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ANALYTICAL MODELING OF AXIAL FLUX PMSM USING A COMBINED SOLUTION OF MAGNETIC EQUIVALENT CIRCUIT (MEC) AND MAXWELL'S EQUATIONS

Ahmed Hemeida[1], Peter Sergeant[1,2]

[1]Ghent University, Department of Electrical Energy, Systems and Automation, B-9000, Ghent, Belgium
E-mail: ahmed.hemeida@Ugent.be

[2]Department of Industrial Technology & Construction, Ghent University, B-9000 Ghent, Belgium
E-mail: peter.sergeant@Ugent.be

Abstract. This paper presents a complete analytical model of axial flux permanent magnet synchronous machines (AFPMSM's). A simple and fast technique was developed to obtain accurate results for the calculation of machine parameters (Electromotive Force (EMF), Torque, and Losses). This technique is based upon the combined solution of two models. The first model generates an exact solution of Maxwell's equations in the air gap area applied to a very simple geometry. The second model gives an accurate solution in the parts with complex geometry, based on a Magnetic Equivalent Circuit (MEC) to obtain fast and accurate results in a simple way. The machine's global quantities are then obtained and validated by the results of a Finite Element Model (FEM) for different loading conditions and geometries. Compared to FEM, the proposed combined solution has the advantage of flexibility in the geometrical machine parameters, a significantly lower CPU time and an accuracy for the considered PMSM.

Keywords: Axial Flux Permanent Magnet Synchronous Machines (AFPMSM), EMF, Losses, Magnetic Equivalent Circuit (MEC), Maxwell's Equations, Torque.

INTRODUCTION

There are several types of Axial Flux PMSM's. A general comparative study was done in [1] between different types of AFPM machines. From this comparison, due to the absence of a yoke, the Yokeless and Segmented Armature (YASA) machine has the highest efficiency and torque density. Therefore, this machine, shown in Fig. 1, is selected for study in this paper.

The development of analytical mathematical tools is important for the design of electrical machines. Numerous modeling techniques were used in the past few decades for these types of machines. The most accurate models are the 3D Finite Element models (FEM). In the pre-design modeling, one needs a fast and accurate model which doesn't consume much time and gives accurate data for the voltage, torque and losses of the machine.

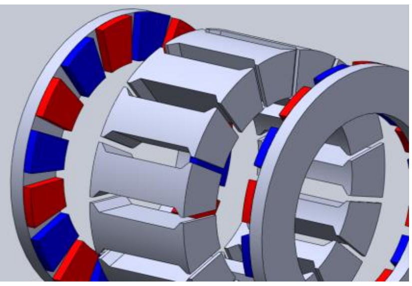

Fig. 1. Double sided axial flux machine.

Analytical models are the most suitable solution for this. Two types are often used: magnetic equivalent circuit (MEC) and analytical models based on the solution of Maxwell's equations for a certain geometry with constant permeability region. The solution based on Maxwell's Equations usually solves the problem with simple geometry assuming the iron material on stator and rotor as an infinite permeability material and no saturation occurs on it. The second solution based on MEC takes into account the non-linearity of the material. To increase the accuracy of the solution, one needs to increase the mesh in the air gap area. On the other hand, this will increase the complexity of aligning the rotor with stator reluctances of the MEC.

In this paper, a combined solution of Maxwell's equations and MEC has been done to solve the problem in the air gap area and inside the magnetic core. A solution of Maxwell's equations is based upon a 2D multi-slice solution for the geometry and applies this solution to the core using the MEC. After obtaining all the induction values everywhere inside the stator tooth assuming nonlinear material, the parameters of the machine (Torque, Back EMF, and Losses) are then obtained.

SIMULATION MODEL AND RESULTS

The same technique as in [2] was used to calculate the magnetic induction in the air gap due to the magnets and armature current. The field is calculated by using Maxwell's equations by stretching the machine into the 2D model and dividing it to many slices. The effect of slotting is taken into account by multiplying the flux density distribution by the permeance function in [3]. Afterwards, the calculated flux densities are induced to the MEC shown in Fig. 2.

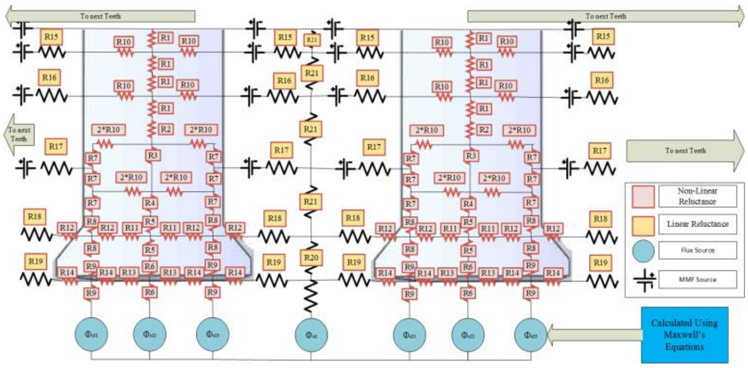

Fig. 2. Magnetic Reluctance Network with Maxwell's resultant flux.

Fig. 3 shows a good agreement for the EMF and torque for different loading conditions between the FEM and the analytical model.

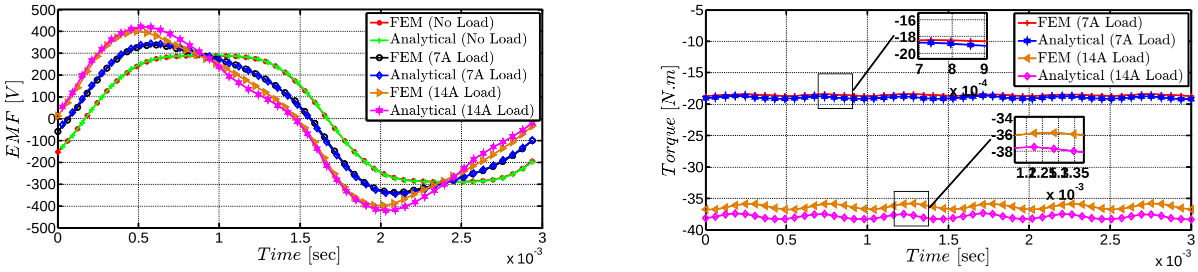

Fig.3. EMF and Torque for different loading conditions.

Table I summarizes the total losses in case of FEM and analytical model. It could be noted that the total error is within 5% for different loading and geometry conditions of different slot opening value (t_{so}).

TABLE I

TOTAL STATOR CORE LOSSES.

	FEM Results (W)	**Analytical Results (W)**	**Error (%)**
No Load (t_{so} = 3mm)	**168.74 W**	**170.72 W**	**-1.2 %**
Irated (t_{so} = 3mm)	***182.36 W***	***184.78 W***	***-1.32 %***
2Irated Load (t_{so} = 3mm)	**208.44 W**	**217.7 W**	**-4.44 %**
No Load (t_{so} = 7mm)	***153.84 W***	***148.86 W***	***3.2 %***

CONCLUSIONS

A general analytical model for the study of Axial Flux PMSM has been proposed for a complete study of the machine parameters of the EMF, torque, and losses. The machine was extensively studied with different geometry and loading conditions till double the rated current. The results of all machine parameters were very comparable with the results of FEM. Under time comparison, the analytical model was up to 200 times faster compared to FEM. The losses were calculated locally in the tooth in many different positions under nonlinear conditions. In conclusion, this model has proven to be very well acting with different machine geometries and loading conditions in very effective time.

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