Cogging Torque Reduction in PM machines Used in Electro-Mechanical Battery

B. Abdi
Islamic Azad University, Tehran, Iran

Abstract—Electro-Mechanical Batteries have important advantages comparing chemical batteries and using them is popularized specially in Low Earth Orbit satellites recently. External rotor Permanent Magnet machines are used in these systems as Motor/Generator. The main problem of these machines is their cogging torque originated from high strength PM's. Different methods for cogging torque reduction are available, anyway not all of them are applicable in spacecraft EMB's machines. In this paper different method of cogging torque will be investigated and proper manners will be extracting. Finite Element Method (FEM) simulations are used for this aim.

Index Terms— **Flywheel, electromechanical, battery, energy storage, PM, design, aerospace.**

I. Introduction

Flywheel energy storage or Electro Mechanical Battery (EMB) structuralized by Maryland University [1] and NASA [2] in 1970 decade and using them is popularized specially in Low Earth Orbit (LEO) satellites recently. LEO satellites usually include nano and micro one witch swing around the earth by period of some minutes to a few hours. Against development of chemical battery technology the most critical part of these satellites are their batteries. They have limited life because of fast charge/discharge rate [3].

Fig (1) shows an EMB. The advantage of EMB presented in [1~6] that unlimited charge/discharge cycle as well as satellite life, more efficiency, energy density, discharge depths thermal independency and using them in altitude control of satellite can be mentioned. Design rules and flywheel optimization for lower stress and weight done in [4] and design and construction of an EMB of satellite application given in [5].

The most important part of EMB's is Electrical machine used for energy conversion. External rotor Permanent Magnet (PM) machines are used in these systems because of more torque to weight ratio and lower rotor dissipation [6,7].Cogging torque is the most important disadvantage of high speed small motor used in these systems. Different methods for cogging torque reduction are presented in [10 to 17], anyway not all of them are applicable in spacecraft EMB's machines.

Different method of cogging torque will be investigated and proper or modified manners will be extracted in this paper. Finite Element Method (FEM) simulations are used for this aim by Ansoft Maxwell-2D software.

A summary of cogging torque emphasis in small PM machines with low torque is presented in section II. Brief introduction to main cogging torque reduction and their FEM simulations are given in III and proper methods selection will be discussed in the forth section and section V is conclusion of the paper.

II. Cogging Torque Emphasis in Small PM machines Used in Spacecraft EMB

Electromechanical torque produced by PM machines can be written as[8]:

$$T_{pm} = \frac{3}{2}\Psi i \quad (1)$$

$$\Psi = 2pNB_pK_\alpha ZR_4 \quad (2)$$

$$K_\alpha = \cos\left(\pi\frac{1-\alpha_p}{2}\right) \quad (3)$$

Where N, Z, ω and α_p are coil turn number, axial length, angular velocity and PM arc to pole pitch ratio of rotor respectively and K_α is fist harmonic coefficient of magnetic field Fourier series and show the effect of α_p. Equation (1) can be rewritten as:

$$T = K\mathcal{F}_s\mathcal{F}_r \quad (4)$$

Where $\mathcal{F}_s$ and $\mathcal{F}_r$ are MagnetoMotive Force generated by stator and rotor respectively. Samarium-cobalt is suitable PM for using in space application because of good thermal behavior [9]. In small machine constructed by high strength PM's, $\mathcal{F}_r$ is large and small $\mathcal{F}_s$ is needed for low torque production. Cogging torque originated from interaction between PM's flux or $\mathcal{F}_r$ with stator dent.

