

# THIRD GENERATION OF FLYWHEELS: A PROMISING SUBSTITUTE TO BATTERIES

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**Abstract** – A review of flywheels as energy storage systems is organized in three generations. The performance is compared with that of batteries and other energy storage systems in terms of power and energy density. It is shown that a new generation, using magnetic bearings and high speeds (>60000rpm) can substitute batteries in the near future. A laboratory prototype illustrates the main parts of a 3<sup>rd</sup> Generation flywheel.

**Keywords** - Energy Storage, Flywheels, Batteries, Magnetic Bearings, Superconductors, SMES, Supercapacitors.

## I. INTRODUCTION

Nowadays, an increasing number of industrial processes and commercial applications ask for a continuous and high quality electric energy supply. In the eventual failure of energy or even voltage variations, a backup system must guarantee the power delivery. Usually, during the first seconds or minutes, this requirement has been fulfilled by batteries. A supervisory control coordinates the switch between the energy sources. These systems are called UPS (Uninterruptible Power Supply) or DVR (Dynamic Voltage Restorer) and the market value reaches  $10^{10}$  US\$ per year.

There are political, technical and economical trends to substitute batteries, which are environmental aggressive. Among the alternatives, the most promising [1-2] are:

- flywheels, that store energy in rotating masses,
- supercapacitors, that store energy in electric fields,
- SMES (Superconducting Magnetic Energy Storage), that store energy in magnetic fields.

This paper shows the advantages of flywheels in comparison with the others.

The drawbacks presented by flywheels are gradually overcome [3-4] due to:

- new composite materials based on carbon and fiber glass, that allow tangential speeds of 1km/s,
- vacuum systems, that reduce air friction,
- magnetic bearings, that reduce contact friction,
- power electronics, that allow power conditioning,
- micro electronics, that allow cheap and sophisticated control systems.

The evolution points to a new generation of flywheels, which can integrally substitute batteries. The effort of the Laboratory of Applied Superconductivity LASUP/UFRJ to follow this tendency is also described.

## II. FLYWHEELS' IMPORTANCE

This section presents the comparison between flywheels and several techniques to storage energy.

### A. Energy Density

Energy density means the ratio between the stored energy and the volume or weight of the equipment. For a flywheel, the stored energy is given according to the equation:

$$E_f = \frac{1}{2} \cdot J \cdot \omega^2, \quad (1)$$

where  $\omega$  is the rotating speed of a disk and  $J$  its moment of inertia.

The energy per volume that can be stored is amazing. For instance, a cylinder of radius  $R$ , mass density  $\rho$ , and volume  $V_0$  has inertia:

$$J = \frac{1}{2} \cdot \rho \cdot V_0 \cdot R^2. \quad (2)$$

Using (1) and (2), the stored energy per volume is:

$$\frac{E_f}{V_0} = \frac{1}{4} \cdot \rho \cdot R^2 \cdot \omega^2 = \frac{1}{4} \cdot \rho \cdot v^2, \quad (3)$$

where  $v$  is the tangential velocity. An up to date estimation can be obtained taking  $v=0.9\text{km/s}$  and  $\rho=7000\text{ kg/m}^3$ :

$$\frac{E_f}{V_0} = 1.42 \times 10^9 \text{ J/m}^3. \quad (4)$$

As comparison, a capacitor ( $C$ ), at a voltage ( $V$ ), stores:

$$E_c = \frac{1}{2} C \cdot V^2. \quad (5)$$

The capacitance of parallel plates of area  $A$ , at a distance  $d$ , is given by:

$$C = \frac{\epsilon \cdot A}{d}, \quad (6)$$

where  $\epsilon$  is the permittivity of the dielectric between the plates. Therefore, using (5) and (6) with  $V_0 = A \cdot d$ :

$$\frac{E_c}{V_0} = \frac{1}{2} \cdot \epsilon \cdot \left(\frac{V}{d}\right)^2. \quad (7)$$

$(V/d)$  is the breakdown strength of the dielectric. A good value is 200 MV/m. Considering  $\epsilon = 8.85 \times 10^{-11}$  F/m, ten times the permittivity of free space, the stored energy per volume is:

$$\frac{E_c}{V_0} = 1.76 \times 10^6 \text{ J/m}^3. \quad (8)$$

Manuscript received on 16/01/2008. Revised on 07/05/2008 and 09/07/2008.  
Accepted by recommendation of the Editor Fernando L. M. Antunes.

