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Experimental validation of an enhanced permeance network model for embedded magnet synchronous machines

D.J. Gómez [a,*], A.L. Rodríguez [a], I. Villar [a], A. López-de-Heredia [a], I. Etxeberria-Otadui [a], Z.Q. Zhu [b]

[a] Control Engineering and Power Electronics, IK4-IKERLAN P°, J.M. Arizmendiarrieta 2, 20500 Arrasate-Mondragón, Spain
[b] Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

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ABSTRACT

This paper presents an enhanced permeance network model (PNM) for embedded permanent magnet synchronous machines. PNMs are characterized by very fast and accurate results. This approach overcomes some weaknesses associated to analytical models, such as the difficulty of accurately predicting the embedded magnet machines behavior or taking into account the nonlinear behavior of the magnetic materials. The proposed model is a parameterized, rotor motion accounting, nonlinear PNM capable of computing the radial and the tangential airgap fluxes, the back electromotive force and the electromagnetic torque. A fully sensorized, 75 kW PMSM has been designed and manufactured in order to perform an experimental validation. The validation has also been supported by finite-element analysis (FEA) in FLUX2D®. The experimental results confirmed the accuracy of the proposed model and the possibility of avoiding the time-consuming FEA in PMSM designs.

1. Introduction

The higher availability and cost reduction of high energy product magnets, since their development in the 1980s, has increased the use of permanent magnet synchronous machines (PMSM). A great research effort has been made during the last two decades in both academy and industry to fully exploit the advantages of PMSMs.

Thanks to the high energy product Neodymium Iron Boron (NdFeB) magnets, higher power density machines are developed [1], with faster dynamics and higher torque to inertia ratios [2]. Moreover, due to the elimination of the rotor losses and the brushes the efficiency is increased and the maintenance cost is reduced. PMSMs are widely employed in hybrid and electric vehicles, elevation applications, renewable energy generation and aircraft industry.

Three classical methods have been used for the analytical design of PMSMs [3]. The first method is based on Ampere's law and it is commonly employed for a rough estimation of the machine's performance. A very simple magnetic equivalent circuit of the electrical machine is constructed, based on one airgap reluctance element, one magnet flux source per magnet pole, reluctances of both rotor and stator back iron and, sometimes, a reluctance for taking into account the magnet to rotor leakage flux [3–5]. In this simple equivalent circuit, due to the small number of elements, there is a lack of accuracy on the airgap flux density waveform and therefore on the machine's performance estimation. Saturation aspects are commonly neglected in these simple equivalent circuits. The second method, commonly known as magnetic potential method, is based on Fourier analysis and yields very good precision for Surface-mounted PMSMs (SPMSM) under the supposition of infinite permeability in the iron core. Finally, the permeance network method is based on the same theory as the magnetic equivalent circuit method. However, the physical domain under study is discretized in many basic magnetic elements which are represented by nodes connected through magnetic reluctances, magnetomotive force (MMF) sources and magnetic flux sources. The equivalent network is similar to an electrical network composed by resistances, voltage sources and current sources, and it is solved in the same way. Compared with Ampere's law, this method comprises much more elements, usually requiring a matrix analysis. Hence, local effects are considered along with the spatial distribution of the normal and tangential flux components in the airgap. Moreover, the nonlinearity of the materials can be taken into account by means of an iterative process in which the permeability of the soft magnetic materials is corrected until the convergence is reached.

* Corresponding author. Tel.: +34 943712400; fax: +34 943796944.
E-mail address: djgomez@ikerlan.es (D.J. Gómez).
URL: http://www.ikerlan.es (D.J. Gómez).

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Nomenclature

A	flux tube area
B	magnetic flux density
c_d	damping factor
EMF	back electromotive force
F_{mi}	magnetic potential of node i
H	magnetic field intensity
H_c	magnet coercive force
h_m	magnet height
I	armature current
I_d, I_q	d- and q-axis currents
N	phase winding turns
M	Park's transformation matrix
p	number of pole pairs
$\mathcal{P}$	permeance of a flux tube
Q	number of stator slots
$\mathfrak{R}$	reluctance of a flux tube
μ	permeability of the material
$\emptyset_s$	equivalent magnetic flux source
$\emptyset$	magnetic flux through a branch
$[P]$	permeance matrix
$[F_m]$	magnetic potential matrix
$[\emptyset_s]$	flux source matrix
Ψ_d, Ψ_q	d- and q-axis flux linkages
θ	rotor angular displacement