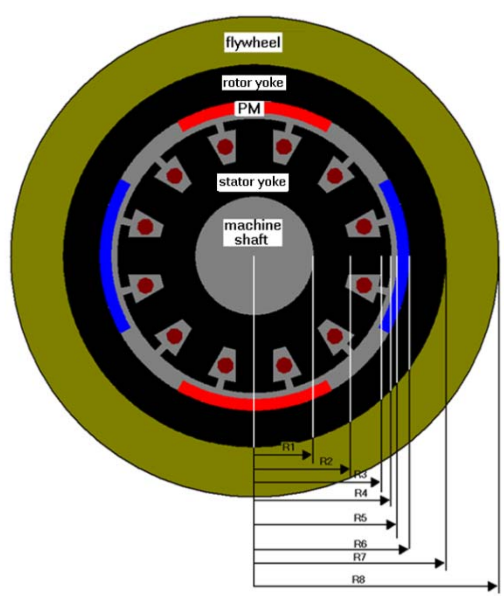


Fig. 1. Dimensions of Electro Mechanical Battery

e-mail: babakabdi@ieee.org

From above discussion it is clear that cogging torque has high value in comparison with nominal torque in small machines. Simulation results using Ansoft Maxwell-2D software for a sample machine with given parameter in table (1) are shown in fig. 2. By comparing total and cogging torque in Fig. 1, it can be find that cogging torque is about 70% of nominal torque and machine can't be work by this condition.

III. Investigation of Cogging Torque Reduction Methods

As has been known, cogging torque T_{cog} is created by variation of energy in motors when rotor rotates. It is the derivative of the coenergy with respect to the rotation angle α. It solved in [10] and the final solution is given by:

$$T_{cog}(\alpha) = \frac{\pi Z N_t}{4\mu_0}(R_6^2 - R_4^2) \times \sum_{n=1}^{\infty} n G_n B_{r\left(\frac{nZ}{2p}\right)} \sin(nZ\alpha) \quad (5)$$

Where:

$$B_{r(n)} = \frac{2}{n\pi} B_r^2 \sin(n\alpha_p \pi) \quad (6)$$

Where R_4 is stator outer diameter, R_5 and R_6 are inner and outer radius of PM respectively, Z, N_t are the number of pole pair and α_p, μ_m, B_r are PM arc to pole pitch ratio, magnet remnant and magnet permeability respectively. G_n is a function of PM and airgap width, slot opening, slot pitch and slot depth. From equation (5) it is obvious that cogging torque is depend on all machine parameters.

The first method for caging torque is stator or rotor skewing [10 to 12] but this manner cause axial force production in rotor. In spacecraft EMB's rotor is floated by tow magnetic bearings and using skewing method cause one more flange magnetic bearing and is not suitable in this application.

The effect of pole and slot number on cogging is discussed in [11]. In this reference $\mathrm{n_{cog}}$ is defined as:

$$\mathrm{n_{cog}} = \mathrm{q} \times \frac{LCM(p, N_t)}{\mathrm{p}} \quad (7)$$

Where LCM is lowest common multiple, q is each integer that makes equation (7) an integer number and p is pole pair. It is shown that cogging torque is inversely depended to $\mathrm{n_{cog}}$ and for its reduction maximum number of pole and slots required. But this manner is not applicable because of small machine is used in spacecraft EMB's and the number of pole and slots are selected 4 and 12 finally.

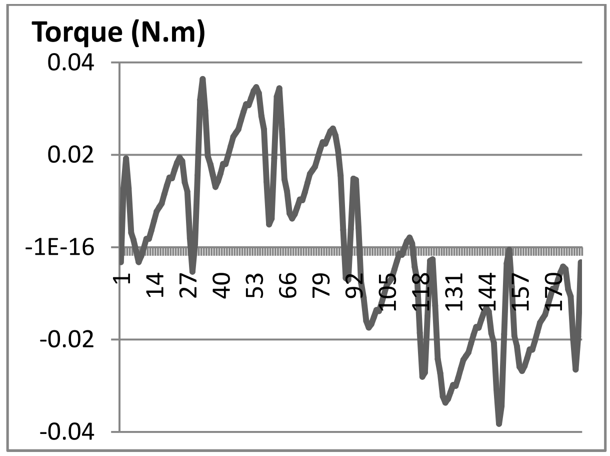
As it can be seen in equation (5), B_r coefficients are zero at $Z\alpha_p/2p = 0$. So the cogging torque is minimized at $\alpha_p = 0.66$ *and* 0.33. For more nominal torque production $\alpha_p = 0.66$ is chosen. Fig. 3 shown the results of FEM simulation of α_p variation on cogging torque and confirm its minimization at $\alpha_p = 0.66$.

