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Simplified Design and Optimization of Slotless Brushless DC Machine for Micro-Satellites Electro-Mechanical Batteries

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Abstract – Electro-Mechanical Batteries have important advantages compared with chemical batteries, especially in Low Earth Orbit satellites applications. High speed, slotless, external rotor, brushless DC machines are proposed and used in these systems as Motor/Generator. A simplified analytic design method is given for this type of machines and, the optimization of machine in order to have maximum efficiency and minimum volume and weight are given in this paper. Particle swarm optimization (PSO) is used as the optimization algorithm and the finite element-based simulations are used to confirm the design and optimization process and show less than 6% error in parametric design.

Keywords: BLDC, Electromechanical, Energy storage, Flywheel, Optimization, PSO

1. Introduction

Flywheel energy storage systems or Electro-Mechanical Batteries (EMBs) are introduced by Maryland University [1] and NASA [2] in 1970s. Recently, they are most commonly used in Low Earth Orbit (LEO) satellites. Nano/micro satellites are usually included in LEO satellites, which rotate around the earth from some minutes to a few hours. Although the development of chemical batteries technology, the most critical part of these satellites, is their energy storage system, their life is limited by fast charge/discharge rating in such applications [3].

Rotational kinetic energy is stored in a high-speed flywheel in EMBs. The advantages of EMBs are presented in [1-7]. Unlimited charge/discharge cycle as well as the satellite lifetime, higher efficiency, higher energy density, higher discharge depths, thermal independency and their usage in attitude control of satellite can be mentioned as some of these advantages. Instruction for design and optimization of flywheel to achieve lower stress and weight for space applications are presented in [4, 5].

The most important part of an EMB is the electrical machine, which is used as Motor/Generator for energy conversion. Permanent Magnet (PM) machines are mostly used in EMBs because of having high torque to weight ratio, low rotor losses, high efficiency and brushless ness.

In comparison with Synchronous Permanent Magnet machines, brushless DC (BLDC) machines can produce more torque by the same mass and volume [6]. So, BLDC machines are recommended by NASA for space applications [7].

From another point of view, slotless PM machines have some advantages over slotted PM machines. Lower stator losses and no cogging torque can be mentioned as their most important privileges. So, slotless PM machines are suggested for high-speed applications [8-12]. Fig. 1 shows Structure for micro-satellite EMB's. According to this figure the effective air gap in slotless machines includes air gap in addition to copper thickness. The large air-gap causes magnetic flux weakening in this kind of machines. Therefore, in high power machines they would not be the best choice because of non-optimal mass and volume. However, in low power applications in which efficiency is important, like micro-satellite EMBs, the slotless machines are preferred to the slotted ones.

In [13, 14], and [15], some analytical models were presented but they were too complex for the design and optimization process. In this paper, a simple design method will be presented by assuming proper approximation for air-gap magnetic flux density. This approximation causes less than 7% error in the design process but it extremely simplifies the design process.

Results of design and optimization process are validated using Finite Element Method (FEM) simulations to insure low errors. Two-dimensional static and AC simulations are used to achieve this aim. Ansoft Maxwell-2D software is utilized for FEM simulations.

Particle Swarm Optimization (PSO) will be used for the machines' optimization because of its advantages like fast convergence and continuity [16]. Simplified design is given in section II, optimization processes with PSO algorithm are given in sections III. FEM simulations confirm the design and optimization process in section IV and section V is conclusion of the paper.

2. Simplified Design

Analytical design of external rotor, BLDC machine are given here. It will be done based on Fig. 1 for the

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specifications given in Table 1. The simple analytical design proposed here is suitable for optimization. It is simplified using acceptable approximations.

Design process of permanent magnet machines for EMB application can be organized as follows:
- Determination of flux density functions in the air gap.
- Calculation of current and winding turn-number according to the required torque and output voltage.
- Calculation of necessary Iron area to have the working point below the saturation, or optimum flux density point.
- Calculation of necessary copper area based on to the copper and insulators area and filling factor.
- Determination of outer radius according to the necessary inertia and kinetic energy.

