15th INTERNATIONAL SYMPOSIUM on
POWER ELECTRONICS - Ee 2009
XV Međunarodni simpozijum Energetska elektronika – Ee 2009
NOVI SAD, REPUBLIC OF SERBIA, October 28th - 30th, 2009

3D GRAPHICAL INVESTIGATION OF AN INVERSE RELUCTANCE MOTOR FOR DRIVING LIGHT ELECTRIC VEHICLES

Viorel Trifa*, Adrian Graur, Calin Marginean***
*Technical University of Cluj-Napoca, Romania
**"Stefan cel Mare" University of Suceava, Romania

Abstract: *The paper is intended to present gradually the new approach of a special reluctance motor using high performance software environment as Flux 3D. The motor is of inverse construction, with an inner 16 pole toothed stator and a toothed outer rotor, that allows a direct low speed – high torque driving of light electric vehicles (LEV), such as bicycles, scooters and tricycles. Starting from classical design, FEM analysis is developed using Flux 3D and significant graphical results concerning flux density inside the motor are given.*

Key Words: ***reluctance motor, classical design, FEM approach, magnetic field, graphical results.***

1. INTRODUCTION

Light electric vehicles, such as bicycles, tricycles and scooters, may be considered today as an alternative to individual urban transportation. Most constructors of LEVs have adopted cheaper solutions of placing a conventional motor (brushless DC motors [1] or PM synchronous motors [2]) for driving back wheels, using preferably classical chain-based transmission. Significant drawbacks of these motors in case of LEV driving are observed lead to their low performance torque/speed characteristics as electric traction means, especially in case of sloped roads.

The solutions of direct (in-wheel) driving can surpass this disadvantage, provided the motor is of special construction, adapted for low-speed/high-torque characteristics. The paper describes a new type of inverse reluctance motor, with a toothed air gap, that allows the reduction of rotor movement, to fulfill the requirement of a direct gearless driving vehicle.

The strategy of designing this new motor involves two main parts: classical design, respectively FEM analysis. Classical design represents a pre-dimensioning stage designated to provide main geometric magnitudes for FEM analysis. This second stage is able to optimize motor as electromagnetic and electro mechanic device and offers an excellent premise for a successful motor prototype.

2. CLASSICAL MOTOR DESIGN

In the particular case of the front in-wheel driving one must consider an inverse construction of the motor, so that the stator is fixed on front wheel shaft and the rotor surrounds the stator and is linked to wheel rim through spokes. An outline of the motor is given in figure 1.

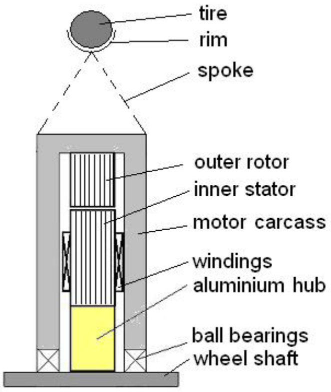

Fig. 1. *Sketch for Inverse reluctance motor.*

Classical design comprises the following steps [3]:

- Defining main driving magnitudes
- Calculating toothed structure of the air gap
- Determining the permeances
- Calculation of inductivities and amper-turns
- Designing the windings and phases
- Obtaining final motor dimensions.

Following the steps shown above, one can start the motor design by defining the drive magnitudes. This is made by taking into account the characteristics of individual urban transportation [4]. Table 1 shows the main drive magnitudes calculated as result.

Table 1. *Electro mechanic characteristics*

Magnitude	**Units**	**Value**
Output torque	Nm	33
Supply power	W	625
Battery voltage	V	36
Battery current	A	17.36
Phase current	A	8.7

The calculus has been made by taking the road slope of 4% and maximal load (rider's weight) of 80kg, the resulting speed of 4.5m/s, that is equivalent to 16.2 km/h in case of a motive wheel diameter of 0.6m. Battery voltage was chosen to 36 V, corresponding to 3-series connected units.

Toothed structure of the air gap is the key of rotor movement reduction, to achieve traction characteristic of speed/torque curve. This structure has been determined before [3] and its magnitudes, together with the rest of motor geometry, are given in table 2.

Table 2. *Motor geometry magnitudes*

Magnitude	**Units**	**Value**
Number of motor phases		4
Number of stator poles		16
Tooth dimension	mm	4
Tooth period	mm	8
Number of rotor teeth		132
Number of steps/rot		528
Number of stator poles		16
Number of teeth/pole		8
Tooth dimension	mm	4
Distance between poles	mm	6
Polar piece length	mm	60
Air gap circumference	mm	1056
Air-gap diameter	mm	336
Air-gap magnitude	mm	0.25
Motor active axial length	mm	40
Motor diameter	mm	352

Motor windings are also designed and the results are given in table 3.