Pole pair and per pole shifting methods are presented in [12,13]. In pole pair shifting manner each pole pair shifted by $\alpha_{pp} = xy_s$ mechanical degree where y_s half of a slot pitch is and x is pole pair issue. FEM results are given in Fig. 4 and shows caging torque minimization at $\alpha_{pp} = 15$.

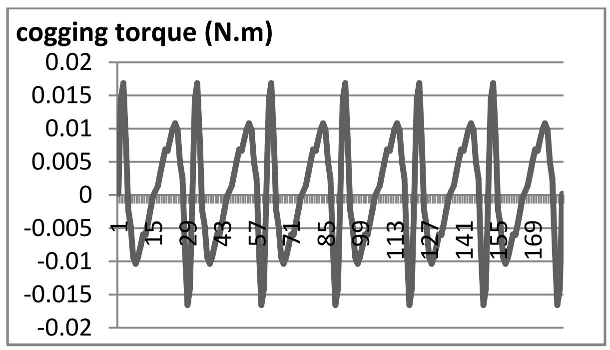
TABLE I

GIVEN PARAMETERS FOR MACHINE DESIGN

P	T	N	$E_{l\text{-}l}$	ff	B_{max}
50 Watt	1800 sec.	20 krpm	24 V	0.6	1.4 T
N_t	N_p	L_g	L_m	Z	a_p
12	4	1 mm	2 mm	30mm	0.66



A: produced torque



B: Cogging torque

Fig. 2. Produced torque resulted by parametric Magneto static FEM simulation

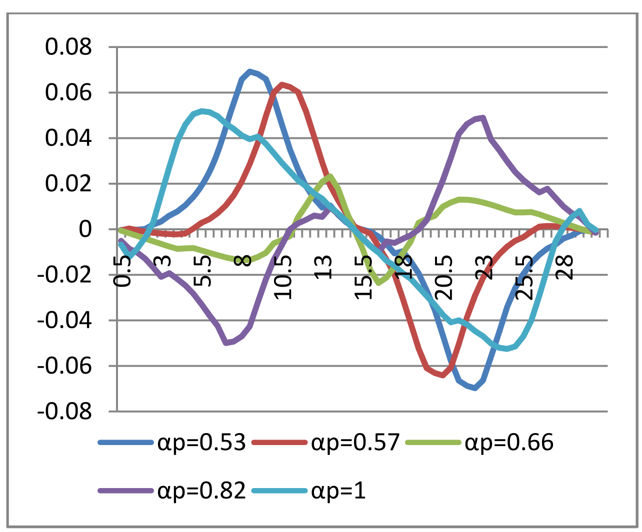


Fig. 3. Effect of α_p on cogging torque

Each pole shifted by α_{Tc} mechanical degree in per pole method. where:

$$\alpha_{Tc} = \frac{2\pi}{N_p N_t}(x-1) \quad (8)$$

$$N_p = \frac{p}{\mathrm{HCC}(N_t, p)} \quad (9)$$

Where HCC is highest common coefficient and x is pole issue. FEM results are given in Fig. 5.this figure shows minimum caging torque in 7.5 mechanical degree and confirms equation(8).

Dummy slots and dent beget are proposed in [14]. Using dummy dent is not applicable because slot space is shortage in small reveres rotor machines. Fig. 6 shows the effect of dummy slots in surface of dents.

Optimizations of slot shape are given at [15 to 17]. Anyway these methods are too complex to apply to a small machine and have a few effects on cogging torque.

IV. Discussion and Proper Methods Selection

Final results for effect of different method on cogging torque are summarized in table II. It can be find from this table that PM arc to pole pitch ratio equal to 0.66 and shifting each pole by 7.5 mechanical degree, have most effect on cogging torque reduction. The result of applying these tow method are given in Fig 5.