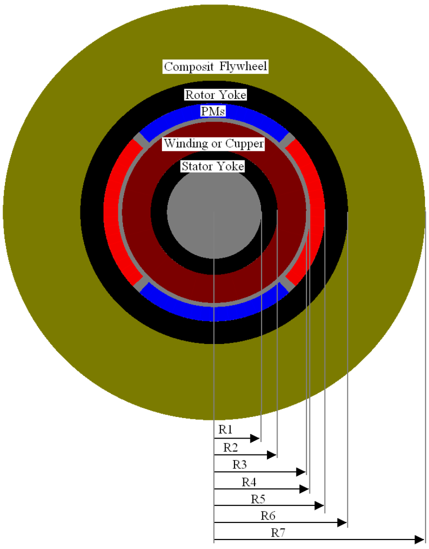


Fig. 1. Structure for micro-satellite EMB's: a hollow cylinder with centered external rotor electrical machine

Table 1. Under design EMB's Parameters

Output Power (Watt)	Charge/ discharge time (sec.)	Min speed ($\min^{-1}$)	Max speed ($\min^{-1}$)	Min line voltage (v)	Max line voltage (v)
40	1800	20000	60000	24	72
Pole number	Filling-factor	air gap (mm)	B_{maxr} (T)	R1 (mm)	
4	0.5	1	1.5	10	

- Determination of efficiency and mass for the optimization.

In the design process, it is assumed that iron permeability is infinite ($\mu_r = \infty$) and PM's permeability is unit ($\mu_m = 1$).

Radial magnetized PMs are used in BLDC machines. Magnetic flux density functions in the air gap are achieved by solving Poisson's equation in the polar coordinate system, which is given for brushless DC machines in [15]. In the mentioned reference, the final equation for magnetic flux density in the air gap, B_{air}, is given by (1).

$$B_{air}(r,\theta) = \frac{(R_5^2 - R_4^2)}{2(R_5^2 - R_2^2)} B_r (\frac{R_2^2}{r^2} + 1)\cos(p\theta) \qquad (1)$$

where R_2 to R_5 are the radii of different parts of machine and are shown in Fig. 1. p is the number of pole-pairs and B_r is PMs' remanent. Eq. (1) is too complex for a simple design, being deeply depended upon PM and air gap thickness and could not be converted into simpler equations. The design and optimization process using such equation will be too complex and time consuming.

On the other hand, in a simple magnetic circuit including an air gap, a permanent magnet with unit permeability and an iron core with infinite permeability, the flux density in air gap, B_{air}, can be calculated as follows [17]:

$$B_{air} = B_r \frac{L_m}{L_m + L_g} = B_r \frac{R_5 - R_4}{R_5 - R_2} \qquad \text{(2-a)}$$

where L_m and L_g are permanent magnet and air gap thickness, respectively. This equation can be rewritten for a p pole-pairs machine as (2).

$$B_{air} = B_r \frac{R_5 - R_4}{R_5 - R_2}\cos(p\theta) \qquad (2)$$

Using Eq. (1), the maximum magnetic flux density in a four pole machine with $R_2=12mm$, $R_4=20mm$, $R_5=24mm$, $r=(R_4+R_2)/2=16mm$, $B_r=1$, $p=2$, is 0.318. However, the maximum magnetic flux density calculated using Eq. (2) is 0.333, which shows 4.5% error, for air gap flux density. FEM simulations will show that the errors of the final design are lower than 6% for this machine and this amount of error is acceptable for a simplified design. So, Eq. (2) is used for the calculation of air gap flux in the analytic design of machine.

The effective air gap in slot less permanent magnet machines is actual air gap plus PM thickness, which is too large in this type of machines. Therefore, the magnetic flux produced by windings is much lower than the flux produced by permanent magnets. Then, the magnetic flux produced by windings can be ignored by a good approximation.

