Simplified Design of PM Machine for Spacecraft Electro-Mechanical Batteries

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***Abstract*—Electromechanical Batteries have important advantages comparing to 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. Simplified parametric design method is given for PM machine design in this paper. Finite element based simulations are used to confirm design presses and show less than 7% error in parametric design that is acceptable for simple primary design.**

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

I. Introduction

Flywheel energy storage or Electro-Mechanical Battery (EMB) introduced 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 rotate 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].

The advantage of EMB presented in [1~6] that unlimited charge/discharge cycle as well as satellite life time, more efficiency, more energy density, more discharge depths, thermal independency and their usage in attitude control of satellite can be mentioned. Design rules and flywheel optimization for lower stress and weight done in [4]. Design and construction of an EMB for satellite application is given in [5].

The most important part of EMB's is their Electrical machine used for energy conversion. A high speed external rotor Permanent Magnet (PM) machines are used in these systems because of more torque to weight ratio and lower rotor dissipation [5, 6]. In previous works like as [7] some analytical model presented but they are too complex for design process.

In this paper simplified design of PM machine for spacecraft EMB's will be presented. The first step for this aim is proper material and structure selection of machine for space applications that is presented in section II. Simplified design is given in III. In the forth section Finite Element Method (FEM) simulation with Ansoft Maxwell-2D software confirm the analytical design and section V is conclusion of the paper.

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II. Material and construction selection

A. Material selection

Motor/Generator used in spacecraft EMB is a variable and high speed small machine with some limitations as thermal, heat transfer, volume and mass. Rotor or flywheel is floated by magnetic bearings in EMB's and rotor dissipations excrete by radiation. Therefore the magnets installed on rotor surface experience high temperature and its variations. Then the adequate PM for this application is samarium-cobalt (Sm-Co).

Ferromagnetic material used in stator and rotor back iron is chosen according their losses at working point and saturation level. Among ferromagnetic materials Iron-cobalt and amorphous iron are candidate. Amorphous iron is chosen because of its lower losses.

Kapton is appropriate for electrical insulation and Litz wires are used for skin effect reduction [5, 8].

B. Proper structure

Kinetic energy stored in a flywheel ($\frac{1}{2}I\omega^2$) is related by inertia and square of angular velocity and inertia($\frac{1}{2}mr^2$) is related by mass and square of flywheel radius then angular velocity and radius have to be as large as possible for volume and mass optimization. Finally proper structure, for spacecraft EMB, is a hollow cylinder with centered, external rotor, electrical machine as shown in Fig. 1. The manner of PM installation on rotor is another important parameter. Surface mounted permanent magnet machines are proper because of higher energy density and lower harmonic production [9]. The final important parameter is the pole number of machine. 2 or 4 pole machines are used for high speed applications to minimize the core losses but torque creation of 4 pole machine is about five times of 2 pole one [5,10,11] and proper pole number for spacecraft EMB is 4.

III. Simplified Parametric Machine Design

Parametric design will be done according Fig.1. Permanent magnet machine design for EMB application consist flowing steps generally [12]:

- Determination of flux density functions in air gap.
- Calculation of current and turn-number according required torque and output voltage.
- Calculation of necessary Iron area according working point remains below the flux density saturation point.
- Calculation of necessary slot space according copper and insulators area and filling factor.

-Determination of outer radius according necessary inertia and kinetic energy.
- Determination of losses.
After solving Poisson's equation for the PM magnetic field [13] in the polar coordinate system, the final solution for the radial air gap field is given by:

$$B_{air1}(r,\theta) = \sum_{n=1}^{\infty} \frac{M_n}{\mu_m} \frac{np}{np^2-1} R_5^{-(np-1)} \times$$
$$\left\{ \frac{(np-1)R_5^{2np} + 2R_6^{(np+1)}R_5^{(np-1)} - (np+1)R_6^{2np}}{\frac{\mu_m+1}{\mu_m}\left[R_4^{2np} - R_6^{2np}\right] - \frac{\mu_m-1}{\mu_m}\left[R_5^{2np} - R_4^{2np}\left(\frac{R_6}{R_5}\right)^{2np}\right]} \right\}$$
$$\times \left[r^{(np-1)} + R_4^{2np} r^{-(np+1)}\right] \cos(np\theta) \qquad (1)$$