V. Conclusion

One of main problem in small PM machines is cogging torque. It originated from high strength permanent magnets. Different methods are available for cogging torque reduction, but not all of them are applicable in spacecraft EMB's machines. Different methods investigated by FEM analysis. PM arc to pole pitch ratio equal to 0.66 and shifting each pole by 7.5 mechanical degrees, have most effect on cogging torque reduction and proper for EMB's cogging torque reduction.

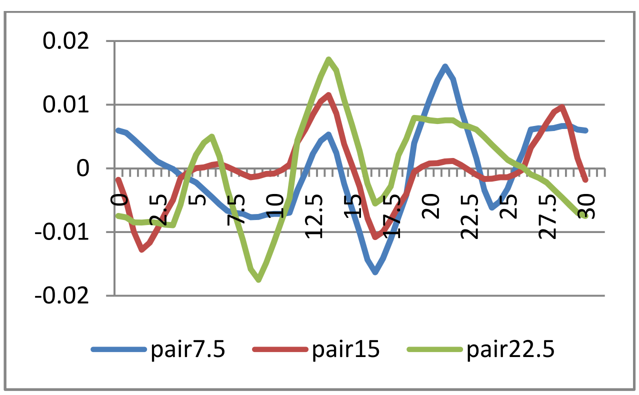


Fig. 4. Effect of pole pair shifting on cogging torque

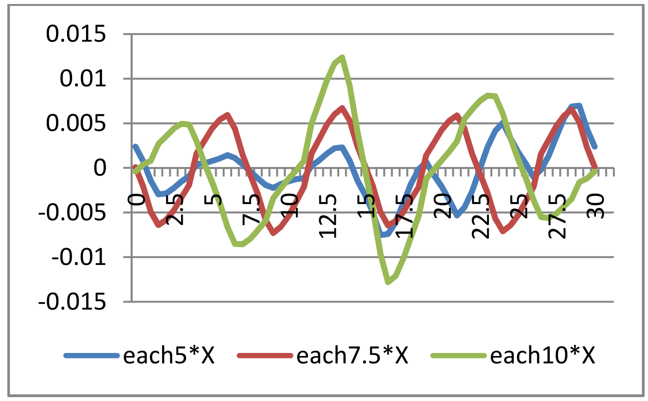


Fig. 5. Effect of per pole shifting on cogging torque

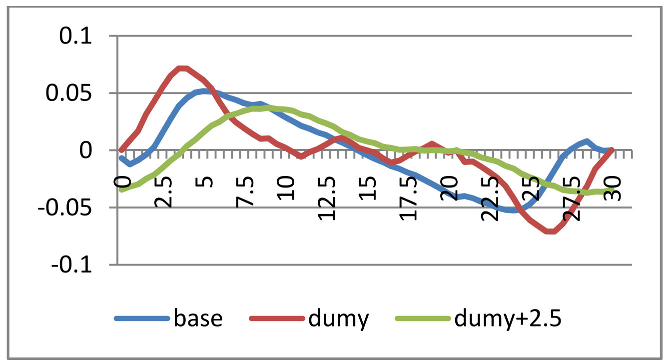


Fig. 6. Effect of dummy slots in surface of dents.

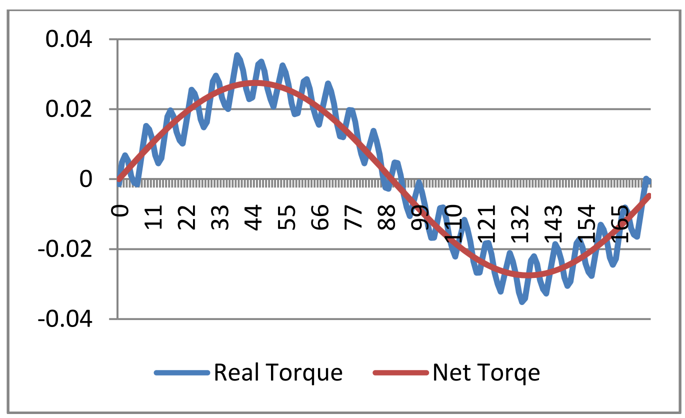


Fig. 7. Magneto static finite element simulation result of machine

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