Original design of Axial Flux PM Motor and modeling of the magnetic leakage using a magnetic equivalent circuit

Romain-Bernard MIGNOT[1], Frédéric DUBAS[1], Christophe ESPANET[1], Cécile CUCHET[2] and Didier CHAMAGNE[1]
[1] Department ENISYS, UMR 6174 CNRS, FEMTO-ST Institute, France-90010 Belfort
[2] UFC, France-25000 Besançon

E-mail: romain.mignot@gmail.com

***Abstract*- This paper deals with a part of the French project TRAX, whose aim is to develop a generation of direct drive electric motorization for "all electric" vehicles. The two objectives of this project are: i) to design an innovative axial flux permanent magnet motor (AFPMM) and industrially feasible in series, ii) to use an analytical model (AM) based on reluctances networks (i.e., a Magnetic Equivalent Circuit M.E.C.) in order to design an optimal electric motor. The magnetic leakage between the magnets is modelized and the analytical results are compared to those of 2D and 3D FEM models.**

***Keyword* – Axial Flux, Analytical Modeling, magnetic equivalent circuit, leakage flux, 2D and 3D FEM.**

I. INTRODUCTION

In this paper, we have chosen to use an AFPMM, since this type of machine has a high potential of specific torque. From an industrial point of view, the specifications requires to develop an electrical machine with using low cost materials for the stator and the rotor and with a reduced process time, while being innovative and patentable. This approach needs to choose a motorization physical structure that fits with the expectations of previous industrial constraints. Moreover, the motor sizing should also be short (reduced time of calculation), so that the use of an analytical model with an optimization procedure is preferred to an approach with only FEM simulations. Those latter should be used rather in a second step of the design as a virtual test bench.

II. CHOICE OF THE MOTORIZATION AND PRESENTATION OF AFPMM

To design AFPMM involves choosing the right architecture. In 2004, Aydin *and al.* [1] has identified several structures. Unfortunately, none of these structures can be used to design an axial flux motorization with respect to the following required items:

- a stator and a rotor with a minimized volume of iron;
- stator windings using pre-wired coil.

Hosseini *and al.* [2] and Jung *and al.* [3] have presented the same structure for rotor and stator, which can meet our specifications. The stator is composed of simple magnetic circuits, having a "U" shape, and the rotor is made of composite material using magnetic circular pieces. Our final choice is therefore focused on a physical structure based on some of the ideas developed in these two articles and improving the following points:

- the rotor material and thickness are carefully chosen to optimize the mechanical rigidity and stability;

Fig. 1 ½ stator yoke

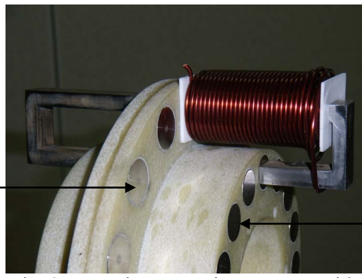


Fig. 2 Rotor in composite structure with magnetic bar and circular PMs

- the use of stator studs on one arm of the "U" which has the following advantages: **i)** the risk of short-circuits between two consecutive coils is minimized, and **ii)** the flux leakages between internal and external magnets of the rotor are minimized.

The stator and the rotor of the considered EFPMM are respectively shown in Fig. 1 and 2.

III. ANALYTICAL MODELING OF AFPMM

A first static MEC (the magnetic bars faced to the magnets) has been developed in 2-D [4] by the authors. It enables to estimate the parameters of a single-phase equivalent electric circuit and to calculate various parameters such as the electromagnetic torque, the magnetic losses and the PM magnetic field (to evaluate the demagnetization risk). In this first MEC, the effects of magnetic saturation, magnetic leakages (between PMs and between coils), and the PM losses were neglected. The analytical results of this first MEC were compared to those obtain with experimental tests. The practical results have shown a significant difference between theoretical and experimental results, in particular regarding the back EMF and the self-inductance.

