An Analytical Approach to Estimate the Cogging Torque in Segmented stator Synchronous Permanent Magnet Machines with large Gaps

E. Fleurot¹, F. Scuiller¹, IEEE Member, and J. F. Charpentier¹, IEEE Member

¹Research Institute of the French Naval Academy (IRENav), CC 600, 26240 Brest FRANCE, eulalie.fleurot@ecole-navale.fr, franck.scuiller@ecole-navale.fr, jean-frederic.charpentier@ecole-navale.fr

This paper presents a new analytical model to determine the cogging torque of stator-segmented permanent magnet machines (with angular air gap, i.e. flux barriers, at the stator). Basically, if the saturation is disregarded, the cogging torque can be seen as the sum of two independent contributing cogging torques: the first resulting from an equivalent slotless machine with a single gap, the second resulting from an equivalent non-segmented slotted machine. For the specifications of a marine current turbine generator, this analytical approach is evaluated referring to numerical 2D Finite Element Analysis (Flux® 2D by Altair).

Index Terms—Analytical model, Cogging Torque, Permanent magnet motors, Segmented Machines.

I. INTRODUCTION

The presented work focuses on unconventional Permanent Magnet Synchronous (PMS) Machines. This type of machines are called PMS segmented stator machines and appears in literature for some years. In this kind of machines the active parts of the stator are divided into several parts (named stator sectors) and these sectors are separated by non-magnetic gaps (which not contain active parts). Fig. 1 depicts a typical example of this kind of unconventional machine with \( n_s = 4 \) sectors and a ratio between total gap width and circumference equal to \( p_{gap} = 0.25 \). Segmented stator PM Machines with large angular gaps could be integrated into Rim-driven systems for propulsion or generation applications with the expected advantages of reducing losses and copper volumes, optimizing the machine/turbine integration and improving the reliability.

However in a segmented stator structure, the cogging torque relates to PM electromagnetic interaction with the slots and with the sector and gap interfaces. This paper aims to develop a simple analytical method to estimate the cogging torque in such structures.

II. SUPERPOSITION PRINCIPLE

The method is based on superposition of the cogging torque resulting from two bases configurations. Actually it is supposed that the contributions to the cogging torque of the slots and angular gaps are independant and can be calculated separately. At first an equivalent slotted machine (without angular gaps) with the same rotor and the same slot geometry as the studied segmented machine is considered. Classical analytical methods (as in [3]) can then be used. In a second step a basic structure with the same dimensions with no slots and with only one gap is considered (mono-gap structure). An example of this basic mono-gap structure is presented in Fig. 2(b).

With Finite Element Analysis, the computation time for estimating segmented machines performances could be large due to the increase of the simulation domain. Analytical method would be particularly useful to fast evaluate the solutions at the pre-design step. Therefore, this paper aims at developing an analytical estimation of the cogging torque for segmented PM machines. Since cogging torque possibly causes high vibrations and acoustic noises, it should be carefully considered at the design step [1].

Analytical cogging torque models have been proposed and validated for classical slotted machine as in [2] (this cogging torque is in this case due to magnets and slots interactions).

The angular width of the gap is, in this basic configuration, supposed to be a multiple of the pole angular pitch. In fact, gap angular width needs to be a multiple of pair of pole to keep a regular slotted structure outside the sector parts, for this kind of machine with \( ½ \) slot per pole and per phase.

Preliminary numerical calculations by 2D Finite Element Method (2D FEM software Flux2D) demonstrate that the number of poles considered for the gap width does not influences the results. That means that the contribution of one
gap does not depend on the gap width if an integer number of pole pitches is considered for the gap width.

In this case the cogging torque of the whole machine can be calculated as the sum of the contribution of the slotted machine $C_{d-slotted}$, multiplied by the relative part of the sectors, $(1 - p_{gap})$ ($p_{gap}$ is the proportion of gap), and the contributions of the $n_g$ gaps (each contribution is identical and equal to the mono-gap contribution, $C_{d-MonoGap}$).

$$C_{d-AirGap}(\theta_r) = C_{d-slotted}(\theta_r) \times p \times (1 - p_{gap}) + C_{d-MonoGap}(\theta_r) \times n_g$$  \hspace{1cm} (1)

III. MONO-GAP MODEL

The analytical mono-gap cogging torque model is an adaptation of analytical classical cogging torque calculation method [2]. Cogging torque is estimated from the calculation of the magnetic flux density created by the rotor in the gap opening $B/I_R$. This calculation is based on the estimation of magnetic pressure in each sector/gap interface. The method of separation of variables (as in [4]) is used to calculate $B/I_R$ and an adapted permeance function is considered. In this case the flux lines which applied on sector sides are considered as circular and the studied structure have a large number of poles, so the bend radius is neglected. The calculation is limited to half a pole pitch in each gap side (red area in Fig. 3). This calculation method will be detailed in the full paper.

![Fig. 3. Computation areas of the cogging torque.]

IV. RESULTS AND VALIDATION

Two machines are considered for validation purpose. Both have the same geometrical parameters and correspond to a “classical” machine based on the machine from [5] where a part of the stator is removed. The circumference of the machines is divided into 6 sectors separated by gaps. For the first machine 5 pairs of poles by gap have been removed and 9 for the second which corresponds to approximately $p_{gap} = 20\%$ and $p_{gap} = 40\%$ of the stator circumference respectively. Fig. 4(a) and 4(b) show the both structures.

![Fig. 4. Structures of the studied machines. (a) Gap of around 20%. (b) Gap of around 40%.]

Fig. 5(a) and 5(b) show the comparison between results for the cogging torque of the both segmented machines from numerical calculation using 2D Finite Element Method (Flux2D software) and from analytical model.

![Fig. 5. Comparison between numerical and analytical cogging torque for segmented machines. (a) $p_{gap} \approx 0.20$. (b) $p_{gap} \approx 0.40$.]

V. CONCLUSION

Synchronous Permanent Magnet Machines with segmented stator are considered in this study. An original analytical model is developed to estimate the cogging torque of these unconventional machines. The model is based on the superposition of the contribution of two basic structures. The model validation with 2D FE Method (Flux2D) calculation shows that the analytical model results are in good accordance with numerical ones.

REFERENCES


