

Research Article

Optimum Speed Calculation for Electrical Machine Optimization in Variable Speed Applications

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Abstract: Electro-Mechanical Batteries have important advantages compared with chemical batteries, especially in Low Earth Orbit satellites applications. High speed, slot-less, external rotor, permanent magnet machines are used in these systems as Motor/Generator. Commonly, optimizations of electrical machines are done in constant, nominal speed. But Electro-Mechanical Batteries are variable speed system. The efficiency is variable versus time, so, optimization in each single speed cannot necessarily cause the overall efficiency optimization. In this study, iron and copper losses are formulated versus speed variations of rotor. Then, for energy optimization, the optimization speed is achieved by equalizing the average iron loss and copper loss over a period of charge and discharge.

Keywords: Battery, EMB, energy storage, variable speed

INTRODUCTION

Flywheel energy storage systems or Electro-Mechanical Batteries (EMBs) are introduced by Maryland University (Kirk and Studer, 1977; Rodriguez *et al.*, 1983). Although the development of chemical batteries technology, the most critical part of low earth orbit, LEO, satellites is their energy storage system (Lee, 2003). Rotational kinetic energy is stored in a high-speed flywheel in EMBs. 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 are some of EMB's advantages over chemical batteries (Arslan, 2008; Wang, 2003). The most important part of an EMB is the electrical machine, which is used as Motor/Generator for energy conversion (Isastia and Meo, 2009). External rotor, Permanent Magnet machines are used in these systems because of more torque to weight ratio and lower rotor dissipation (Wang, 2003). Slot-less, halbach array permanent magnet machine and synchronous permanent machines are introduced and proposed to be used in EMBs respectively in Abdi *et al.* (2008, 2009) because of their higher amplitude and more sinusoidal air gap magnetic flux, more sinusoidal back EMF, no need to rotor back iron, self-electromagnetic shielding, lower stator losses and no cogging torque (Jang *et al.*, 2004).

In spite of all the previous studies which are focused on the optimization at constant nominal speed, flywheel or rotor speed is a time variable parameter in electro-mechanical batteries.

In such applications, copper loss is higher than iron loss in low speeds. But it is less than iron loss in high speeds. So, the optimization speed has to be determined before optimization process. Optimization speed can be calculate based on function of speed variations versus time in charge and discharge state using copper and iron losses formulations.

Determination of optimization speed for permanent magnet machines in variable speed applications is done in this study. In the presented manner, the energy efficiency of flywheel energy storage system will optimized due to one period of charge and discharge operation.

EMB concepts: Figure 1 shows an EMB. Electrical energy converts to kinetic energy in charge duration and flywheel speeds' increase until maximum allowable speed which determined by mechanical limitations. It is decreased to its primary level, ω_1 , during discharge state. Stored energy on flywheel, E , calculates by Eq. (1) (Abdi *et al.*, 2008):

$$E = \frac{1}{2} I (\omega_2^2 - \omega_1^2) \quad (1)$$

I is flywheel inertia, calculates by Eq. (2):

$$I = \frac{1}{2} m (r_{out}^2 - r_{in}^2) \quad (2)$$

Maximum speed of rotation is kept as high as possible for mass and volume optimization. Usually, the flywheel rotational speed is kept between 20000 and 60000 rpm in satellite application (Wang, 2003).