In a p pole-pairs machine, the pole area in front of stator, A_p, can be calculated using (3).

$$A_p = \frac{\pi}{p} R_2 z \qquad (3)$$

where z is the axial length of rotor.

Half of the magnetic flux produced by PMs, ϕ_p , is passed through each branch of stator and rotor yoke. Then, to keep working flux density below the saturation level of stator, the width of stator yoke is calculated by (4) that can be rewritten as (5).

$$\phi_s = \frac{\phi_p}{2} \Rightarrow (R_2 - R_1) z B_{\max} = \frac{1}{2}\frac{\pi}{p} R_2 z B_{air} \quad (4)$$

$$\pi R_2 B_{air} + 2p(R_1 - R_2) B_{\max} = 0 \quad (5)$$

where ϕ_s is the flux passing through each stator yoke leg and ϕ_p is the created flux by each rotor pole. B_{max} is the maximum flux density allowed in the stator core and B_{air} is the flux density of operation point and is obtained using (2). The term (R_2-R_1) refers to the stator yoke thickness.

With the same manner, the thickness of rotor yoke can be calculated using Eq. (6).

$$\pi R_5 B_{air} + 2p(R_5 - R_6) B_{\max-r} = 0 \quad (6)$$

where B_{max-r} is the maximum flux density allowed in rotor yoke and must be kept below the saturation level.

Since Eq. (2) is independent from the radius, the overall torque, T, and phase-induced voltage, E, can be determined by using $F=liB$ and $E=-lVB$ lows as follows:

$$T = 2\Psi i_p \quad (7)$$

$$E = \Psi \omega \quad (8)$$

Where Ψ depends on machine parameters and is calculated using (9).

$$\Psi = 2pNB_{air} z \left(\frac{R_2 + R_3}{2} \right) \quad (9)$$

N, ω and i_p are coil turn number and angular velocity of rotor and peak current of winding, respectively. Coil current and turn number can be found according to the machine torque and the induced voltage (equations 7 and 8) for each machine. In slotless machines, windings distribute by hand and each pole pair consist one coil. Each coil has two sides therefore the number of coils for a three phase machine is 6 and number of weirs is $6\times2\times N\times p$. So, the necessary copper area in a three-phase machine, A_{cu}, is calculated by (10).

$$A_{cu} = \frac{12pNi_p k_{cu}}{\sqrt{2} ff} \quad (10)$$

where k_{cu} is necessary cupper area for one ampere of current (rms) and ff is filling factor which shows the amount of cupper aria filled by pour cupper. It is a coefficient less than 1 that mostly depends on winding discipline.

On the other hand according to Fig. 1, available copper area, A_s, is calculated by (11).

$$A_s = \pi \left(R_3^2 - R_2^2 \right) \quad (11)$$

By equalizing the necessary and available copper area (10 and 11, 12) can be obtained.

$$A_s = A_{cu} \Rightarrow R_3^2 - R_2^2 - \frac{12pNi_p k_{cu}}{\pi\sqrt{2} ff} = 0 \quad (12)$$

Substituting N and i_p from (7) and (8) in (12) and solving (2, 5, 6), and (12) all together, machine dimensions will be found except for the outer radii of flywheel.

The kinetic energy stored on a hollow cylinder can be calculated by using (13) [4].

$$E_n = Pt = \frac{1}{2} I_{total} (\omega_2^2 - \omega_1^2) \quad (13)$$

$$I_{total} = I_{PM} + I_{Fe} + I_{Com} = \frac{1}{2} z\pi [\rho_{PM} \left(R_5^2 - R_4^2 \right)^2 + \rho_{Fe} \left(R_6^2 - R_5^2 \right)^2 + \rho_{Com} \left(R_7^2 - R_6^2 \right)^2] \quad (14)$$