978-1-4673-0954-7/12/$31.00 ©2012 IEEE

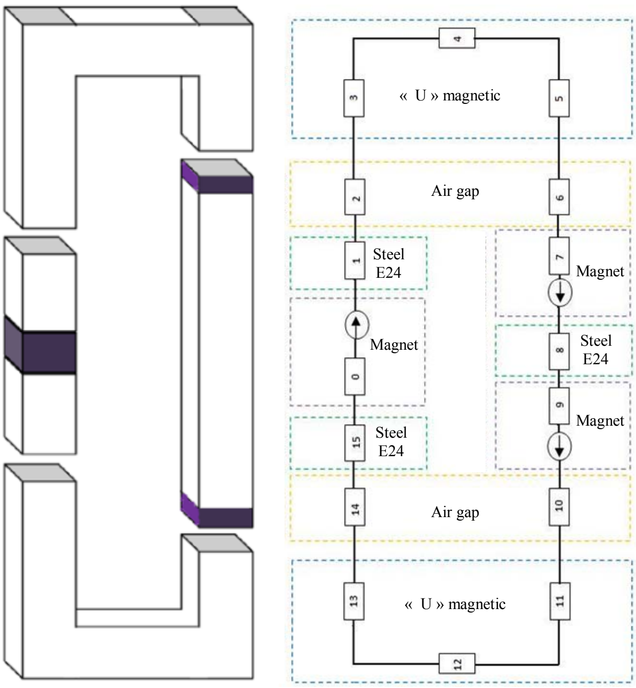


Fig. 3 Modeling of one phase magnetic circuit

In order to improve the first model [4], the flux between the magnets set on the same rotor radius and the saturation of the materials, are now taken into account. We always assume that magnetic characteristics of ferromagnetic materials do not depend on temperature.

A. Main magnetic equivalent circuit

1. First modeling

The main MEC (Fig. 3) consists of two ferromagnetic circuits using M330-35 [6] and E24 laminations [7] and permanent magnets UHT 38UH [8]. The motor geometry is simplified, assuming a rectangular shape for the rotor magnetic circuit instead of a circular one; it makes the main flux calculation easier.

2. Refinement of the modeling

Once the main flux of the magnetic circuit is known (Fig. 3), the circular shape of the rotor magnetic circuit can be modelized. The refined model consists in considering a secondary flux in the upper and lower parts (blue in Fig. 4b) of the rectangular magnetic circuit defined in the previous section (Fig. 4a). The very thin parts on the right and left sides (red in Fig. 4b) have not been taken into account.

Then, the secondary flux circulates in a rotor magnetic circuit and in the air gap. The connection of the two magnetic fluxes (mail and secondary) occurs in the "U" ferromagnetic stator as shown in Fig. 5. We assume that, in the air gap and in the stator, the SF flows through a surface equal to the rotor one (blue). Then, Fig. 5 shows the principle of the junction between the two fluxes and Fig. 6 focuses on junction of the fluxes associated to their respective reluctance.

Fig. 7 shows the refined model of the MEC taking into account the circular shape of the cores and inner and outer permanent magnets of the rotor.

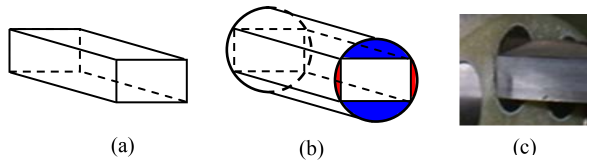


Fig. 4 Representation of the PM geometry in the rotor
(a) rectangular, 1st model (b) circular, real geometry
(c) picture showing the circular PM at the rotor and the rectangular « U » magnetic circuit at the stator

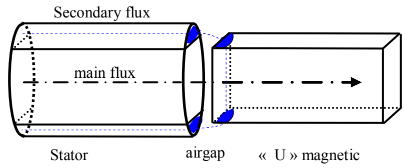


Fig. 5 Representation of the flux paths in the stator, the rotor and the air-gap according to their respective geometry

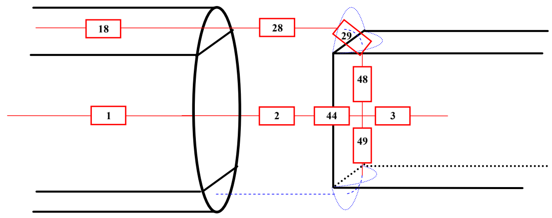


Fig. 6 Focus on the junction of particular fluxes flowing through the stator and on the corresponding reluctances