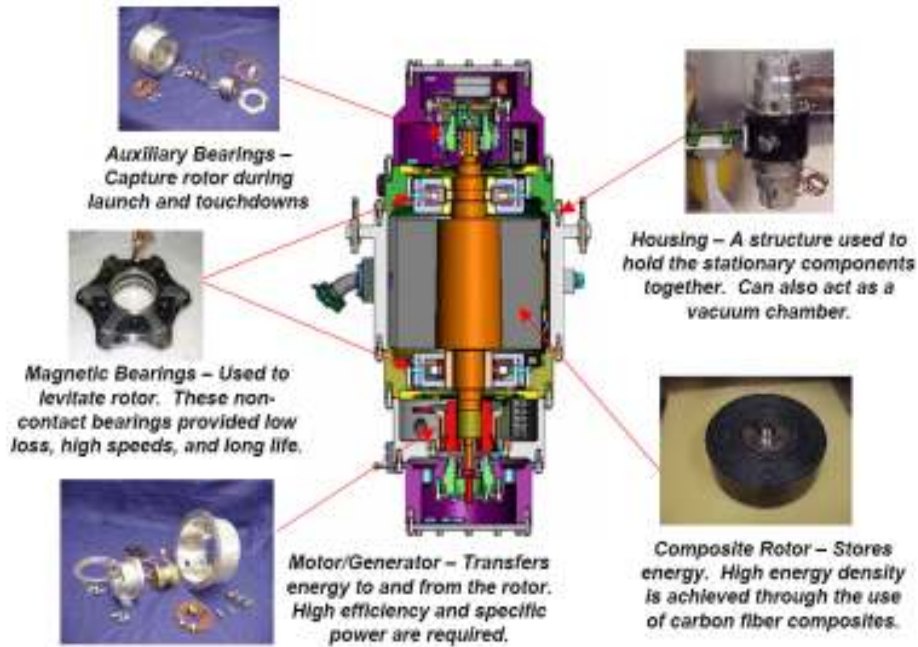


Fig. 1: Elements of an electro-mechanical battery

Table 1: Specifications of case study EMB

T_c , charge duration	T_{dc} , dischar. duration	P, satellite consumption	EMB capacity
60 min.	30 min.	40 W	20 Wh
Min. speed	Max. speed	p, pole number	ff, filing factor
20000 rpm	60000 rpm	4	0.5
R_1	B_{max}	Air gap	
10 mm	1.5T	1 mm	

PROBLEM FORMULATION

A case study LEO satellite, with given parameters in Table 1, is used for calculations of this study.

The output voltage and current of EMB are given in Fig. 2 and 3. In this figures the average power of input, during charge state and output, during discharge state, are taken to be constant, 20 and 40 W, respectively. It is noticeable that in PM machines output voltage is depended to rotor speed. So the rotor, or flywheel, speed and produced voltage are shown in a single figure.

Generally, Maximum Efficiency and minimum weight are target functions of optimization. They have to formulate versus machine dimensions and some other parameters like turn number of each phase, maximum allowed flux density in rotor and stator irons. So, a design process is needed firs, to optimization. Detail of simplified design of external rotor, halbach array permanent magnet machine is given in Abdi *et al.* (2008).

Cross section of a satellite EMB including electrical machine is shown in Fig. 4 and the electrical machine's parameters are given in Table 2.

Losses and efficiency can be founded according to machine dimensions. According (Abdi *et al.*, 2008) and

