Design and Control of an Electrical Machine for Flywheel Energy-Storage System

M. I. L. Marques

Abstract

Flywheel energy storage systems are now considered as enabling technology for many applications including space satellite low earth orbits, pulse power transfer, hybrid electric vehicles, and many stationary applications.
The purpose of this study is the development of a flywheel system for possible application in road vehicles. The present paper reports on the design of the flywheel's rotor, the electrical machine and its control.
The flywheel's rotor was designed by calculating its dimensions, weight and material's cost for different energy capacities.
The most appropriate machine was chosen as being the Permanent Magnet Synchronous Machine. The main factors that influence the design of this machine are costs, material limitations, standard specifications and special application factors.
For the machine's control, the sensorless control is desirable instead of using mechanical sensors, in order to reduce total hardware complexity, size, cost and maintenance requirements. The Direct Flux and Torque Control was chosen to control the system for this application.

I. INTRODUCTION

The high price of fossil energy in the beginning of the 21st century increased the demand for new alternatives to power vehicles and other applications.

This was the main driving force for the study and design of a flywheel for possible application in electric vehicles. This energy-storage system could be applied as power peaking, in hybrid vehicles, or as energy storage, in electric vehicles.

A flywheel is a mechanical battery, represented in figure 1, that typically consists of a high speed inertial composite rotor to store kinetic energy, a magnetic bearing support and control system, an electrical machine that can function either as a motor or a generator to make the energy transfer to and from the flywheel, a vacuum support housing and containment, compact heat removal and exchangers, instrumentation monitoring and control, and power electronics for electrical conversion.

Unlike chemical batteries, the design life has no degradation during its entire cycle life. A flywheel can cyclic discharge to zero energy without any degradation whatsoever, unlike the failings of all chemical batteries.

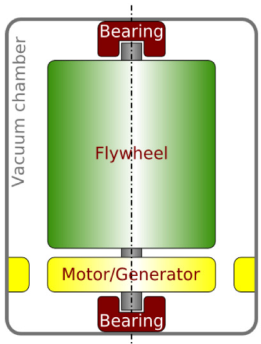

Figure 1. Schematic view of the flywheel's storage system. [2]

II. FLYWHEEL DESIGN PRINCIPLES

There are some factors that influence the design, which are costs, material limitations, standard specifications and special application factors.

The major issues in designing an electric machine may be divided into 5 areas: electrical, magnetic, insulation, thermal and mechanical.

The most efficient way to increase the energy stored in a flywheel is to speed it up. However, there is a problem with this solution: the materials that composes the wheel of that rotating system will limit the speed of the flywheel, due to the stress developed, called tensile strength, σ.

- *Analysis of stress forces:*

The tensile strength of a rotation system is composed by two kinds of forces, the radial and the tangential stresses, respectively σ_r and σ_t [3].

$$\sigma_r = \frac{3+v}{8} \cdot \rho \cdot \omega^2 \cdot \left(r_o^2 + r_i^2 - \frac{r_o^2 \cdot r_i^2}{r^2} - r^2 \right)$$

$$\sigma_t = \frac{3+v}{8} \cdot \rho \cdot \omega^2 \cdot \left(r_o^2 + r_i^2 + \frac{r_o^2 \cdot r_i^2}{r^2} - \frac{1+3 \cdot v}{3+v} \cdot r^2 \right)$$

Where ρ is the mass density, ω is the rotor speed, v is the Poisson ratio (constant of the material, which value is 0.3), r_o is the outer radius and r_i is the inner radius.

The analysis of the stress forces for the generic cylinder is an important factor in the wheel's dimensioning.