Table 3. *Motor windings dimensions*

Magnitude	**Units**	**Value**
Maximal phase current density	A/mm^2	5
Minimal area of wire section	mm^2	1.74
Number of wires per slot		360
Copper area per slot	mm^2	597
Minimal area needed per slot	mm^2	760

All dimensions regarding motor geometry, as determined by classical design, will consist in start data for 2D-3D modeling in Flux environment.

3. FE MODELING

As usually known, FEM analysis may optimize motor design. In this purpose Flux 3D environment is used, which indicates general steps for study, as follows [5]:

- Geometric construction or import
- Mesh generation
- Assignation of physical properties
- Solving process
- Result post-processing.

In order to prevent memory out when using Flux 3D, one must reduce the field of analysis to a representative part of the motor. In the particular case of actual motor, FE-model can be reduced to one-sixteenth of its original size by taking into account the machine symmetry along its axial length and by using the periodicities.

In this way, the **base geometry module** is created, as depicted in figure 2.

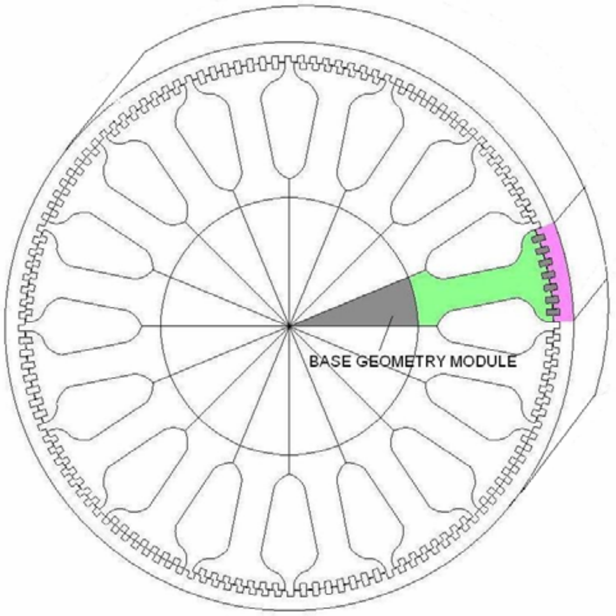

Fig. 2. *Definition of base geometry module.*

For a better development of analysis, 2D model of the motor must be built first and then 3D model will be deduced by extrusion.

2D model is represented on Z plane in cylindrical system of coordinates and comprises the following faces: stator, rotor, air gap, and shaft, as shown in figure 3.

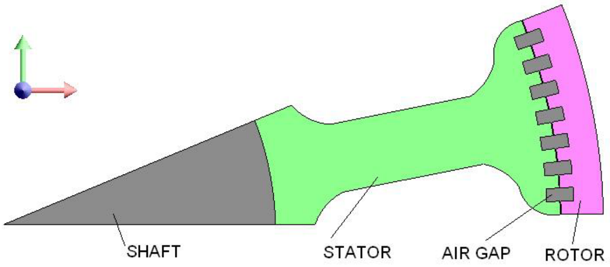

Fig. 3. *2D model.*

Meshing the 2D model has been made after choosing mesh lines and also mesh points for the four faces. High density of mesh points have been adopted for critical regions, i.e. teeth and air gap, as seen in figure 4.

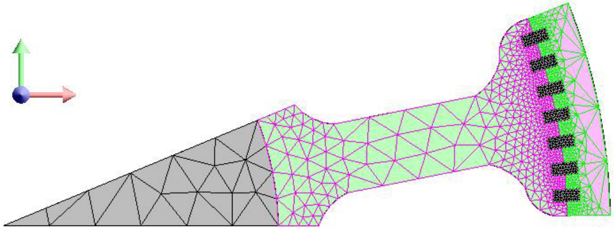

Fig. 4. *Mesh for 2D model.*

3D model is obtained by using dedicated commands, as extrusions. The 2D geometry of the base model is extruded in the direction of Z-axis of coordinate system. Extrusion of the 2D model is performed via an extrusion line of a length equal to axial length of the machine. The infinite box of cylinder shape is used for surrounding extruded model by a determinated air region, in order to delimitate volumes when Flux 3D performs field computation. There are six volumes deduced from extrusions as: stator, rotor, air gap, shaft, air and infinity cylinder. Figure 5 depicts these volumes.

