Design of an Electromechanical Flywheel for purpose of Renewable Energy Storage

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Abstract: The aim of this study is the design of an electromechanical flywheel energy storage system applied to PV system energy storage. A full design of the system constituted by the flywheel, the magnetic bearings and the motor/generator according to the specifications is carried out. A full dimensioning features of the flywheel is performed in such a way that it may restitute energy of 100 Wh, furthermore, dimensioning of a 4 kW powered permanent magnet motor / generator with less core winding stator, is accomplished. Finally, an optimization and a simulation study of full system are explored. Results are rather satisfactory and could promote further applications as perspectives.

Keywords: Renewable Energies, Energy storage, electromechanical accumulator, flywheel, permanent magnet synchronous machine, Hall Bach array, PV systems

1. Introduction

Kinetic energy storage is, nowdays getting more and more interesting for either researchers and/or industrials. One of the several applications of flywheel systems is the renewable energy storage systems. The purpose of our present study is the design of an electromechanical energy accumulator for PV systems storage purposes.

Firstly, a complete design of the flywheel and its motor-generator according to the required specifications is done. The device in its final version is constituted by a glass/epoxy cylinder able to restitute 100 Wh associated to 4 kW permanent magnet synchronous machine.

Secondly, we achieved the dimensioning of a magnetic bearing sustainable flywheel and gave the PV system operating characteristics according to the PVDIMENS software.

Finally, a simulation study with the help of Maxwell and Matlab softwares, is carried out, so to test the performances of the designed device.

2. Design Features of the studied system

Figure 1 shows the principle scheme of the designed device, an electromechanical energy storage system. Composite materials are foreseen to be used because of their aptitude to the present application for which a cylindrical shape is more convenient. The flywheel (rotating part) is a cylinder made of epoxy/glass composite material. The motor is located inside the cylinder. This requires that the motor should be of open core type. We foresee an ironless PM synchronous motor/generator with an inductor magnets disposed as a circular Halbach array which design scheme is shown in figure 3. The rotor permanent magnet and the stator winding have been designed in such a way that the system could restitute the desired energy.

A. The flywheel Study [1], [2], [3]

After of a complete study of the cycle efficiency, the following relations [1], [2] which are necessary for the device dimensioning, are defined.

The massive energy:
\[
\frac{E_u}{M} = \frac{r^2 - 1}{r^2} \frac{\eta_c}{1 + \rho \eta_c} s K R_s \rho
\]

(1)

The volumic energy:
\[
\frac{E_u}{V_{enc}} = \frac{r^2 - 1}{r^2} \frac{\eta_c}{1 + \rho \eta_c} s K R_s R_c
\]

(2)

The velocity ratio \( r = \frac{V_{\text{max}}}{V_{\text{min}}} \) defines the depth of discharge \( \lambda = \frac{E_u}{E_{\text{max}}} \) as the ratio of restituted energy out of the maximum stored energy.

Figure 2. Discharge depth as function of the velocity ratio

We assume a ratio of velocities \( r = 3 \) [3] which allows restricting the maximum of stored energy as shown on figure 2. For this ratio, we calculate a global losses of whole system \( p_s = 20\% \) which needs a motor / generator with an efficiency \( \eta_i \) over than 92\%, the value of this parameter is chosen here to merely 94\%, as well as the self discharge coefficient \( p_s = 6\% \). We also define the shape coefficients respectively of massive energy \( K \) and volumic energy \( K_{\text{enc}} \). For composite materials, these parameters calculation is done according to the anisotropy of resistances \( \beta \), the anisotropy of rigidities \( \lambda \) and the ratio \( \alpha = \frac{R_s}{R} \) of the inner and the outer radii of cylinder. In this study, we are interested on an optimized coefficient \( a_m \) which is a good compromise between the energetic and volumic characteristics. This parameter changes according to the anisotropy of resistances \( \beta \) and the anisotropy of rigidities \( \lambda \). As for the Glass R/epoxy material for which \( \lambda = 2.1 \) and \( \beta = 40 \), we have \( a_m = 0.84 \), \( K = 0.45 \) and \( K_{\text{enc}} = 0.13 \). For the composite materials [2], the influence of fatigue is defined by the fatigue coefficient \( s \). For the Glass R/epoxy, \( s = 0.23 \).

The maximum of velocity on fatigue is given by equ. (3).

\[
V_{\text{max}} = s K \sqrt{\frac{R_c}{\rho}} = 402 \text{ m/s}
\]

(3)

\[
K_\sigma = \frac{3 + \nu}{4} \left( 1 + \frac{1 - \nu}{1 + \nu} \alpha^2 \right)
\]

(4)

where \( K_\sigma = 1/K_\sigma \) and \( \nu = 0.3 \) the coefficient of Poisson.

After an operating cycle simulation, a fatigue mechanical study of the rotating part is done; we determine the dimensions of a 100 Wh flywheel. Table 1 gives the calculated dimensions of the flywheel, such as inner and outer radii and the cylinder height. These dimensions are not the finite ones; they could be revised when working out of the device, taking into account several practical aspects such as vibrations and / or losses...