Nowadays, supercapacitors, made of a porous structure that awards very large contact areas and extremely thin layers, can present values 40 times higher [5], reaching

$$\frac{E_c}{V_0} = 0.7 \times 10^8 \text{ J/m}^3. \quad (9)$$

Nevertheless, this is one order of magnitude lower than that of flywheels.

On the other hand, the energy stored in magnetic fields per volume is given by:

$$\frac{E_m}{V_0} = \frac{1}{2} \cdot B \cdot H = \frac{B^2}{2 \cdot \mu}, \quad (10)$$

where  $\mu$  is the material permeability.

For ferromagnetic circuits, usual values of  $B$  are 1T and  $\mu = 4\pi \times 10^{-4}$  H/m, thousand times the value of free space. This gives:

$$\frac{E_m}{V_0} = 0.40 \times 10^3 \text{ J/m}^3. \quad (11)$$

Using SMES devices [6], this value can be improved. In extreme cases, fields of 3.3 T can be obtained in free space, which would lead to:

$$\frac{E_m}{V_0} = 0.40 \times 10^7 \text{ J/m}^3. \quad (12)$$

Again, it is much lower than that of flywheels.

Large amounts of energy are stored in water dams.

$$\frac{E_w}{V_0} = \rho \cdot g \cdot h, \quad (13)$$

where  $g$  is the acceleration of gravity and  $h$  the reservoir height. With  $\rho = 10^3$  kg/m<sup>3</sup> and  $g = 10$  m/s<sup>2</sup>, equation (13) shows that heights as large as 10<sup>5</sup> m (100 km!) would be necessary to reach values comparable to that of flywheels.

The calculations presented above are summarized in Table I and explains the interest of the scientific community to investigate the storage of energy in rotating masses.

**TABLE I**  
**Order of magnitude of the Stored Energy/Volume**

Energy storage type	Energy density expression	Order of magnitude (J/m <sup>3</sup> )
Flywheel	$\frac{1}{4} \rho v^2$	10 <sup>9</sup>
Supercapacitor	$\frac{1}{2} \epsilon (V/d)^2$	10 <sup>8</sup>
SMES	$B^2 / (2\mu)$	10 <sup>7</sup>
Water Dam	$\rho g h$	10 <sup>6</sup>

For batteries, the energy stored depends on the materials employed and there is no simple deduction for the energy density. Typical values of energy density of representative types of batteries are shown in TABLE II. All batteries present the same energy density order of magnitude (10<sup>9</sup>) in J/m<sup>3</sup>, the value obtained for flywheels.

### B. Power Density

Besides the energy density, the power density characterizes the energy storage technology. Power gives the rate at which energy can be transferred. It depends not only on the power rating of the conversion unit, but also on the

**TABLE II**  
**Energy Density of Different Types of Batteries\***

	J/m <sup>3</sup>	J/kg	Wh/kg
Lead-Acid	0.36 x 10 <sup>9</sup>	0.15 x 10 <sup>6</sup>	41
Nickel Cadmium	0.50 x 10 <sup>9</sup>	0.14 x 10 <sup>6</sup>	39
NiMH	1.08 x 10 <sup>9</sup>	0.34 x 10 <sup>6</sup>	95
Alkaline	1.15 x 10 <sup>9</sup>	0.40 x 10 <sup>6</sup>	110
Lithium-ion	0.83 x 10 <sup>9</sup>	0.46 x 10 <sup>6</sup>	128

\*<http://www.allaboutbatteries.com>

response rate of the storage device. In this respect, direct storage devices, where energy is already stored in electrical (supercapacitors) or magnetic form (SMES), have higher response rates in comparison with indirect storage devices, where an intermediate medium is necessary, for instance chemical (batteries) or mechanical (flywheels, water dam) [7]. Figure 1 presents a qualitative view of Power Density x Energy Density of the considered storage devices.

