201, 2020.
- [5] H. Xiaoyan, M. Zhu, C. Wei, Z. Jian and F. Youtong, "Dynamic Reluctance Mesh Modeling and Losses Evaluation of Permanent Magnet Traction Motor," *IEEE Transactions On Magnetics*, 2017.
- [6] G. Liu, S. Jiang, W. Zhao and Q. Chen, "Modular Reluctance Network Simulation of a Linear Permanent-Magnet Vernier Machine Using New Mesh Generation Methods," *IEEE Transactions On Industrial Electronics*, pp. 5323 - 5332, 2017.
- [7] J. Kasper, P. Kuo-Peng, T. Bazzo and G. Menezes, "Methodology to Generate a Reluctance Network Applied to Permanent Magnet Synchronous Generators," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, 2022.
- [8] G. G. d. Menezes, N. A. R. Maciejewski, E. S. d. Carvalho and T. d. P. M. Bazzo, "A Thorough Procedure to Design Surface-Mounted Permanent Magnet Synchronous Generators," *Machines*, 2024.
- [9] B. d. Peloux, L. Gerbaud, F. Wurtz and V. Leconte, "Automatic generation of sizing static models based on reluctance networks for the optimization of electromagnetic devices," *IEEE Transactions On Magnetics*, pp. 715 - 718, 2006.
- [10] "FLUX2D," [Online]. Available: <https://altairengineering.fr/altair-one/>.