The use of permeance network models is widespread in electrical machine design. A generalized, saturation accounting permeance network model is proposed in [6] for PMSM design with any pole-slot combination. In [7], a nonlinear, adaptative lumped parametric circuit model is developed for predicting the main characteristics of a flux switching permanent magnet machine and an experimental validation is presented. In [8] the permeance network is employed for modeling a PMSM under inter-turn fault. Inductances, fluxes and EMFs of a faulty machine accounting for saturation and leakage inductances are estimated with good accuracy. In [9] very promising results are obtained for modeling a fractional-slot concentrated-winding interior permanent magnet machine by means of lumped parameter magnetic circuit model with the purpose to be included in optimization processes. A sophisticated, saturation accounting reluctance network is used in [10] to model wound rotor synchronous machines with special emphasis in the analysis of the convergence behavior of the model. In [11] a flexible magnetic equivalent circuit for SPMSMs is developed with higher and also controllable mesh resolution in the airgap proximity, which detects the change in the direction of the airgap flux and increases the accuracy.

As mentioned before, PNMs can be employed for both SPMSMs and Interior-mounted PMSMs (IPMSM). Sometimes the SPMSM is not a feasible solution, due to manufacturing difficulties or the need for a robust construction, and the magnets have to be embedded in the rotor, leading to a rotor topology like the one shown in Fig. 1. Nevertheless, using this rotor topology the d- and q-axis inductances are not identical and the machine becomes an IPMSM. Furthermore, the iron bridges at the permanent magnet sides carry a large amount of magnetic flux called leakage flux.

In the aforementioned situation, even magnetic potential methods have an important lack of accuracy because they are not able to calculate neither the leakage flux nor the difference between d- and q-axis inductances. In order to avoid the high computational and temporal cost of FEA, permeance network method is suitable for modeling the IPMSM. Accounting for the saturation in the iron core, especially in the iron at the sides of the magnet, allows the airgap magnetic flux density to be obtained with remarkable accuracy. The remainder performance characteristics of the machine can be easily derived from this result.

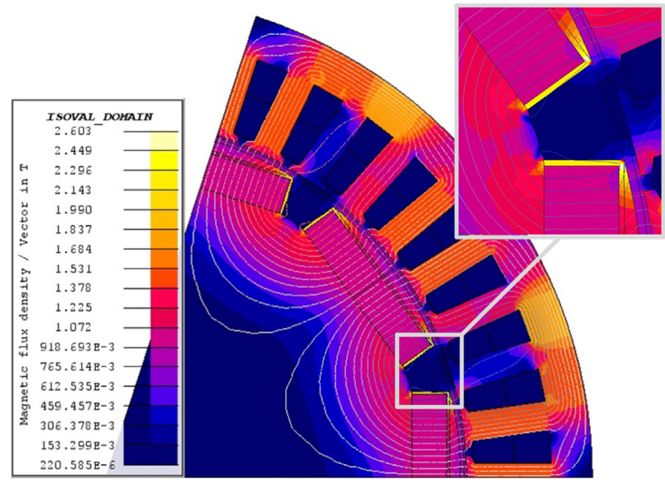

Fig. 1. Embedded magnet synchronous machine.

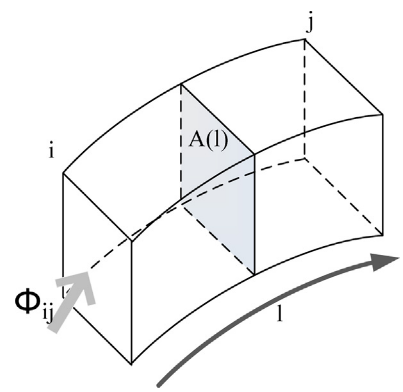

Fig. 2. Unidirectional flux tube.

In this paper a parameterized, rotor motion accounting, nonlinear PNM is developed for embedded magnet synchronous machines. The model is based on the one presented in [11] for surface mounted permanent magnet motors and enhanced by including important modifications in both the rotor and the stator, in order to be adapted to embedded-magnets synchronous machines. This paper extends the previous work presented in [12] by including more physical effects and an experimental validation of the proposed machine.

2. Electromagnetic concepts for reluctance circuit model

2.1. Magnetic flux tube reluctance and permeance

The magnetic reluctance of a flux tube like the one shown in Fig. 2 is the resistance that opposes to the magnetic flux to travel through that flux tube. The reluctance, $\mathfrak{R}$, depends on the permeability of the material along with the geometrical dimensions of the flux tube that forms the path for the magnetic flux [13]:

$$\mathfrak{R} = \int_i^j \frac{1}{\mu(l) \cdot A(l)} \cdot dl \tag{1}$$

where $\mu(l)$ is the permeability of the material at the l position and $A(l)$ is the flux tube cross-sectional area at the l position.