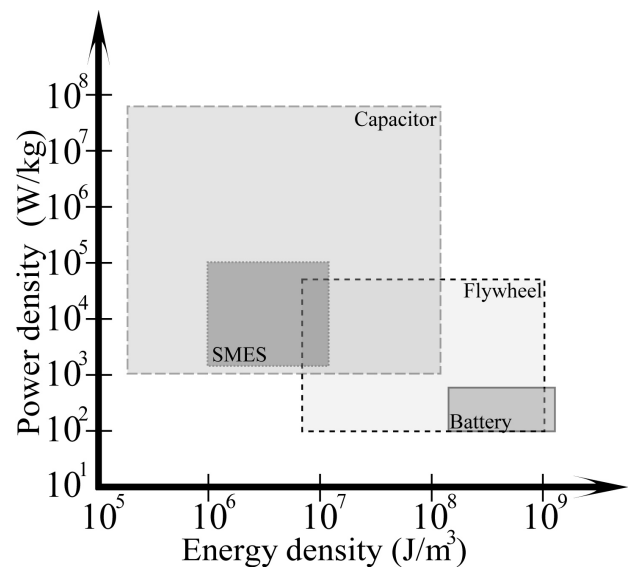


Fig. 1 Power Density x Energy Density.

As can be concluded, there exists an overlapping area between flywheels and batteries regarding power and energy densities. Other aspects will be considered in the next section.

### III. STATE OF THE ART

The idea of using rotating masses to avoid velocity variations of motors and generators is an old one. It is based on the fact that energy does not change abruptly with the application of limited forces. This kind of flywheel can be classified as the 1<sup>st</sup> Generation and the objective is just to maintain a fixed rotational speed with low variations.

With the introduction of power electronics rectifier and inverter circuits and control methods, it was possible to generate a fixed voltage and frequency from a flywheel at different speeds. Figure 2 illustrates this 2<sup>nd</sup> Generation of flywheels. The energy flow, indicated by arrows, can also be reversed to charge the flywheel. The rotating mass can now vary its speed and even so the rectifier/inverter circuit is able to produce a fixed frequency and voltage. The objective is to store energy to fill up grid failures. This application is known as FESS (Flywheel Energy Storage System).

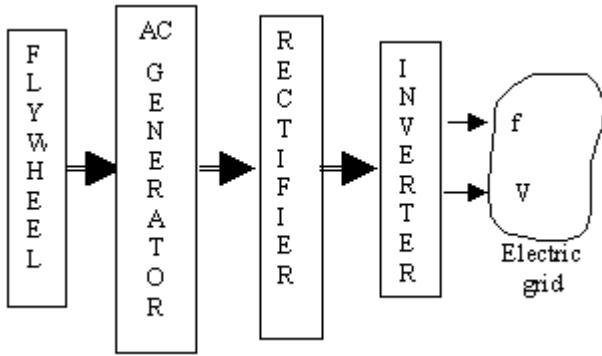


Fig. 2. Flywheels at the 2<sup>nd</sup> Generation.

An initial comparison of this system with BESS (Battery Energy Storage System) is depicted in Table III [6].

Losses during the energy conversion process refer to the transformation from chemical to electrical energy for BESS and from mechanical to electrical for FESS.

Idle losses are mainly due to leakage currents, in the case of batteries, and friction and eddy currents, in the case of flywheels.

The ratio between recharging and discharging time is important when considering operational cycles.

The life cycle gives the expectation of use and 5 years is the best valuation for BESS.