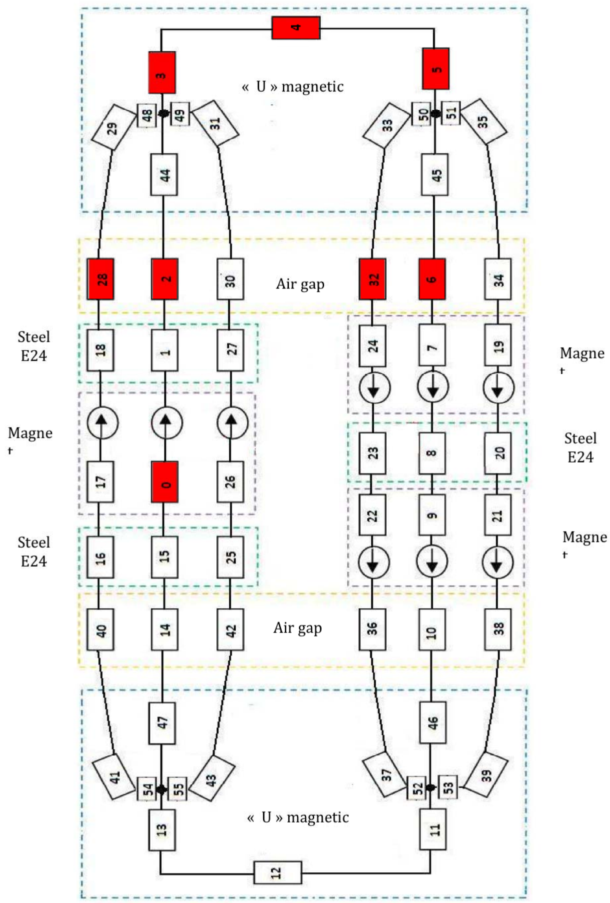


Fig. 7 MEC of the motor taking into account the circular geometry of the rotor cores and PMs

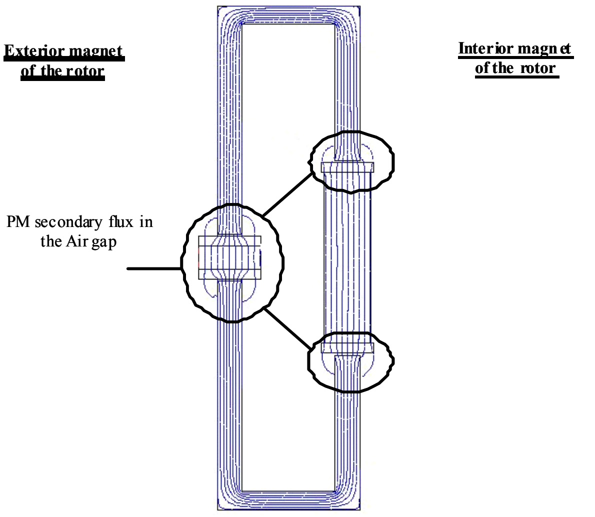


Fig. 8 Flux leakages in the air gap and et around the PM.

Fig. 8 shows flux lines obtained with 2DFEM and highlights the secondary magnetic flux around the air-gap. The real junction of these fluxes is in accordance with the one defined in Fig. 6.

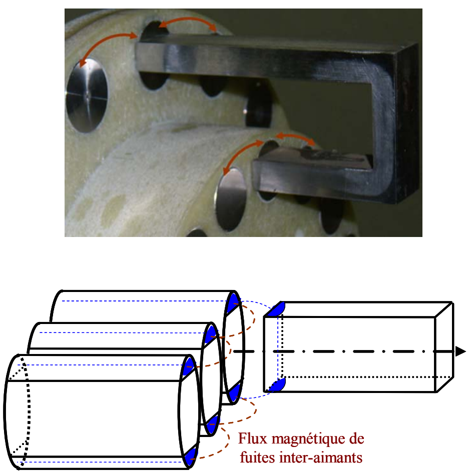
B. Magnetic leakages between PM

The rotor is made of two cylinders having two different radii and of PMs embedded in the two cylinders as shown in Fig. 9. Once again, due to the particular 3D geometry, leakages between two adjacent PMs embedded in the same cylinder at the same radius are possible. Fig. 9 shows those PM leakages represented in brown in this figure.

Each leakage flux comes from the secondary flux defined in IV-2. In the air gap, the leakage flux flows through the same surface as the one in blue in the rotor (see Fig. 6). Those leakages will lead to a reduction of the flux density in the stator, and, as a consequence, the back EMF magnitude. Thus it is necessary to limit those leakages.

Fig. 10 summarizes for the whole flux (main flux, secondary flux and leakages) for a fixed position of the rotor.