Where En is the energy stored in EMB, P is output power, t is operation time (charge or discharge) of EMB, ω_1, ω_2, are rotor's lower and higher angular speed and ρ_{PM}, ρ_{Fe}, ρ_{Com} are weight density of PMs, rotor back Iron and flywheel composite, respectively. Solving (14) all machines dimensions is determined. Now losses and efficiency can be founded according to machine dimensions. In order to calculate losses, first length of each phase wire, l_{phase}, must be determined by (15).

$$l_{phase} = 2pN \left[(Z + 2e) + \frac{\pi (R_3 + R_2)}{2p} \right] \quad (15)$$

Where e is axial salient length of coil from stator. The resistance of each phase, R_{phase}, and total copper loss, P_{cu}, can be calculated by (16, 17).

$$R_{phase} = l_{phase} \rho_{cu} = 2pN \left[(Z + 2e) + \frac{\pi (R_3 + R_2)}{2p} \right] \rho_{cu} \quad (16)$$

$$P_{cu} = 3R_{phase} i^2 \quad (17)$$

Where ρ_{cu} is special copper resistance.

Iron loss can be achieved from factory datasheets. It is usually given in watt per weight. So, stator mass must be identified for determination of iron loss. It should be noticed that rotor back iron flux is negligible and its losses can be ignored. Stator mass, m_{fe}, can be calculated by (18).

$$m_{Fe} = Vol_{Fe} \rho_{Fe} = \pi (R_2^2 - R_1^2) z \rho_{Fe} \quad (18)$$

Where ρ_{Fe} is iron weight density and Vol_{fe} is stator iron volume.

The iron loss, P_{fe}, can be written as (19) [18].

$$P_{Fe} = m_{Fe} K B_{\max}^{a} F^{b} \tag{19}$$

Where *K*, *a* and *b* can be defined from core material datasheet. Micro-satellite's EMBs work in vacuum. So, wind losses are equal to zero. In the other hand rotor or flywheel is floated by magnetic bearings and the mechanical loss is also zero. Then the efficiency, *Eff*, can be written as (20).

$$Eff = \frac{P_o}{P_o + P_{cu} + P_{Fe}} \tag{20}$$

3. Optimization

In design section, the machine dimensions (R_1 to R_7 and z) are unknown. R_1 deals with heat pipes and inter-connections. So R_1 and L_g are defined base on mechanical constraints. In the other hand the turn numbers of each coil (N) has to be calculated from given parameters. B_{max} is the final unknown parameter that affects the iron loss of machine. If B_{max} is assumed to be small, machine mass increased and if it is chosen close to saturation level the iron loss will be increased. Finally we have nine unknown parameters and six equations in the design process (5 to 8, 12 and 14). So, three of the unknown parameters are remaining free and have to be chosen arbitrary. In ordered, to obtain maximum efficiency and minimum mass, three unknown parameters must be optimized. Particle Swarm Optimization (PSO) is the optimization algorithm that is used in this paper. PSO has the advantage of algorithm simplicity, fast convergence, low probability of local convergence and continuity [19]. Efficiency is the objective function and Z, L_m and B_{max} are variables of optimization. Boundaries of the variables are chosen as below:

$$2mm \le z \le 100mm$$
$$0.5mm \le L_m \le 10mm$$
$$0.7T \le B_{\max} \le 1.5T$$

The behavior of efficiency and weight regard to variation of Lm and Z at constant Bp ($B_p=0.9T$) are illustrated in Figs. 2 and 3.

As Fig. 3 shows, high efficiency can be achieve either low Z with high L_m or high Z with low L_m. However the higher Z with lower L_m leads to higher machine mass. Referring these figures, it can be obtained that higher efficiency can be obtained in the machine mass around 100gr. So, in optimization process, it can be take a penalty factor for optimum tradeoff between mass and efficiency. This factor acts for more than 100gr mass.