**TABLE III**  
**BESS x FESS**

	BESS	FESS
Energy conversion losses	Chemical → Electrical ~35%	Mechanical → Electrical ~10%
Idle losses	0.05%	1 to 3 %
Recharging / Discharging time	15 to 50	2.5 to 90
Life cycle	5 years	25 years

This table shows that FESS's are advantageous in case of frequent use, since the higher idle losses are compensated for with the higher energy conversion efficiency. Moreover, the recharge of flywheels can be quicker than that of batteries.

Table IV shows a comparison between commercially available FESS and BESS highlighting the power and energy density. The differential advantage of FESS lies in its power density and that of BESS in its energy density. In other words, FESS application niche is for energy quality, when the requirement is of short duration (~10 seconds), whereas BESS are appropriate for power failure of longer duration.

Table V clarifies this point showing the values of a flywheel for 2 hours. In this case, both power and energy density present no advantage in comparison with batteries.

**TABLE IV**  
**Power and Energy Density of BESS and FESS**

Producer	Available Energy (kWh)	Available Power (kW)	Duration (seconds)	Energy density (Wh/kg)	Power density (W/kg)
Acumetrics <sup>a</sup>	0.4	140	10	1	340
Active Power <sup>b</sup>	0.8	240	12.5	0.7	190
Trinity Flywheel <sup>c</sup>	0.4	100	15	3	730
Optimal Energy Systems <sup>d</sup>	33.7		45	5	
Lead-Acid batteries	-	-	-	41	150

<sup>a</sup><http://www.acumetrics.com>

<sup>b</sup><http://www.activepower.com>

<sup>c</sup><http://www.afstrinity.com>

<sup>d</sup><http://www.optimalenergysystems.com>

**TABLE V**  
**FESS for long periods or time**

Producer	Available Energy (kWh)	Available Power (kW)	Duration (seconds)	Energy density (Wh/kg)	Power density (W/kg)
Beacon Power <sup>d</sup>	2	1	7200	5.5	2.8

<sup>d</sup><http://www.beaconpower.com>

**TABLE VI**  
**BESS x FESS of the 3<sup>rd</sup> Generation**

Producer	Available Energy (kWh)	Available Power (kW)	Duration (seconds)	Energy density (Wh/kg)	Power density (W/kg)
Boeing	8.3	100	300	56	670
Lead-Acid batteries	-	-	-	41	150

#### IV. FUTURE PERSPECTIVES: THE 3<sup>RD</sup> GENERATION

The limits imposed to flywheels can be overcome by increasing the rotating speed. As the stored energy depends on the velocity squared (Equation 1), gains in velocity advantageously increase the energy without compromising the weight (mass).

High speeds (~60000rpm) are possible with rotating masses of composite materials of high strength, like carbon or glass fiber, vacuum chambers and magnetic bearings to avoid friction losses [6,8,9]. Research groups all over the world pursue this goal, including the Laboratory of Applied Superconductivity/UFRJ. Some results are presented in [10]. Figure 3 presents a photograph of the laboratory prototype.

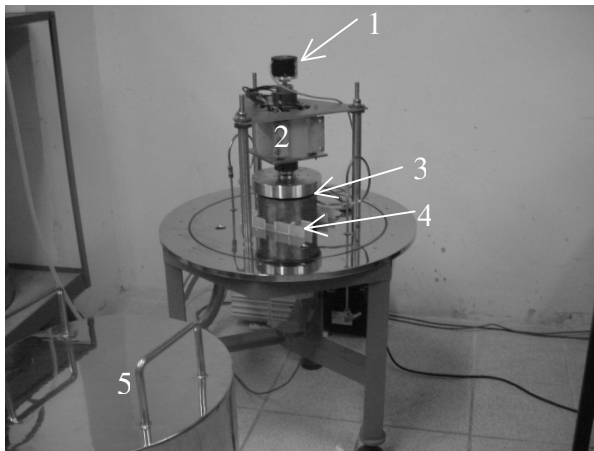


Fig. 3. Flywheel prototype photograph showing: the encoder(1), SR drive(2), flywheel and SMB rotor(3), SMB stator(4) and vacuum chamber enclosure(5).