Four paths have been added to the model in Fig. 7. Each one corresponds to a rotor magnetic circuit placed on the two sides of the studied main magnetic circuit and enabling the leakages calculation.



(a)

(b)

Fig. 9 (a) Indication visuelle de l'emplacement des FMIA, (b) Représentation des FMIA et FS sortant des aimants du rotor

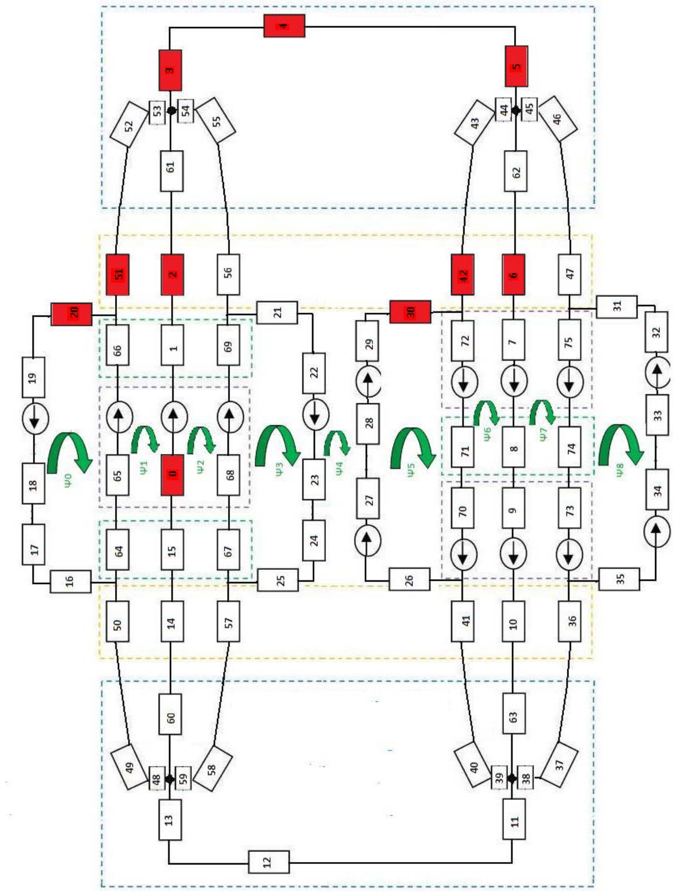


Fig. 10 Complete MEC taking into account the PM circular cross-section and leakages between PM

The reluctances in red in Fig. 7 and 10 correspond to the different places where the authors have proposed to had reluctance in order to improve the 3D modeling of the flux distribution. A comparison of the results obtained with the MEC with the ones obtained with a 3DFEM model (see Fig. 11) should give conclusions about the proposed refinements.

C. Calculation of the whole fluxes (complete model)

To calculate the different potential and magnetic flux in each branch of the circuit, the authors applied the two Kirchhoff's laws. For this, the original and efficient method proposed by [5] has been applied.

D. Consideration of the magnetic saturation

Reference [6] gives the non-linear *B–H* of the used laminations We can see that the relative permeability of the material is not constant. To take into account the influence of the non-linearities, the authors have used the *B–H* models proposed in [9] and [10]. The best results are obtained with the well known formulation of Marocco presented in [10]:

$$H(B)=\frac{B}{\mu_0}\bullet\left[\frac{b^{2\bullet k_{h1}}}{b^{2\bullet k_{h1}}+k_{h3}}\bullet\left(k_{h4}-k_{h1}\right)+k_{h2}\right] \quad [A/m] \quad (1)$$

where b represents the reduced value of the flux density B and k_{hi} represents the interpolation coefficients of the different functions. Theses coefficients are calculated according to the values given by the vendor. For instance, [11] shows how to approximate the real characteristics *B=f(H)*. This method is said global: the interpolated curve will minimize the distance between the real values y_i and the ones given by the function $f(x)$.

$$\varepsilon_{int} = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{y_i - f(x_i, k_{hi})}{y_i}\right] \qquad (2)$$

IV. Comparison between the M.E.C. and the F.E.M. in 3D

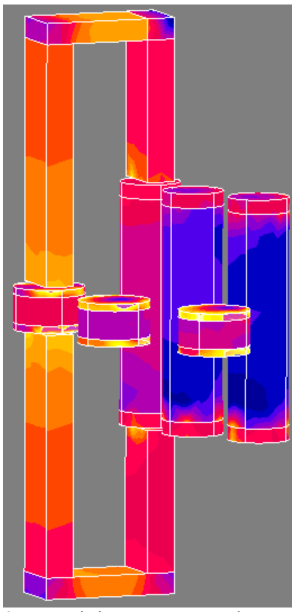


Fig. 11 F.E.M. in 3D permitting to compare the results with the M.E.C.