Where M_n is magnetic vector and for radially magnetized PM:

$$M_n = 2B_r\alpha_p \frac{\sin\left(\frac{n\pi\alpha_p}{2}\right)}{\left(\frac{n\pi\alpha_p}{2}\right)} \qquad (2)$$

And R_4 is stator outer diameter, R_5 and R_6 are inner and outer radius of PM respectively, p is the number of pole pair andα_p, μ_m, B_r are PM arc to pole pitch ratio, magnet remnant and permeability respectively. Equation (1) is a complex series and deeply depend on PM and air gap width and couldn't be convert to a simple equation.
Using equation (1) in parametric design cause very complex design equations and their solving need too much time. By assuming $\mu_m = 1$, $\mu_r = \infty$ where μ_r is Iron permeability, air gap flux can be rewritten as[12]:

$$B_{air2} = B_r \frac{L_m}{L_m + L_g} = B_r \frac{R_6 - R_5}{R_6 - R_4} \qquad (3)$$

Difference between Amount of equations (1) and (3) for $R_4 = 17mm$, $R_5 = 18mm$,$R_6 = 20mm$, $\alpha_p = 0.66$ is about 5% and acceptable for a simple design procedure. Considering independency of B_{air2} to radius in equation (3), overall torque and phase induced voltage can be determined as follows:

$$T_{pm} = \frac{3}{2}\Psi i \qquad (4)$$

$$E_{PM(phase)} = \Psi\omega \qquad (5)$$

$$\Psi = 2pNB_pK_\alpha ZR_4 \qquad (6)$$

$$K_\alpha = \cos\left(\pi\frac{1-\alpha_p}{2}\right) \qquad (7)$$

Where N, Z, ω are coil turn number, axial length and angular velocity of rotor respectively and K_α is fist harmonic coefficient of magnetic field Fourier series and show the effect of α_p .
According Fig.1 air gap reluctance in front of dent and pole is:

$$\mathcal{R}_t = \frac{N_t(R_6 - R_4)}{\mu_0\pi Z(R_6 + R_4)} \qquad (8)$$

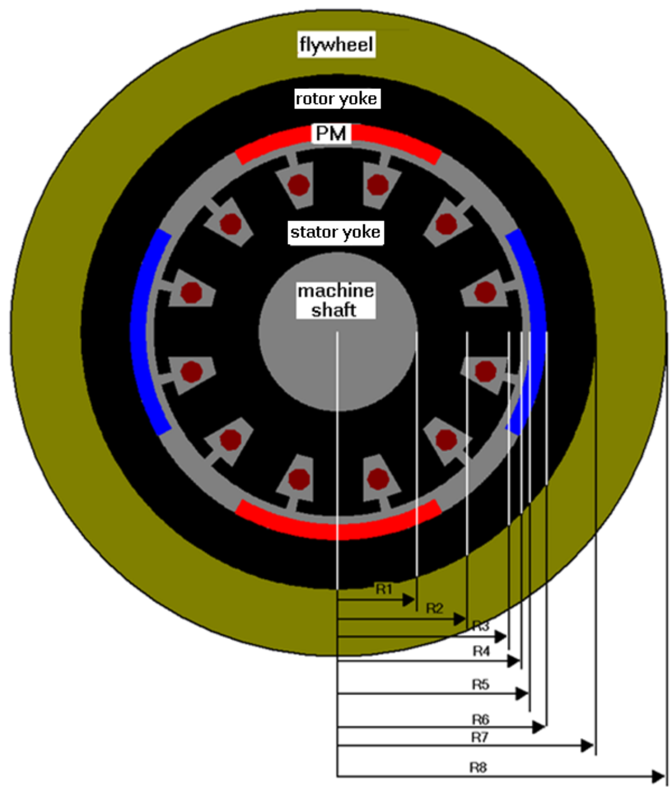

Fig. 1. Electro mechanical Battery under design

$$\mathcal{R}_p = \mathcal{R}_t \frac{2p}{N_t} \qquad (9)$$

So the produced flux by coil and magnet can be calculated as:

$$\varphi_{t(coil)} = \frac{Ni}{\mathcal{R}_t} \qquad (10)$$

$$\varphi_{t(magnet)} = \frac{B_r(R_6 - R_5)}{\mu_0\mathcal{R}_t} \qquad (11)$$

And maximum total flux of each dent determined by:

$$\varphi_{t(total)} = 1.5\varphi_{t(coil)} + \varphi_{t(magnet)} \qquad (12)$$

From working point below flux density saturation width of stator and rotor yoke and dent can be calculated as:

$$W_t = \frac{\varphi_{t(total)}}{ZB_{max}} \qquad (13)$$

$$W_y = \frac{1}{2}\frac{N_t}{2p}W_t\alpha_p \qquad (14)$$

Coil current and turn number can be finding according machine torque and induced voltage (eq. 4 to 6) then the necessary slot space is:

$$A_{cu} = \frac{12pNiK_{cu}}{N_t ff} \qquad (15)$$

Where ff, K_{cu} are filling factor and necessary cupper area for flow one ampere of current respectively. On the other hand according Fig.1 available slot space is:

$$A_s = \frac{\pi(R_3^2 - R_2^2)}{N_t} - W_t(R_3 - R_2) \qquad (16)$$

By equalizing necessary and available space:
$A_s = A_{cu} \Rightarrow$

$$R_3^2 - \frac{N_t W_t}{\pi} R_3 + \frac{N_t W_t}{\pi} R_2 - R_2^2 - \frac{A_{cu} N_t}{\pi} = 0 \quad (17)$$

Where:

$$R_2 = W_t + R_1 \quad (18)$$

By solving equation (17) all machine dimension will be find except outer radius of flywheel. The kinetic energy stored on a hallow cylinder define as [4]:

$$E = Pt = \frac{1}{2} I_{total} (\omega_2^2 - \omega_1^2) \quad (19)$$

$$I_{total} = I_{PM} + I_{Fe} + I_{com}$$
$$= \frac{1}{2} Z\pi[\rho_{PM}(R_6^2 - R_5^2)^2 + \rho_{Fe}(R_7^2 - R_6^2)^2 + \rho_{com}$$
$$+ (R_8^2 - R_7^2)^2] \quad (20)$$

Where ω_1, ω_2 are lower and higher cylinder speed and ρ_{PM}, ρ_{Fe}, ρ_{com} are weight density of PM, rotor back Iron and flywheel composite. By solving equation (21) all machine dimension are calculated.

Wire length of each phase is:

$$l_{phase} = 4pN[(Z + 2e) + \frac{\pi(R_3 + R_2)}{2p}] \quad (21)$$

Where e is axial salient length of coil from stator. The resistance of each phase and total copper loss can be calculated as:

$$R_{phase} = l_{phase}\rho_{cu} = 4pN[(Z + 2e) + \frac{\pi(R_3 + R_2)}{2p}]\rho_{cu} \quad (22)$$

$$P_{cu} = 3R_{phase} i^2 \quad (23)$$

Where ρ_{cu} is special copper resistance. Finally stator mass is determined by:

$$m_{Fe} = Vol_{Fe} D_{Fe} =$$
$$[\pi(R_2^2 - R_1^2) + W_t N_t (R_4 - R_2)] Z D_{Fe} \quad (24)$$

Where D_{Fe} is iron weight density. Iron loss can be defined from factory datasheets. It is noticeable that the flux of rotor back iron is constant and its losses can be ignored.