**TABLE 1. Optimized dimensions of 100 Wh flywheel**

<table>
<thead>
<tr>
<th>R (cm)</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_s (cm)</td>
<td>4.2</td>
<td>8.4</td>
<td>12.6</td>
</tr>
<tr>
<td>H (cm)</td>
<td>116.63</td>
<td>29.16</td>
<td>12.96</td>
</tr>
<tr>
<td>I (kg·m²)</td>
<td>0.012</td>
<td>0.047</td>
<td>0.097</td>
</tr>
<tr>
<td>Ω_{max} (tr/min)</td>
<td>76776</td>
<td>38388</td>
<td>25592</td>
</tr>
<tr>
<td>Ω_{min} (tr/min)</td>
<td>25592</td>
<td>12796</td>
<td>8530</td>
</tr>
</tbody>
</table>

**B. The Motor / Generator (M/G) Design [4]**

Figure-3 shows a 4 kW full pitch windings slot less permanent magnet synchronous machine which maximum torque that could be performed is equal to 2.98 N.m. The permanent magnets are made up of samarium cobalt arranged in circular Hal Bach array [4]. The optimization of the motor / generator was done according to figure 3 in such a way that produces the maximum of torque. The ironless technique we have opted to has considerably reduced its total volume. The stator coil windings must be arranged and oriented so to embrace the maximum of the flux induced by the PM Hal Bach array. The stator axis must be made up of an amagnetic material. The air gap must be optimized to its minimum value allowed by the vibration and the magnetic suspension study.

R: outer radius of flywheel
R_s: inner radius of flywheel
The produced torque $C$ of the machine presented in figure 3, is given by the following formula [2], [4], (equation (5));

$$C = \frac{3}{\sqrt{2}} I J_{eff} \sin \left(\frac{\pi}{3} B \left(\frac{1}{R_{ir}} - \frac{1}{R_{os}}\right) (R_{os}^2 - R_{ir}^2)\right) \quad (5)$$

Where $J_{eff} = 3 \text{ A/mm}^2$ is the density of current.

The geometrical parameters of the machine are given in table-2 and table-3 gives the electrical ones such as the stator winding resistance and inductance and the flux produced by the permanent magnets.

**TABLE 2. Geometrical parameters of the designed machine**

<table>
<thead>
<tr>
<th>$R_{or}$ (mm)</th>
<th>$R_{ir}$ (mm)</th>
<th>$R_{os}$ (mm)</th>
<th>$e$ (mm)</th>
<th>$l$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.4</td>
<td>81.69</td>
<td>80.62</td>
<td>1.07</td>
<td>38.5</td>
</tr>
</tbody>
</table>

**TABLE 3. Electrical parameters of designed machine**

<table>
<thead>
<tr>
<th>$R_s$ (Ω)</th>
<th>$L_s$ (mH)</th>
<th>$\Phi_{max}$ (mWb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>0.08</td>
<td>37.92</td>
</tr>
</tbody>
</table>

3. **Flywheel Magnetic Bearing Design** [7]

The purpose of the present paragraph is the study and design of a magnetic sustentation of the flywheel system studied in the above. This task of study consists in introducing a passive magnetic suspension and an active one in the drive of the flywheel for the advantages which it can bring to the system equilibrium. In the majority of cases, the suspension controls five degrees of freedom and the motorization controls the remaining degree. A magnetic suspension controls these degrees of freedom totally per magnetic interaction. A complete dimensioning study of the magnetic suspension should be made so that the rotor turns without any contact around its axis with a very low level of vibrations.

**Figure 3. Design Scheme of Flywheel Motor / Generator**

Figure 3 shows preliminary design of the magnetic element disposal for the suspension. For radial equilibrium, four annular magnets are disposed as shown at the lateral parts of figure 4. The axial one is ensured by one passive element and an active one as shown in the same figure. We think that the active bearing gives much more stability on correcting the vibrations due to the high speed. We remind hereafter the equilibrium conditions [6]. The suspension must, imperatively, respect these following eight conditions [7] (equ. (6)).

$$\overrightarrow{F}_{ext} = 0 \text{ and } \overrightarrow{M}_{ext} = 0 \text{ and } K_x > 0, K_y > 0, K_z > 0 \text{ and } K_{\theta x} > 0, K_{\theta y} > 0, K_{\theta z} > 0 \quad (6)$$

With

$$\overrightarrow{K} = \begin{pmatrix} \frac{dF_x}{dx} \\ \frac{dF_y}{dx} \\ \frac{dF_z}{dx} \\ \frac{dM_x}{dx} \\ \frac{dM_y}{dx} \\ \frac{dM_z}{dx} \end{pmatrix}$$

$$\overrightarrow{K}' = \begin{pmatrix} \frac{dF_x}{dY} \\ \frac{dF_y}{dY} \\ \frac{dF_z}{dY} \\ \frac{dM_x}{dY} \\ \frac{dM_y}{dY} \\ \frac{dM_z}{dY} \end{pmatrix}$$

(7)

Where $\overrightarrow{F}_{ext}$ and $\overrightarrow{M}_{ext}$ are respectively the resulting external forces and torques.