Result of optimization and design are given in Table II. In order to show that the unknown parameters are globally optimized, the curve of efficiency in respect to the number of iterations is shown in Fig. 4, for ten different start points.

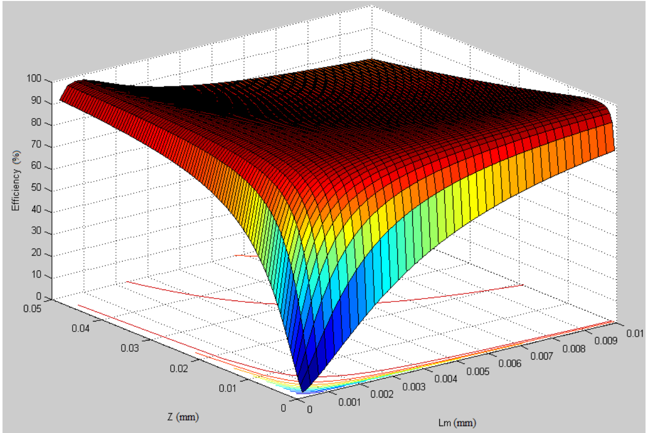


Fig. 2. Behavior of efficiency regard to variation of L_m and Z at constant B_{air} ($B_{air}=0.9T$).

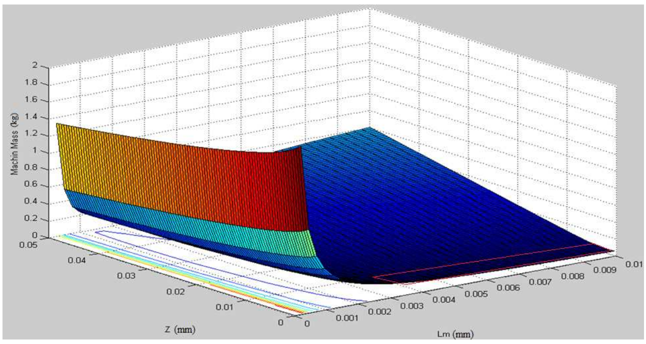


Fig. 3. Behavior of weight regard to variation of Lm and Z at constant B_p ($B_p=0.9T$).

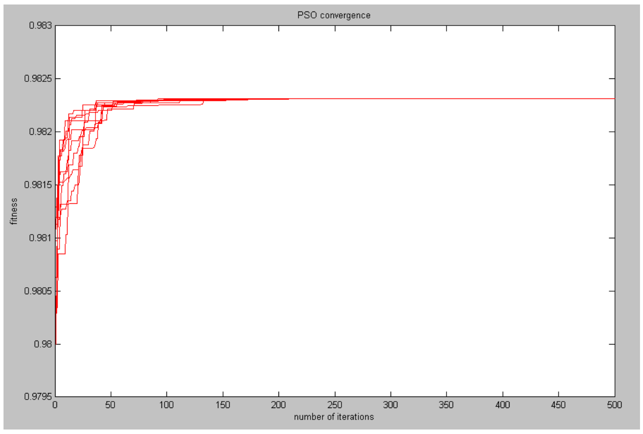


Fig. 4. Optimization results for ten run

Table 2. Optimization and Design Results

Optimization Results				R_2(mm)	R_3(mm)
$B_{(max)}$ (T)	Z (mm)	L_m (mm)	Eff. (%)		
0.9	9.4	3	98.23	13.5	19.6
R_4(mm)	R_5 (mm)	R_6(mm)	N (Coil turn number)		Mass (Kg)
20.6	23.6	28.8	32		0.118

As can be inferred from this figure, it is obvious that all optimizations reach the same point. It should be noticed that the optimized efficiency excludes magnetic bearing and other additional losses. It should be considered that iron losses are related to the frequency and speed. So, the variables are optimized at speed of 40000 min^{-1} for overall efficiency optimization.

