Study of Cogging Torque in Axial Flux Permanent-Magnet Machines Using an Analytical Model

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***Abstract*—Cogging torque is a source of vibration and noise in permanent-magnet (PM) machines. Its reduction is always sought by electrical machines designers. While its study, in radial-flux permanent-magnet machines (RFPM), can often be done using 2D finite element analysis (2D FEA), three-dimensional FEA (3D FEA) is always required when it comes to its study in axial-flux permanent magnet machines (AFPM). AFPM machines have an inherent three-dimensional electromagnetic structure. There is a reach literature concerning the study of cogging torque in AFPM machines. Indeed, most of authors use 3D finite element analysis (3D FEA) for its study. However, 3D FEA is time consuming and always requires expertise to be done correctly. The goal of this paper is to show that alternative techniques, to study cogging torque in AFPM machines, do exist. It is shown that the analytical model, presented in this paper, can be as efficient as the 3D FEA while saving a huge time and necessitating less initial expertise.**

***Index Terms*—Axial flux machines, cogging torque, permanent magnet, torque ripple.**

I. INTRODUCTION

Cogging torque is one of the major contributors to torque ripple in PM machines [1], [2]. It is source of vibration and noise. Its reduction is always sought by electrical machines designers. Many authors have studied cogging toque characteristics in RFPM machines [2]–[5] and AFPM machines [6]–[8]. While its study, in RFPM machines, can often be done using 2D finite element analysis (2D FEA), 3D FEA is always required when it comes to its study in AFPM machines. AFPM machines have an inherent 3D electromagnetic structure. Indeed, most of authors use 3D finite element analysis (3D FEA) for its study [6]–[8]. However, 3D FEA is time consuming and always requires expertise [9] to be done correctly.

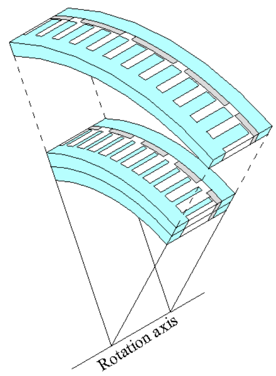
The goal of this paper is to show that alternative techniques to study cogging torque in AFPM machines do exist. It is shown that the analytical model, presented in this paper, can be as efficient as the 3D FEA while saving a huge time and necessitating less initial expertise [10].

II. MULTISLICE (QUASI-3D) ANALYTICAL MODEL

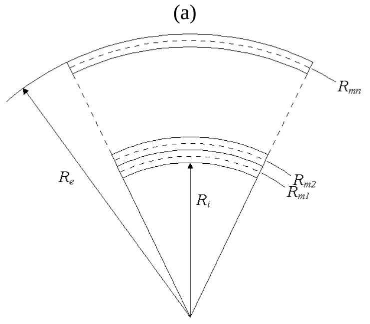
Figure 1 presents the principle of the quasi-3D model. The machine is divided into a certain number of annular slices in the radial direction. The analytical model based on the solution of Maxwell equations is established at the average radius (R_{mi} for the ith slice) of each slice (Fig. 1(b)). The analytical solution for the magnetic field distribution is established based on following assumptions: 1) the stator and rotor cores are assumed to be infinitely permeable; 2) eddy current effects are neglected (no eddy current loss in the magnets or armature windings); 3) the permeability of permanent magnets is assumed to be equal to that of air; and finally, 4) the end effects are neglected. Details about the developed analytical model can be found in [10].

III. STUDY OF COGGING TORQUE CHARACTERISTIC

The cogging torque characteristic is analyzed through a parametric study. The goal of this study is first to validate the developed analytical model by comparing it to 3D FEA, and secondly to demonstrate its usefulness in replacing the time consuming 3D FEA. This study is done using both 3D FEA and analytical models. Table 1 gives constant design parameters of axial flux machines to which both 3D FEA and quasi-3D analytical models have been applied to study cogging torque characteristic. Figure 2 shows a front view of a permanent magnet of studied AFPM machines. For the parametric study the interior radius R_i will be equal to 200 mm, 250 mm, 300 mm, 350 mm, and finally 375 mm, and α_i will be equal to 0.3, 0.4, 0.5, 0.6, 0.7 and 0.85 (α_e = 0.85).



(a)



(b)

Fig. 1. Subdivision of the axial flux machine in annular slices.