Its main components are an axial Superconducting Magnetic Bearing (SMB), a Switched Reluctance (SR) drive, which operates as motor/generator, a Vacuum Chamber, a Liquid Nitrogen (LN<sub>2</sub>) feeder and a rotating mass (the SMB rotor plus the SR rotor). The encoder is necessary for the drive control. The power electronic rectifier/inverter circuits are not shown. The control is embedded in a DSP development system.

More details can be seen in Figure 4. This drawing shows the radial positioning given by Permanent Magnet Bearings (PMB), the Superconducting Magnetic Thrust Bearing (SMB) and the power electronics circuits that control the motor/generator and make the connection to the grid. The SMB is an assembly of Nd-Fe-B magnets and superconducting blocks of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-y</sub> (YBCO), which are cooled with liquid nitrogen.

Recently, Boeing announced its brand new flywheel [11] also based on superconductor bearings, which data are compared with BESS in Table VI. Energy and power density of this 3<sup>rd</sup> Generation of flywheels are both higher than that of Lead-Acid batteries.

It is illustrative to compare the energy density of this flywheel (56Wh/kg) with the estimation presented in Eq.(4). From (3), the ratio Stored Energy/Mass is simply  $\frac{1}{4} v^2$ . For  $v=0.9\text{km/s}$  and remembering that  $3600 \text{ J} = 3600 \text{ Ws} = 1 \text{ Wh}$ , it follows:

$$\frac{E_f}{\rho \cdot V_0} = \frac{1}{4} v^2 = 56 \text{ Wh/kg}, \quad (14)$$

which is exactly the same value.

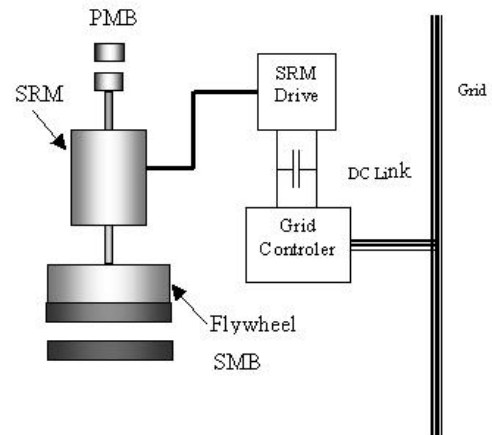


Fig. 4. Flywheel drawing showing the connection of the flywheel mechanical system with the switched reluctance drive, the grid controller and the grid.

Since the pioneer work of Alessandro Volta in 1800, an improvement of batteries have been observed, parallel to the described development of flywheels. The Lead Acid batteries, developed at the second half of the XIX century, continue to be the cheapest one. The Nickel Cadmium cell dates the threshold XIX-XX century and the Alkaline batteries are from the middle of last century. New kinds of batteries like Lithium-ion with energy density as high as 128 Wh/kg and power density of 720 W/kg are still better than the 3<sup>rd</sup> generation numbers presented above (see Table II).

Nevertheless, considering that the life cycle of FESS is at least five times greater than the lifetime cycle of BESS, the higher initial costs of FESS can be diluted along the years. Moreover, the prices of the 3<sup>rd</sup> Generation of flywheels tend to decrease with the production growth and technological improvements and a promising substitute to batteries can be foreseen.

#### V. SMB: THE 3<sup>RD</sup> GENERATION PILLAR

The development of new FESS depends strongly on the bearing used in the system. The application of active magnetic bearing in high-speed rotors is well known in the literature [12], but the use of SMB for FESS is still under investigation [13-14]. The advantages of SMB are:

- no need of control systems,
- relatively high magnetic pressure,
- very-low energy losses during operation (no contact),
- low maintenance cost.

The superconductors used in the SMB are based on YBCO blocks and need to be cooled below 92K. This can be done with the cheap Liquid Nitrogen. Due to the high non-linearity involved in the superconductor levitation, the investigation of better topologies for superconductor bearings has been extensively researched by our group [15-16]. The

main goal and top contribution of these works are the increase of levitation force and stiffness.