4. Design Validation by FEM Simulation

Two-dimensional finite element simulations with ANSOFT Maxwell-2D software were carried out for analytical design validation. Two types of simulation are done for this aim. The first one is the magneto-static simulation which investigates the maximum flux density in the static condition and the second one is the AC simulation that investigates the dynamic performances of machines, like back EMF, dissipations and torque in the nominal speed and frequency. Fig. 5, shows the magnetic flux density distribution resulted by magneto-static simulation of machine with parameters given in Tables I and II. It is clear that the flux density in stator of all three types of machine is less than 0.9 Tesla, achieved in the optimization process. Fig. 6, shows back EMF and produced torque for the machine resulted from AC simulations.

Referring to table I, maximum back EMF of each phase in 40000min^{-1} is 24v and the nominal torque is 9.55 (10^{-3}N.m) in this speed. In Fig. 4 maximum back EMF of each phase resulted by simulation is 24.9v and the nominal torque is 8.98 (10^{-3}N.m) that show 3.7% and 5.9% errors for produced back EMF and Torque respectively. This amount off error can be originated by air gap flux density approximation (Eq. 2) and finite element method simulations.

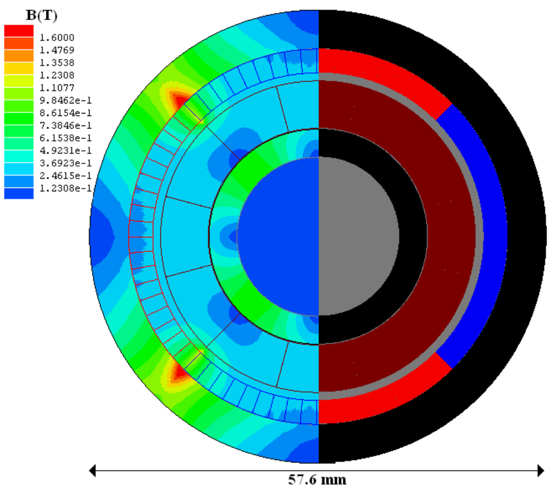
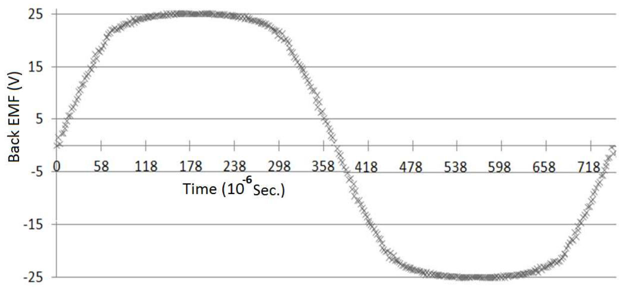
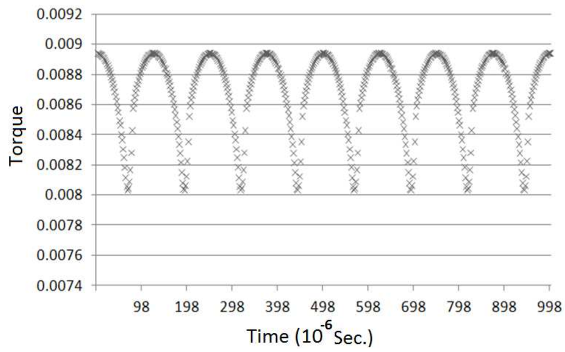


Fig. 5. Magnetic flux density distribution resulted by magneto-static simulation



(a) Generated Back EMF



(b) Created torque

Fig. 6. AC FEM simulations results

5. Conclusion

In this paper, Slot less, external rotor, synchronous permanent magnet machine is designed and optimized. An approximation is used for air gap flux density calculation of the machines for parametric design simplification. The error of this approximation, which simplifies the design process extremely, is less than 6%. Particle swarm optimization was used for optimizing the machine. Static and dynamic finite element simulations were used to validate the design and optimization processes. Simulations confirmed the design accuracy.

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