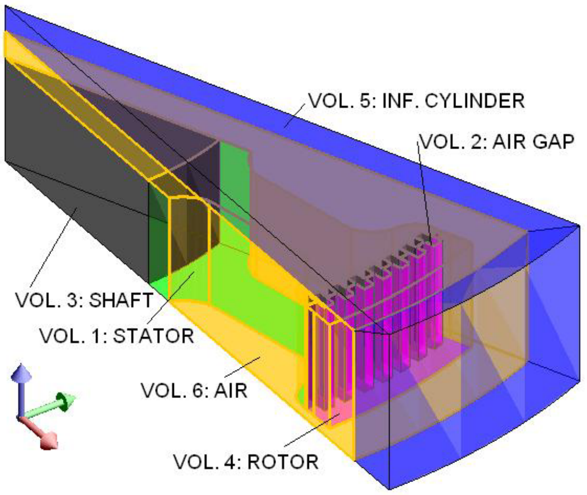

Fig. 5. *Volumes of base geometry module.*

Another important step consists in **coil management**. In this purpose, the entire winding per one stator pole must be first designed. Then Flux 3D produces coil placement, as given in figure 6.

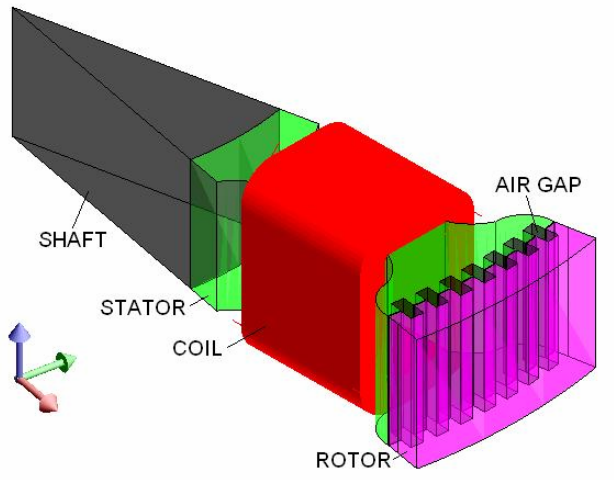

Fig. 6. *Coil placement per pole.*

At this point all preliminaries for FEM approach of the motor are completed. The 3D FE model may be extended to 4-pole or 16-pole analysis in order to acquire magnetic and mechanic characteristics of the motor.

4. 3D RESULTS

The magneto-static model of the motor is defined by Flux 3D as result of following the last three steps, as shown before. For the present application the map of magnetic flux density is taken for the analysis. Flux 3D allows this procedure within post-processing step, searching for isovalues of magnetic field.

To avoid working with big pictures, captures from Flux 3D have been fragmented with respect to the 6 volumes, as defined above (see fig. 5). So, figure 7 depicts magnetic isovalues for iron part of the base geometry module, that is for stator and rotor.

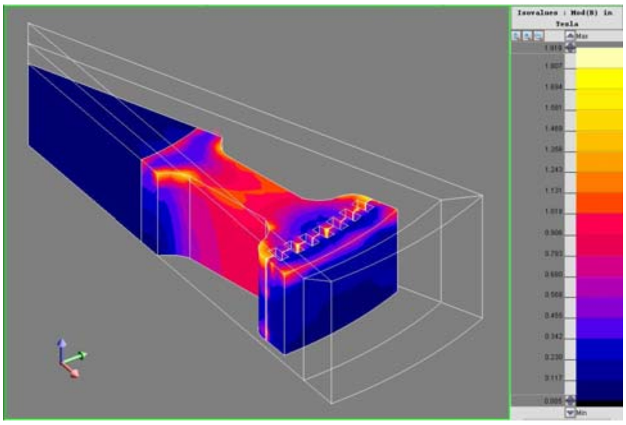

Fig. 7. *Magnetic field inside iron part.*

Volume of aluminum shaft is also included, even it may be considered as air volume. Flux density is depicted by colours, as seen on the right scale in the figure, which extends from 0.2 to 1.9 Tesla. No important saturated regions are observed, but some reduction of iron part could be taken into consideration.

Magnetic field around iron part is studied taking as entities the rest of volumes. Figure 8 depicts isovalues in the vicinity of stator/rotor volumes.