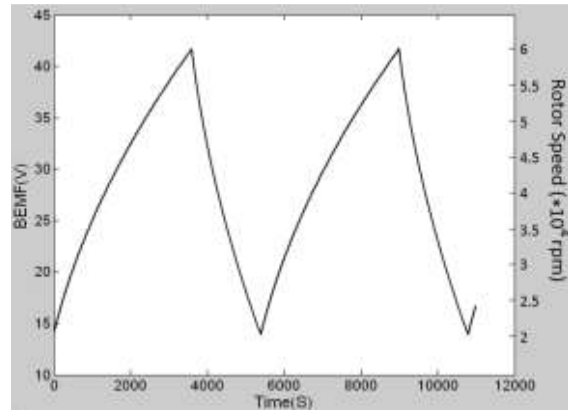


Fig. 2: Rotor speed and phase BEMF versus time

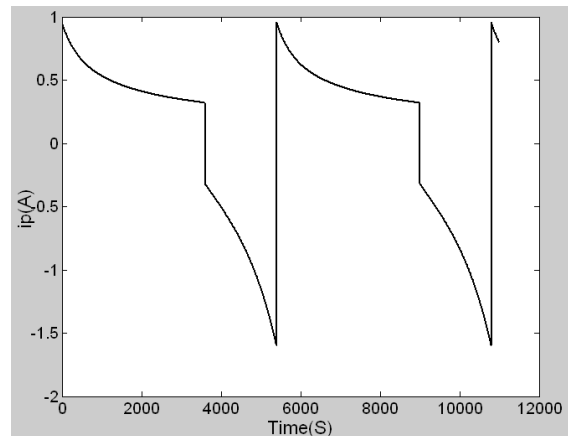


Fig. 3: Output current versus time during charge and discharge states

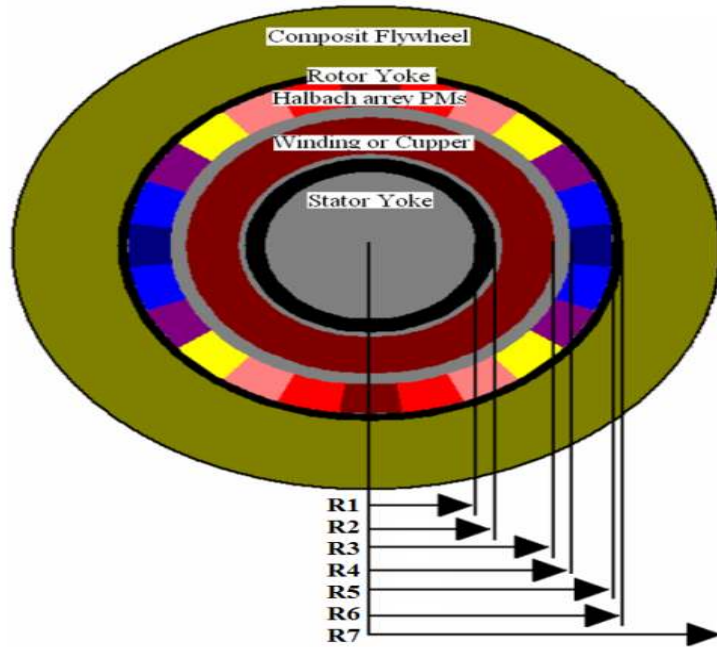


Fig. 4: Structure for micro-satellite EMB's: a hollow cylinder with centered external rotor electrical machine

Table 2: Electrical machine's parameters

$B_{(max)}$ (T)	Z (mm)	L_m (mm)	Eff. (%)	R_2 (mm)
1.5	10	5	95.4	12
R_3 (mm)	R_4 (mm)	R_5 (mm)	R_6 (mm)	N (coil turn number)
17.1	18.1	23.1	24.1	25

Fig. 4 the resistance of each phase and total copper loss can be calculated by (3), (4):

$$R_{phase} = l_{phase} \rho_{cu} = 4pN \left[(z + 2e) + \frac{\pi(R_3 + R_2)}{2p} \right] \rho_{cu} \quad (3)$$

$$P_{cu} = 3R_{phase} i_{rms}^2 \quad (4)$$

Variation of copper loss versus time and speed is shown in Fig. 5. Constant power causes more current during low speed and consequently low voltage.

It makes high power dissipation during low speed which is clear in this figure. Iron loss can be achieved from factory datasheets. It is usually given in watt per weight. It should be noticed that rotor back iron flux is negligible and its losses can be ignored. The iron loss can be calculate as (5) (Hurley *et al.*, 1998):

$$P_{Fe} = m_{Fe} K B_{max}^a F^b = \pi \cdot (R_2^2 - R_1^2) \cdot z \cdot \rho_{Fe} \cdot K \cdot B_{max}^a \cdot F^b \quad (5)$$

where K , a and b can be defined from core material datasheet.

Magnetic Metal's iron based amorphous alloy is considered in this study. According product datasheet (Magnetic Metals, 2001) iron loss can be formulated as:

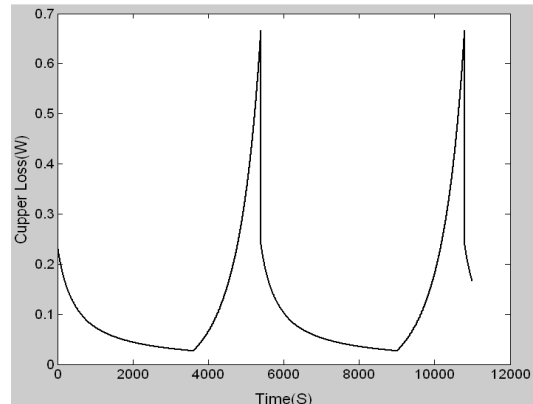


Fig. 5: Variation of copper loss versus time during charge and discharge states

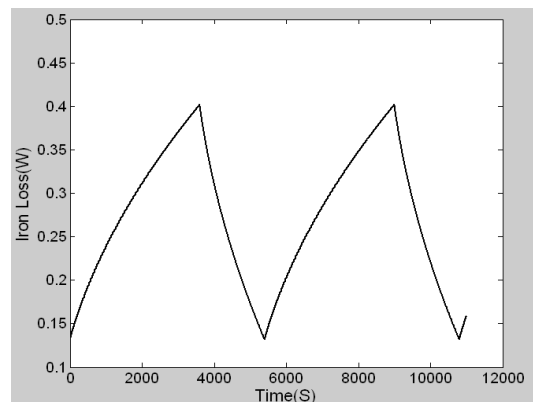


Fig. 6: Variation of iron loss versus time during charge and discharge states

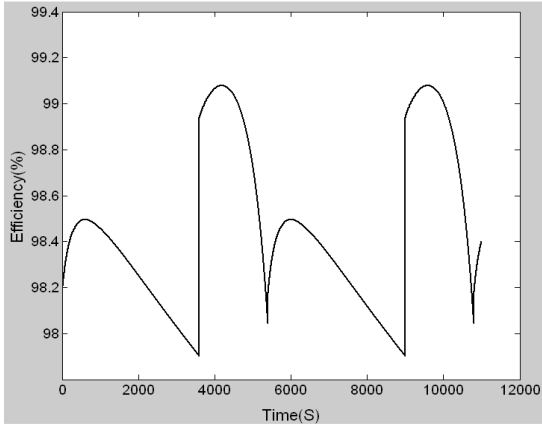


Fig. 7: Variation of efficiency versus time during charge and discharge states

$$P_{Fe} = m_{fe} 0.01 f^{1.015} B^{1.919} \quad (6)$$

Variation for iron loss versus time and, consequently, speed and frequency is demonstrated in Fig. 6.

Micro-satellite's EMBs work in vacuum. It is floated by magnetic bearings. So, there are no wind and friction losses and, the efficiency can be written as (7):

$$Eff = \frac{P_o}{P_o + P_{cu} + P_{Fe}} \quad (7)$$

Figure 7 shows the relation between efficiency and time during charge and discharge states. The necessity of optimization speed is clear in this figure. The efficiency is variable versus time, so, optimization in each single speed cannot necessarily cause the overall efficiency optimization.

CALCULATION OF OPTIMIZATION SPEED

Maximum efficiency of electrical machinery are generally happens when static losses be equal to variable losses. In satellite EMBs there are no mechanical losses including ball bearing and wind losses. In the other hand, both iron and copper losses are variable during variable speed in this application. Therefore, if electrical machinery optimize in each speed, it will be suboptimum in other speeds. So, the optimization has to be done in which speed that energy efficiency is maximum.

To achieve this goal, the average of iron loss has to be equal to average of copper loss over a cycle of satellite rotation (charge and discharge). Therefore iron and copper losses have to be formulated versus time. The optimization speed is determined by equalizing the integration of both losses together over a cycle.

Using Eq. (1), angular rotational speed of flywheel versus time can be determined in charge and discharge states by Eq. (8) and (9), respectively:

$$E = Pt = \frac{1}{2} I(\omega^2 - \omega_1^2) \Rightarrow \omega_c = \sqrt{\frac{2Pt}{I} + \omega_1^2} \quad (8)$$

$$E = Pt = \frac{1}{2} I(\omega_2^2 - \omega^2) \Rightarrow \omega_{dc} = \sqrt{\omega_2^2 - \frac{2Pt}{I}} \quad (9)$$

where, P is input (or output) power and t is time. Momentum of inertia, I , can be determined by Eq. (10):

$$I = \frac{2P.T}{\omega_2^2 - \omega_1^2} \quad (10)$$

Frequency of rotational field of stator in a p pole pair PM machine can be calculated by Eq. (11):

$$f(t) = \frac{\omega}{2\pi} p \quad (11)$$

where, T is period of charge (or discharge). The function of frequency versus time can be achieved by substituting Eq. (8) and (10) in (11) during charge state as well as Eq. (9) and (10) in (11) during discharge state as following:

$$f_c(t) = \frac{p}{2\pi} \sqrt{\frac{\omega_2^2 - \omega_1^2}{T} t + \omega_1^2} \quad (12)$$

$$f_{dc}(t) = \frac{p}{2\pi} \sqrt{\omega_2^2 - \frac{\omega_2^2 - \omega_1^2}{T} t} \quad (13)$$