A. **Permanent magnet bearings (PMB) [5]**

**Figure 4. Design principle scheme of magnetic bearings**

**Figure 5. Principle Scheme of Permanent Magnetic Bearing**
The repulsive type of PMB is used in a stable way which the two pairs of permanent magnetic rings must be aligned to be co-axial accurately (Fig. 5), otherwise we may have undesirables vibrations which would arise from the instability caused by the assembly asymmetry.

**B. Electromagnetic bearing (EMB)** [6]

The well-known Earnshaw Theory tells us that the totally passive bearing is impossible to suspend stably without any active control. The permanent magnetic bearing PMB ensure the restriction of the radial motion in a stable way, whereas, the flywheel will stick to the either side of stationary permanent magnetic bearing without any active control in the axial direction. Therefore, the axial position must be controlled actively by a closed servo loop. The force generated by the electromagnet can be expressed by the following equation (8):

\[
f_{oe} = \frac{\mu_0 S n^2}{4} \frac{i^2}{(x - x_0)^2}
\]

in which, \(S\) is the pole area surface, \(N\) is the number of coil turns, \(x_0\) and \(x\) are respectively the static and incremental gap between magnetic pole and the rotor and \(i\) is the current in the coil winding. This hybrid magnetic bearing system we designed further simplifies the structure of EMB and reduces the power consumption of the whole system (Fig.6).

4. Flywheel Simulation Study and Results

**A. Flywheel Motor – Generator (M/G) Simulation**

Simulation of the M/G permanent magnet Hall Bach array has been performed with the help of specific software such as Maxwell. A sample of simulation is given in figures 7, 8 and 9. We consider respectively the field lines on conventional magnet figure 7, partial Hal Bach array figure 8, and integral Halbach array figure 9. The flux is more important for the two later with Hal Bach arrays than for the former with conventional magnets. It increases with the number of segments per pole figures 8 and 9. The field lines become more and more radial.
Besides, to test its electromechanical performances, the machine was simulated with Mat lab software. A sample of results is given in figures 10 (speed / time) and 11 (torque / time).

Figure 10. Speed of the machine as function of time

Figure 11. Torque of the machine as function of time

Figure 10 and 11 gives a sample of simulation result where the performances such as synchronization speed and torque of the machine are shown. Notice the oscillations either of speed and torque while transitory period. This is only due to numerical problems.

B. Simulation of EMB System

Figure12. Sample of simulation results of PMB system with Maxwell Software

Figure12 presents the field lines in the permanent magnetic bearing for different cases of rotor position. We note a large concentration of flux in the air gap.
Eventually, the magnetic bearings are simulated with Matlab Simulink based on the model shown in fig.6. For our present case, considering that the integral control might arise the accumulated error, we propose a PD controller instead of PID one.

The step response of the magnetic bearing is finally simulated as shown in Figure 13. The first and the second cases (fig.13-a and fig.13-b) show respectively the responses to an entry of reference 0 and to a 1 mm of eccentricity magnitude entry. The rotor practically returns to its previous position in less than 0.4s. For the last case of simulation, the response to a rectangular signal of 5sec. of duration and 1mm of magnitude is shown (fig. 13-c). It can be observed that the rotor always returns back to the desired position in a rather short time (equal merely to 0.4s), as well as, the over taking magnitude does not reach 2% in all cases we have seen.

5. PV System Characteristics

Once, the different elements of the PV chain are defined (from the captor to the supplied load), we have to define the characteristics of each of them. For the purpose of dimensioning we have to consider, in one hand, the energy demand and the solar provided energy, on the other hand the intermediary energy managing. To well approach the adaptability and the feasibility of a flywheel storage system to PV systems, a simulation study has been carried out. Energetic dimensioning was facilitated thanks to a commercial numerical package called PV DIMENS witch is rather simple for utilization; it allows dimensioning of a PV system including a PV generator (PV cell panel), a load regulator and an electromechanical energy storage device, figures 14, 15 and 16 show the power characteristic of the PV block set and its operation when associated to the storage system. Firstly, we have proceeded to a pre-dimensioning with an estimated efficiency value in order to have an approximated value of power.

6. Conclusion

In this paper, a full design of energy storage system of an electromechanical battery is performed. A 100 Wh composite flywheel with an open core and an Hall Bach array permanent magnet synchronous
machine, are retained for the study. To achieve it, the design of a magnetic suspension device is also taken into account. Simulation of the designed system performances with the help of Maxwell and Mat lab software is also carried out. Results are rather satisfactory. The PV system study is taken in charge by PVDIMENS package. Sample of results is grid out, taking into account the specific characteristics of each part of the system.

Flywheels are a good opportunity for energy storage; our present study is a modest contribution to a large one of an electromechanical batteries devoted to be implemented in renewable energy Storage. Applications could be interesting in PV powered installations such as water pumping systems or motorised workshops in isolated sites. Further applications and fulfillment of this study should be carried out in near future.

References