Design result for given parameters of table (1) are shown in table (2).

IV. Design Confirmation by FEM Simulation

Fig. 2 shows magneto static finite element simulation results by using ANSOFT Maxwell-2D software and confirms analytical design.

Fig. 3 shows parametric magnetostatic simulation in $\omega t = \pi/2$, where phase's currents are $I_a = 2.4$, $I_b = I_c = 1.2$. In the simulation each pole shifted 7.5 degree [14] and $\alpha_p = 0.66$ [15] for cogging torque reduction.

The maximum obtained torque from FEM simulation is 0.0255 and according table I produced torque at 20000rpm is 0.0238 so the error is 6.6%.

TABLE I
GIVEN PARAMETERS FOR MACHINE DESIGN

P	T	N	E_{l-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

TABLE II
DESIGN RESULTS

R_1 (mm)	R_2 (mm)	R_3 (mm)	R_4 (mm)	R_5 (mm)	R_6 (mm)	R_7 (mm)	R_8 (mm)
10	16.1	21.3	22.8	23.8	25.6	32.4	135.7
N	P_{cu}	P_{fe}	Eff.	Machine Mass (Kg)	Overall Mass (Kg)	Machine Volume (cm3)	Overall Volume (cm3)
4.2	0.54	2.79	0.93	0.552	6.24	98.9	3471

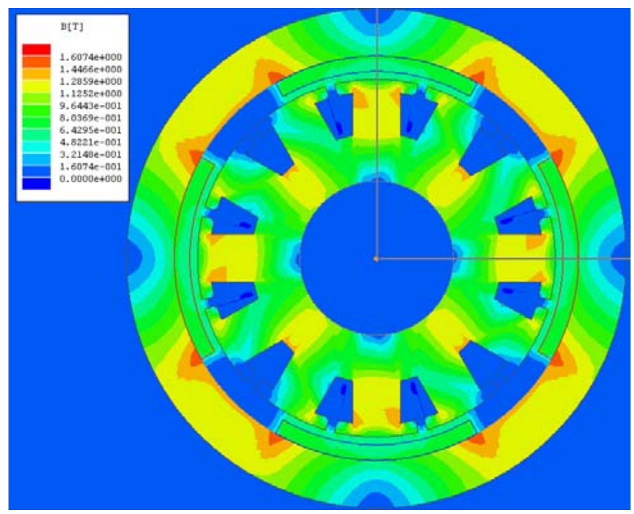

Fig. 2. Magneto-static finite element simulation result of machine

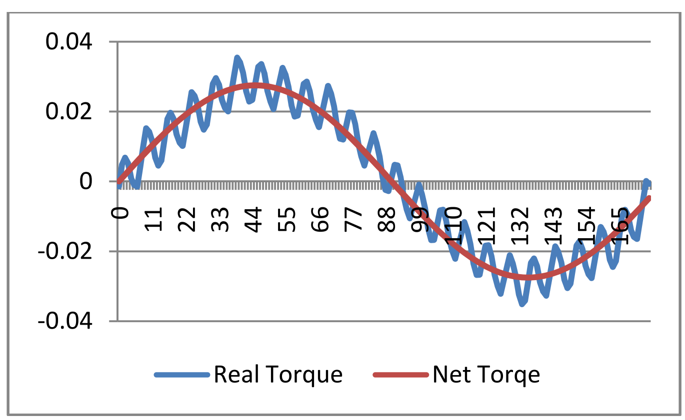

Fig. 3. Magneto-static finite element simulation result of machine

V. CONCLUSION

Simplified Parametric design of external rotor permanent magnet machines used in spacecraft electro-mechanical batteries presented in this paper. The results of parametric design applied to finite element method simulation. The simulation results show less than 7% error that originated from estimations in design process and acceptable for primary design.

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