- *Outer radius and rotation speed relations:*

Having the approximation, $\frac{\sigma_t}{\rho \cdot \omega^2 \cdot r_o^2} \approx 1$ [1], for a limited σ_t, the outer radius and the rotation speed are related and when the outer radius is chosen, the flywheel speed is limited, as the next graphic expresses:

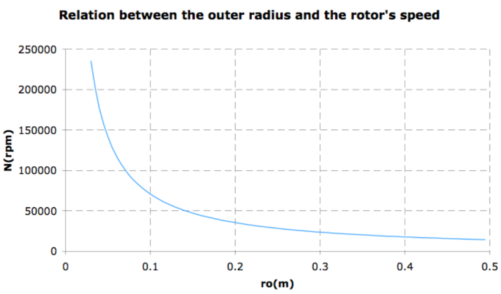

Figure 2. Relation between the outer radius and the rotor's speed, for a carbon composite material. [1]

- *Relation between the energy storage capability and the flywheel geometry:*

A general expression for the maximum energy density, valid for all flywheel shapes, is given on the next equations, obtained from [3]:

$$e_v = K \cdot \sigma$$

$$e_m = \frac{K \cdot \sigma}{\rho}$$

Where e_v and e_m are respectively the kinetic energy per unit volume and per unit mass, K is the shape factor, σ is the maximum stress in the flywheel and ρ is the mass density.

The shape factor K is a constant that represents the cross section geometry of the flywheel and its value is less than 1.

The adopted flywheel geometry was the hollow cylinder, which has a shape factor close to 0.5.

This geometry was chosen due to its simpler manufacture and lower cost, when compared with other geometries.

- *Rotor materials:*

The materials that compose the flywheel's rotor will limit its rotational speed, due to the tensile strength developed. Lighter materials develop lower inertial loads at a given speed therefore composite materials, with low density and high tensile strength, are excellent for storing kinetic energy. Then, the carbon composite materials were chosen for the simulations represented in tables 1 and 2.

- *Flywheel rotor's dimensions, weight and material's cost:*

The next tables show the results as examples, for the design of a flywheel rotor's dimensions, weight and material's cost.

Table 1. Rotor's dimensions for different energy capacities. [1]

E_{lim}	W (rpm)	r_o (m)	r_i (m)	h (m)
2.5 kWh; 9MJ	33613	0.21	0.148	0.42
2.5 kWh; 9MJ	42350	0.167	0.118	0.667
1kWh; 3.6MJ	45620	0.155	0.109	0.31
25 kWh; 90MJ	15602	0.452	0.32	0.905
0.44kWh; 1.58MJ	60000	0.118	0.083	0.235

Table 2. Rotor's volumes, weight and material's price for different energy capacities. [1]

E_{lim}	Occupied volume (m^3)	Material's volume (m^3)	Weight (Kg)	Material's cost ($)
2.5 kWh; 9MJ	0.0582	0.0293	44	1385
2.5 kWh; 9MJ	0.0584	0.0293	44	1385
1kWh; 3.6MJ	0.0234	0.0118	18	558
25 kWh; 90MJ	0.581	0.290	438	13706
0.44kWh; 1.58MJ	0.0103	0.00519	8	245

To calculate the rotor's weight, the density of ρ=1510Kg/m^3 was used, and to calculate the material's cost, the carbon price of 31,3$/Kg was used.

By the analysis of tables 1 and 2, the most interesting results are in the 1st and 2nd lines of the tables. It can be concluded that the energy depends on the gyrating volume and not directly on the rotor's radius and height. As it can be seen, both attempts have a wheel with the same energy capability storage, the same mass and the same price.

Based on the highlighted results in the tables, a flywheel energy-storage system with 5 kWh capacity could be designed for the application on an electric vehicle, having two robust rotors of 2,5 kWh, each one.

The transformation between rotational kinetic energy and electrical energy can be performed with two permanent magnet synchronous motor/generator of 30 kW (40.23 hp) each.

III. Synchronous Machine Analysis and Design

The two major types of machines used in flywheels are the axial-flux and the radial-flux Permanent Magnet Synchronous Machines, shown in figure 3.

The axial machines seems to have more advantages over the radial such as, a planar adjustable air gap and easy cooling arrangements, which is important when working in vacuum.