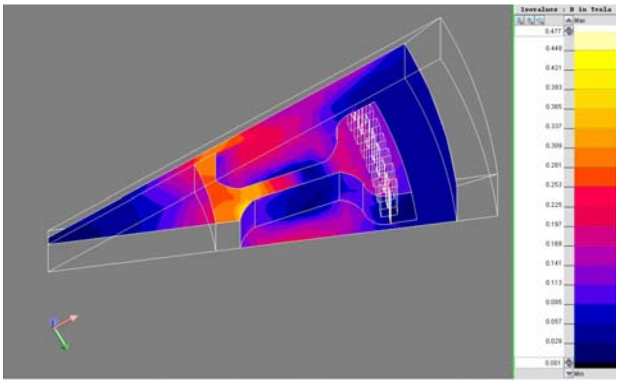

Fig. 8. *Magnetic field for air.*

In this case the flux density scale is between 0.01-0.4 Tesla, so the colours for isovalues are different from the previous case.

The air gap is also studied and figure 9 shows magnetic field accordingly. No saturation effect is observed.

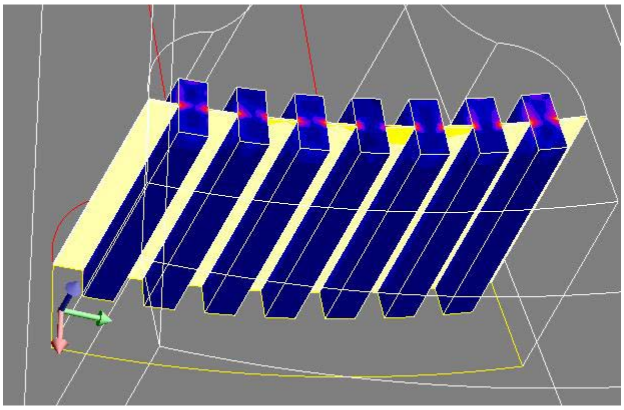

Fig. 9. *Magnetic field for air gap.*

Finally, the isovalues of magnetic field for the rest of infinity cylinder are deduced, as shown in figure 10. The flux density scale is identical for the figures 8-10.

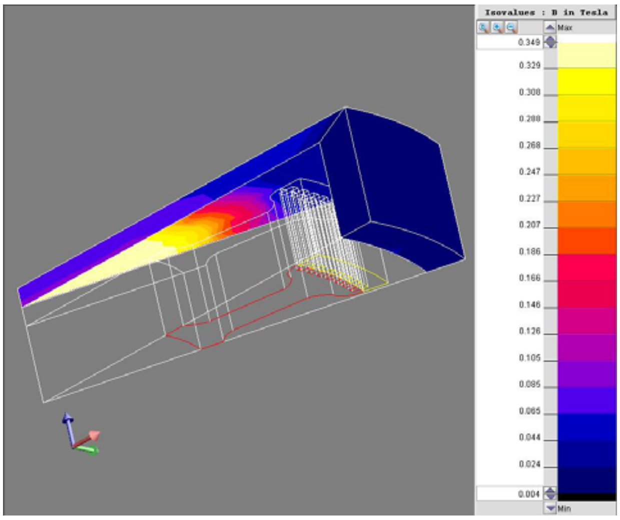

Fig. 10. *Magnetic field for infinity box air.*

5. CONCLUSIONS

Optimal design of the new motor for direct driving the LEV means to combine classical design with 3D-FEM analysis. Classical design offers geometrical and material data for starting the 3D study, using the Flux 3D environment. Isovalues of flux density reveal no saturation effects inside the iron part of the motor. The study may be easily extended to 4, 8 or 16 pole configuration and also for the study of other aspects of the magnetic field.

ACKNOWLEDGENMENT

The authors bring special thanks to Cedrat - France, which provided conveniently for us the software license of Flux 3D in the Laboratory of Reluctance motors and applications, Technical University of Cluj-Napoca, Romania.

REFERENCES

[1] Wiak, S., Nadolski, R. and Ludwinek, K.: *Electric Bicycle – the example of mechatronic inter-disciplinary case study.* Proceedings of the 6th Electromotion Conference, Lausanne, Switzerland, 2005, printed on CD.

[2] Zire, H.S., Espanet, C. and Miraoui, A.: *Three dimensional finite-element analysis of high-torque permanent-magnet synchronous machines.* Ibd.

[3] Trifa, V., Marginean, C. and Trifa, Olivia: *Setting-up 3D-FEM analysis of an inverse reluctance motor for driving light electric vehicles*. Proceedings of the 8th Electromotion Conference, Lille, France, 2009, printed on CD.

[4] Trifa, V., Cistelecan, M. and Marginean, C.: *Direct electric in-wheel driving of a bicycle using reluctant motors.* Proceedings of the 7th Electromotion Conference, Bodrum, Turkey, 2007, ISBN 978-975-93410-2-2, pp.17-20.

[5] *** Cedrat: Flux 10, 3D Application. Generic tutorial. June 2007.