Fig. 11 presents the 3D FEM model that has been developed to validate the MEC. To limit the calculation time, only three rotor magnetic circuits and one stator magnetic circuit have been defined. Table 1 summarizes the results between the two models (the reluctance numbers are defined in Fig. 10). It shows globally a good agreement, except in reluctance 20, which corresponds to leakages around the air-gap. However, the prediction of the air-gap flux density is satisfying, so that the EMC can be used to model the magnetic behavior of the motor.

TABLE I
Comparison of the results between the two models

Reluctance reference	Flux density (T) 3D FEM	Flux density (T) MEC	Relative error (%)
0	0.885	0.921	3.9
2	0.885	0.921	3.9
3	1.414	1.474	4.07
4	1.886	1.965	4.02
5	1.414	1.474	4.07
6	1.09	1.32	17.4
20	0.223	0.119	46.6
30	0.385	0.311	19.2
42	0.412	0.511	19.4
51	0.315	0.423	25.5

V. Conclusion

This paper deals with the magnetic modeling of special axial flux permanent magnet synchronous machine, having interesting features for automotive application (in particular small HEV and EV).

In [4], the authors obtained first results of modeling with a very simple MEC, which gives results quite different from those obtained with experimental tests on a prototype. The main difference concerned the value of the air-gap flux density and cyclic inductance. It justifies the need to develop a refined model.

Thus, in this paper, the authors have focused on the improvement of the MEC through the determination of the main magnetic leakages. The results confirm that: i) the choice of the hypotheses regarding the magnetic flux distribution (main flux, secondary flux and leakages) was correct; ii) the fast resolution make this model a simple and efficient tool for the magnetic behavior analysis of the considered type of machine; iii) the use of real saturation curves is essential to obtain results closer to the experimental ones.

However, the 3D FEM simulations show that it still remains magnetic leakages between:

- magnetic circuits placed side by side;
- two branches of the same magnetic circuit;
- permanent magnets from the same circuit placed on two different radii.

The magnetic model should thus be more complex in order in particular to improve the mutual inductance determination.

References

[1] M. Aydin, S. Huang and T. A. Lipo "Axial Flux Permanent Magnet Disc machines; A Review" Speedam 2004.

[2] S. Hosseini, J. Shokrollahi Moghani, N. Farrokhzad Ershad, and B. Bech Jensen, "Design, Prototyping, and Analysis of a Novel Modular Permanent-Magnet Transverse Flux Disk Generator" IEEE transactions on magnetics, Vol. 47, N°4, April 2011.

[3] Y-B Jung, T Long, J Nelson, C Landon, "Unique Axial Flux Motor Design Delivers Superior Torque Density" EET-2008 European Ele-Drive, Conference International Advanced Mobility Forum Geneva, Switzerland, March 11 – 13, 2008;

[4] R. Mignot, F. Dubas, C. Espanet, D. Chamagne, "Design of axial flux PM motor for electric vehicle via a magnetic equivalent circuit" REVET-2012 Renewable Energies and Vehicular Technology, First International Conference on, IEEE Conference Publications, pp.212-217, March 26 – 28, 2012;

[5] M. Séguin, B. Tardif, J. Descheneau, "Physique XXI, Electricité et magnétisme", édition De Boeck 2010.

[6] http://www.arcelormittalinox.com

[7] http://www.steelstrip.co.uk

[8] http://www.bkmagnet.com

[9] Flux2D et Flux3D, "Manuel d'utilisation", Version 9.1, Cedrat S.A., 10 Chemin de Pré Carré, Zirst 38240 Meylan, France, www.cedrat.com

[10] A. Marrocco and F. Hecht, "A Finite Element Simulation of an Alternator Connected to an Non Linear External Circuit", IEEE Trans. on Magn., Vol 26, No 2, pp. 964-967, March 1990.

[11] C. Brezinski, "Basic Numerical Methods", Technical Ingineer, Treaty of Electrical Engineering.