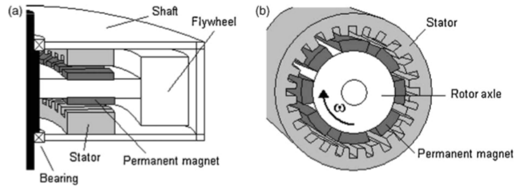

Figure 3. (a) show an AFPM machine arrangement and (b) show an RFPM machine arrangement. [3]

The factors that influence the design are costs, material limitations, standard specifications and special application factors. The major issues in designing the machine, can be divided into 5 areas: electrical, magnetic, insulation, thermal and mechanical designs.

The next equation relates the machine dimensions with its power rating, and is known as the output equation [4]:

$$D^2 \cdot L \cdot N = \frac{5480}{A \cdot B_{gav} \cdot K_w \cdot \cos\theta \cdot \eta} \cdot P_{kW}$$

Where D is the diameter of the stator bore, L is the active length of the core, N is the speed (with the value of 15000 rpm), A is the specific electric loading (with the value of 20000 ampere-conductors per metre), B_{gav} is the specific magnetic loading (with the value of 0.6Wb/m^2), K_w is the winding factor (with the value of 0.966, which corresponds to a 2 slots per pole per phase machine), $\cos\theta$ is the power factor (with the value of 1), η is the machine's efficiency (with the value of 95%) and P_{kW} is the active power (with the value of 30 kW).

- *Calculation of the machine dimensions D and L* [1]:

Using the output equation and an aspect ratio of $\frac{L}{\tau} = 4.00 \Rightarrow L = \frac{\pi \cdot D}{1}$:

D=0.0682m

L=0.2142m

- *Design of the stator winding* [1]:

$conductors/phase = 136$;

Number of stator slots: q=12$slots$;

$conductors/slot = 34$;

Slot pitch: $\lambda = 0.0179m$

Materials like iron and another classic materials don't have the strength to hold high rotation speeds.

The synchronous machine was designed for 15000 rpm, and then, the materials used on the rotating mass, which supports the machine, must have the strength to hold the stresses.

The best option could be to choose the same material that was chosen for the flywheel's rotor (a carbon composite material), which has a high resistance to twist forces.

IV. Synchronous Machine Sensorless Control

A sensorless control, for application at the Permanent Magnet Synchronous Machine designed at the previous section, is desirable instead of using mechanical sensors, in order to reduce total hardware complexity, size, cost and maintenance requirements.

After the control principles and methods were studied, the Direct Flux and Torque Control was chosen as the best and most efficient control system, for the desired application.

V. Conclusions

The current work intended to study and design an electrical machine and its control, for application at a flywheel energy-storage system, for possible application at road vehicles.

The chosen flywheel's rotor material were the carbon based fibers, because they make the rotor less heavy and with the ability to sustain much higher speeds and energy, comparing with iron and other classical materials.

There was made a study of the stress forces variation along the rotor, which permitted to conclude that the tangential stress is more limitative than the radial stress.

The flywheel's rotor dimensions were related with the rotation speed, the cylinder weight and the material's cost. That relation permitted to conclude that a flywheel energy-storage system with 5 kWh capacity could be designed for the application on an electric vehicle, having two robust rotors of 2,5 kWh and 44 Kg, each one. The two rotors material's cost will be around $3000.

The transformation between rotational kinetic energy and electrical energy was performed with two permanent magnet synchronous machine (motor/generator) of 30 kW (40,23 hp) each.

The permanent magnet synchronous machine was chosen due to its efficiency, smaller size and easier control, when compared to direct current machines or induction machines.

For the machine's control, a sensorless control is desirable instead of using mechanical sensors, in order to reduce total hardware complexity, size, cost and maintenance requirements.

Due to its efficiency and simplicity, the Direct Flux and Torque Control, was the chosen technique.

References

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