A rotating SMB may be a thrust (axial) or a journal (radial) bearing. Both of them have influence on the axial and radial directions. There are three principal topologies that can be used in the SMB bearings: Flux Shaper (FS), Axially Magnetized Ring (AMR) and Halbach array. The SMB is composed of a magnetic rotor and YBCO superconductors in the stator. Figure 5 shows a cut view comparing three magnetic rotors topologies of thrust bearing and the respective flux lines. The Halbach configuration may present higher levitation force than the other configurations [15], but it is extremely hard to be built. In the authors' opinion, the increase in the levitation force does not compensate for the work necessary to construct this rotor.

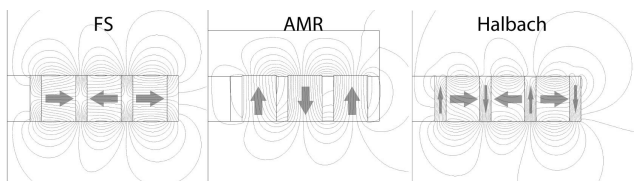


Fig. 5. Three topologies of magnetic rotors for thrust SMB.

One FS and two AMR prototypes of rotating SMB with ~75mm of diameter were developed, and the magnetic rotors are presented in Figure 6. The stator base is composed of an YBCO disk having 75mm in diameter and thickness of 16mm.

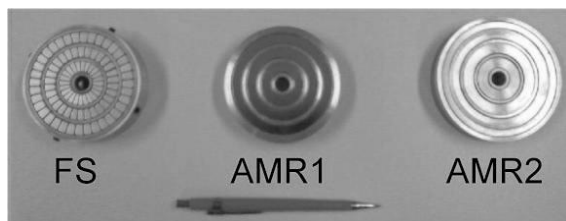


Fig. 6. Magnetic rotors built for tests.

The levitation force measurement of the prototypes shown above, for refrigeration in the absence of the rotor magnetic field, is shown in Figure 7. Masses up to 25kg can be levitated above a circle having just 75mm of diameter. This result illustrates a magnetic pressure of up to 60kPa presented by the SMB, without friction loss, independently of the angular velocity.

Experimental results of energy transfer with this prototype are reported elsewhere [10] and [18].

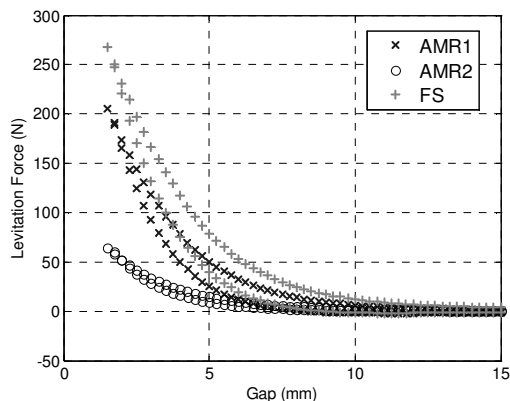


Fig. 7. Levitation force measurements of SMB prototypes.

## VI. CONCLUSION

A 3<sup>rd</sup> Generation of flywheels is on the verge of applications. New materials allow speeds of the order of 60000 rpm. Magnetic bearings based on superconductors or active feedback loops can be implemented. The stored energy and the power capacity are comparable to that offered by traditional lead-acid batteries.

This 3<sup>rd</sup> Generation breaks old technological concepts, offering to developing countries an opportunity to jump engineering gaps.

This paper highlighted the advantages of flywheels and illustrated the main components of the 3<sup>rd</sup> Generation with the help of a laboratory prototype.

## ACKNOWLEDGEMENT

To CNPq and FAPERJ for the financial support. To A.C.Ferreira, L.G.B.Rolim, J.L.da Silva Neto, W.Suemitsu, R.Nicolosky and O.J.Machado for their contribution to the LASUP/FESS Project.

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