TABLE I – MACHINES PARAMETERS

Pole number	28
Slot number	84
Magnets distribution and remanence	Axial magnetization, 1.21 T
Exterior R_e radius (mm)	400
l_a, e, h_s and w_s (mm)	10, 1.5, 61, 12

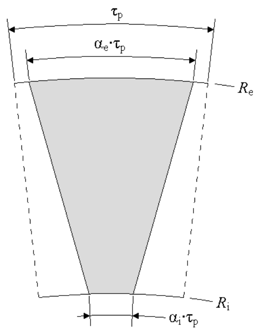


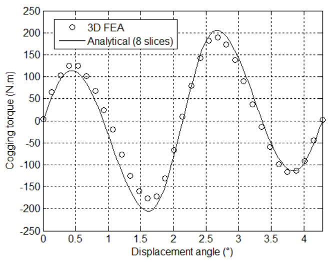
Fig. 2. Magnet shape and outlines of a rotor pole.

Fig. 3 shows comparison of cogging torque waveforms obtained from both 3D FEA and analytical models, for an AFPM machine with α_i = 0.3, and R_i = 200 mm [Fig. 3(a)] and R_i = 375 mm [Fig. 3(b)] respectively.

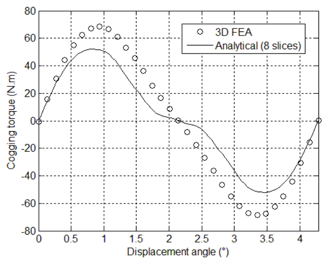
Fig. 4 shows another comparison of cogging torque waveforms obtained from both 3D FEA and analytical models, for an AFPM machine with R_i = 375 mm, and α_i = 0.4 [Fig. 4(a)] and α_i = 0.85 [Fig. 4(b)] respectively.

It can be noticed that results from both methods agree fairly well.

A simple and fast parametric study, based on the analytical model, helped to identify the value of α_i allowing to minimize the cogging torque (α_i = 0.55), while the value of α_e is kept constant (α_e = 0.85) for a machine having R_i = 375 mm. Fig. 5 compares cogging torque waveforms for an AFPM machine with R_i = 375 mm and R_e = 400 mm, and α_e = 0.85, for α_i = 0.5, α_i = 0.55 and α_i = 0.6, obtained from 3D FE analyses As expected the cogging torque is minimized for α_i = 0.55.

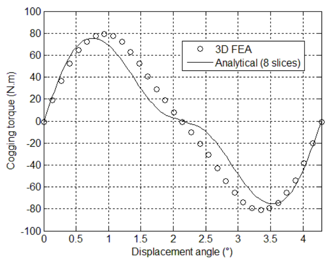


(a) R_i = 200 mm

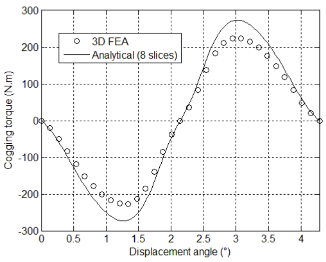


(b) R_i = 375 mm

Fig. 3. Cogging torque waveforms comparison (α_i = 0.3).



(a) α_i = 0.4



(b) α_i = 0.85

Fig. 4. Cogging torque waveforms comparison (R_i = 375 mm).

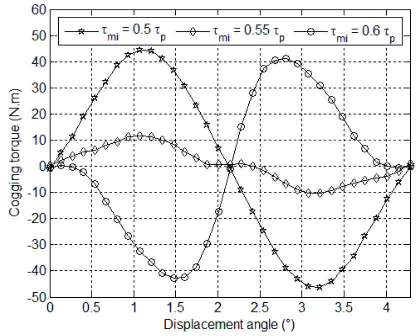


Fig. 5. Cogging torque waveform comparison ($\tau_{mi} = \alpha_i \cdot \tau_p$, with α_i = 0.5, α_i = 0.55 and α_i = 0.6).

IV. CONCLUSION

An efficient analytical tool for the design and analysis of axial flux PM machines has been developed. The main features of this analytical design tool have been presented. Compared to 3D finite element computations the developed model gives sufficiently accurate results.

It has been demonstrated that analytical models can become an appreciable alternative to the finite elements method especially for 3D problems for some analysis studies.

The full paper will contain more details about the proposed approach and present more results to support it. Influence of magnet shapes on cogging torque characteristic will be further investigated using the developed analytical model.

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