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# 3D Hybrid Model of an Ideal but True Toroidal Flux Machine

Theo Carpi, Yvan Lefevre, and Jean-François Llibre

Laboratoire Plasma et Conversion d'Énergie (LAPLACE), University of Toulouse, CNRS, 31000 Toulouse, France

**Abstract**— This paper deals with a 3D hybrid model of a new concept of electrical machine. It is an ideal but true toroidal flux permanent magnet machine that presents the advantage of having no end-winding and thus a better use of copper to produce torque. The model is developed in toroidal coordinates by R-separation variables and then compared to finite element analysis.

**Index Terms**— Hybrid model, R-separation of variables, toroidal coordinates, toroidal flux motor.

## I. INTRODUCTION

The structures of rotating permanent magnet machines have changed a lot in order to improve the specific torque. The performances of electrical machines depend on the air-gap area, thus increasing this parameter and maintaining the mass constant allow increasing the torque to mass ratio.

First, conventional radial flux machines (RFM) with one air-gap have evolved to a novel structure called dual-rotor radial flux permanent magnet machines [1] where a toroidally wounded stator is placed between two rotors with radially magnetized permanent magnets (PM). In the same way, single sided axial flux permanent magnet machines (AFPM) have been developed to create double sided AFPM such as the yokeless and segmented armature (YASA) topology [2] and the ‘Torus’ concept [3] where the windings are encapsulated in two layers of PM axially magnetized.

Finally, a novel hybrid radial and axial flux permanent magnet machine [4] emerged combining both radial and axial flux machines structures. All these evolutions led to a better use of the copper in electrical machines. This brings the idea of the new structure of electric machine developed in this paper.

An ideal but true toroidal flux permanent magnet motor (ITFPM) is modeled. It is called ideal because it is a concept and it is called true toroidal because it is described in toroidal coordinates. Its geometry allows the use of the whole copper to produce torque in order to maximize the specific torque. A 3D hybrid model in toroidal coordinates [5] of the ITFPM motor is developed and compared to finite element analysis (FEA).

## II. MODEL OF THE ITFPM MOTOR

The toroidal coordinate system  $(\eta, \theta, \psi)$  used to model the machine is presented in [5]:

$$(x, y, z) = ((a \sinh \eta)/\Delta \cos \psi, (a \sinh \eta)/\Delta \sin \psi, (a \sin \theta)/\Delta) \quad (1)$$

with:  $\Delta = \cosh \eta - \cos \theta$  and  $a$  is a parameter that determines the scale of the coordinates. This coordinate system is chosen because it allows applying an R-separation of variables necessary to have an analytical model. A 2D cut view in the azimuthal plane is shown in Fig. 1 which unveils a part of the machine structure. An internal iron torus on which are placed

the toroidal PM magnetized in the  $e_\eta$  direction constitute the rotor. The stator is made of a hollow iron torus surrounding the rotor and leaving an airgap between it and the magnets. The stator current layer is modeled by the current density  $K$ .

The open-circuit magnetic flux density of the example shown in Fig. 1 is solved in 3D by a hybrid model based on R-separation of variables and 1D finite difference (FD) method. The solution is compared to a FEA (Fig. 2).

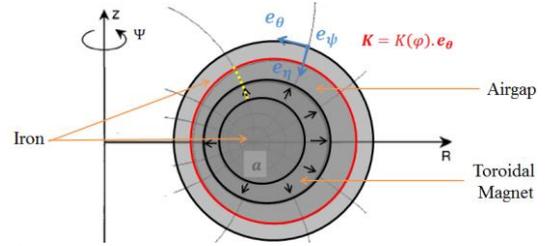


Fig. 1. 2D cut view in the azimuthal plane of the proposed TFPM machine.

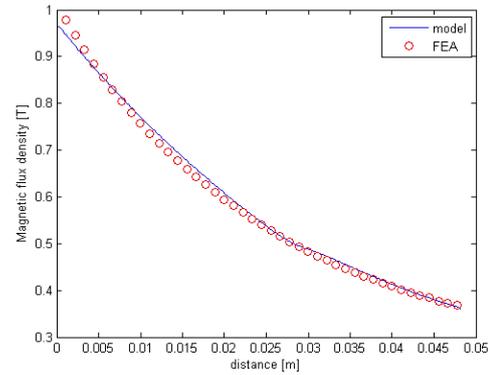


Fig. 2. Magnetic flux density  $B_\eta$  along the  $\eta$  coordinate line (model-FEA).

## III. CONCLUSION

An ITFPM motor is presented. ‘‘Ideal’’ means that it cannot be manufactured and ‘‘True’’ it is modeled in toroidal coordinates. The whole structure of the motor and the 3D hybrid model will be described in the final paper.

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