Finally, the average of iron loss can be achieved by Eq. (12):

$$P_{fe(avg)} = \frac{1}{T} \left\{ \int_0^{T_c} K \left[\frac{p}{2\pi} \sqrt{\frac{\omega_2^2 - \omega_1^2}{T} t + \omega_1^2} \right]^b B_{max}^a m_{fe} dt + \int_{T_c}^{T_c+T_{dc}} K \left[\frac{p}{2\pi} \sqrt{\omega_2^2 - \frac{\omega_2^2 - \omega_1^2}{T} t} \right]^b B_{max}^a m_{fe} dt \right\} \quad (14)$$

where T_c and T_{dc} are charge and discharge durations respectively and T is the total period of satellite rotation, $T_c + T_{dc}$.

Copper loss is determined by Eq. (4). But, BEMF of each phase is variable during speed variation of flywheel or rotor. Continuously, the output current is variable because of constant power and variable voltage. So, the average of copper loss has to be calculated by the same manner for iron loss.

The output power of PM machines can be determined by Eq. (15):

$$P = 3E_{rms} \cdot i_{rms} \quad (15)$$

In PM machines the induced voltage is proportion by the rotor speed by Eq. (16):

$$E_{peak} = \psi \omega \quad (16)$$

Substituting peak induced voltage, i_{rms} can be achieved by Eq. (17):

$$i_{rms} = \frac{\sqrt{2} \cdot P}{3 \Psi \omega} \quad (17)$$

The average of copper loss can be achieved by integration over total period as follow:

$$P_{cu(avg)} = \frac{1}{T} \left\{ \int_0^{T_c} \frac{2 \cdot R_{phase} \cdot P^2}{3 \Psi^2 \cdot \left(\frac{(\omega_2^2 - \omega_1^2)}{T} t + \omega_1^2 \right)} dt + \int_{T_c}^{T_{dc}} \frac{2 \cdot R_{phase} \cdot P^2}{3 \Psi^2 \cdot \left(\omega_2^2 - \frac{(\omega_2^2 - \omega_1^2)}{T} t \right)} dt \right\} \quad (18)$$

By substituting the parameters from Table 1 and 2 and equalizing Eq. (14) and (18), the time of equalization is achieved $t = 1660$ sec. The rotational speed of rotor is determined by Eq. (8), $\omega = 4540$ rad/s and $n = 43355$ rpm. So, the PM machine has to be optimized in this speed for energy optimization of EMB.

CONCLUSION

Electro-Mechanical Batteries have important advantages compared with chemical batteries. Electrical energy converts to kinetic energy in charge duration and flywheel speeds' increase until maximum allowable speed which determined by mechanical limitations and vice versa in discharge state. So, they are variable speed systems. But, usually optimizations of electrical machines are done in constant, nominal speed. In this study, the optimization speed is achieved by equalizing the average iron loss and copper loss over a period of charge and discharge for energy optimization. Iron and copper losses are formulated versus charge and discharge time and speed variations of rotor.

NOMENCLATURE

- e : Axial salient length of coil from stator (v)
- E : Phase-induced voltage or BEMF (v)
- En : Stored energy in rotor or flywheel (J)

- F : Rotational magnetic field frequency (Hz)
- ff : Winding filling factor
- i : Phase rms current (A)
- i_p : Phase peak current (A)
- L_{phase} : Total length of each phase wire (m)
- m_{Fe} : Mass of stator iron (kg)
- P : Output power (W)
- P_{Fe} : Iron losses (W)
- P_{cu} : Copper loss (W)
- ρ_{Fe} : Iron density (kg/m³)
- R_1 : Inner radius of stator (m)
- R_2 : Outer radius of stator (m)
- R_3 : Outer radius of winding (m)
- R_4 : Inner radius of permanent magnets (m)
- R_5 : Outer radius of permanent magnets (m)
- R_6 : Outer radius of rotor yoke (m)
- R_7 : Outer radius of flywheel (m)
- R_{phase} : Each phase resistance (Ω)
- r : Radius in cylindrical system (m)
- r_{in} : Inner radius of flywheel (m)
- r_{out} : Outer radius of flywheel (m)
- t : Charge or discharge time (s)
- ω : Angular rotational speed (rad/s)
- ω_1 : Minimum Angular speed of rotor (rad/s)
- ω_2 : Maximum rotational speed of rotor (rad/s)
- z : Rotor length (m)

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