Abstract — This paper presents a flywheel energy storage system, which uses a switched reluctance motor/generator. It is shown how this device can be used either together with a DVR or alone in order to attenuate the effects of voltage sags and short interruptions. In order to improve the system efficiency, some design alternatives are presented. Finite elements analyses results, validated against laboratory measurements, indicate the advantages of a suitable choice of ferromagnetic material. The implementation of the control system was simulated with a commercial program. The energy loss, due friction, will be reduced using a superconducting magnetic bearing.

I. INTRODUCTION

The current energy scenario in Brazil is calling for a global effort towards a more efficient use of electrical energy, as well as for a global improvement in the quality of its delivery. However, as budgets are limited, an acceptable alternative is the offering of different levels of supply quality, according to the concept of Custom Power, proposed by Hingorani in [1]. For the practical implementation of this concept, several types of equipment can be used, as described in [2]. Some of these equipments may employ some sort of energy storage device such as batteries or flywheels [3].

The above reasons have motivated the launch of a joint project between the Federal University of Rio de Janeiro (UFRJ) and a local energy distribution company, concerning the development of a flywheel-based energy storage device for custom power equipments. Two major potential applications are under consideration for further development: the compensation of voltage sags and a short-term uninterruptible power supply, to provide ride-through capability to critical loads under momentary fault conditions.

In the case of voltage sag compensation, the most appropriate configuration would be the series connection, between the bus that must have a controlled voltage and the rest of the system. Devices that operate according to this principle are being currently commercialized under the trademark Dynamic Voltage Restorer (DVR) [4]. In a DVR without energy storage, the active power that is required for voltage control must be taken in real time from the same grid where the device is connected. Some authors propose the use of a diode rectifier feeding a filter capacitor in a voltage dc link to solve this problem. However, this solution can lead to situations of voltage collapse, because more energy is drawn from the system, at the same instant and just from the point where the voltage sag occurs. With a flywheel energy storage system these situations can be avoided, because energy can be drawn from the grid in a smooth way during periods of light system loading, causing minimum voltage drop while the flywheel is accelerated.

One significant aspect of the energy storage device is concerned to the electromechanical energy conversion between the flywheel and the electrical system to which it is connected. In this regard, it can be very advantageous if one and the same electrical machine is used not only to accelerate the flywheel when it is absorbing energy from the grid, but also for returning energy to the grid when the flywheel should operate as a generator. In such a high-speed flywheel system, the mechanical and magnetic stresses imposed to the driving electrical machine are very high. For these reasons, the switched reluctance machine (SRM) can be pointed out as a good potential candidate for the intended application. There are several references in the literature [5-7] describing the application of SRMs as a reversible starter/generators for direct coupling to the shaft of aircraft engines. The main requirements for this kind of application are:

- Operation at very wide speed ranges from zero up to several ten thousand rpm;
- Fault tolerance, in order to achieve a high reliability.

Both requirements can be fulfilled by the SRM and are also necessary for applications in high-speed flywheel energy storage systems.

The aim of this paper is twofold. First a flywheel energy storage system will be presented using a SRM based motor-generator. Then it will be shown how the system performance can be improved with reduction of the core losses and using a superconducting magnetic bearing.

II. SWITCHED RELUCTANCE MACHINE

The operation of a switched reluctance machine (SRM) is based on the principle of minimal reluctance. When the coil of some phase is excited, forces are developed over the magnetic material. The current through the energized coil, at this position is maximum, as seen from the energized coil. At this position coil inductance reaches a maximum. If this phase is switched off and the next phase is switched on slightly before this position is reached, continuous movement of the rotor can be achieved. Figure 1 shows cutways view of an SRM with six stator poles and four rotor poles (6/4 configuration), and figure 2 shows the reference frame which has been used throughout this work.

Symmetry of the magnetic circuit allows for nearly null mutual flux linkage, even under saturated conditions. As a result, the contribution of each phase for torque production is mainly defined by the self-inductance profile of that
phase. Figure 3 shows a family of inductance profile curves for one phase, which have been calculated as a function of rotor position for different values of phase current. The calculations have been carried out with the ANSYS® package, which uses the finite element method (FEM). The electromagnetic torque produced by one single coil is given by equation (1), where $T_e$ is the torque, $\theta_r$ is the rotor angular position, $\lambda$ is the total flux linked to the coil and $i$ is the coil current.

$$T_e(\dot{\theta}_r, i) = \frac{\partial}{\partial \theta_r} \left[ \int_0^i \dot{\theta}(\dot{\theta}_r, i) di \right]$$

(1)

A. DYNAMIC MODELING OF THE SRM

Both relationships $T_e(\theta_r, i)$ and $\lambda(\theta_r, i)$ are strongly non-linear, a fact that makes it difficult to develop an analytical mathematical model for the SRM. Thus instead of trying to obtain such an analytical model, the methodology adopted in this work was to use tabulated data for $T_e(\theta_r, i)$ and $\lambda(\theta_r, i)$, which may have been obtained off-line by means of static measurements or FEM computations, over a range of values wide enough to cover any situation that may occur within given simulation limits. The tabulated data is then used directly in the solution of the electrical and mechanical dynamic equations (2) and (3), doing online linear interpolation to obtain intermediate values when needed.

$$V = r_s \cdot i + \frac{d\lambda(\theta_r, i)}{dt}$$

(2)

$$\frac{J \cdot d^2\theta_r}{dt^2} = T_e - T_m$$

(3)

In equation (2), $V$ is the coil terminal voltage, $r_s$ is the coil resistance and $i$ is the current flowing through the coil. In equation (3), $J$ is the combined moment of inertia (SRM rotor plus flywheel), $T_e$ is the electromagnetic torque and $T_m$ is the opposing torque caused by mechanical losses.

Equations (2) and (3) have been used in digital computer simulations to estimate the behavior of the proposed system both under dynamic and steady-state conditions.

III. FLYWHEEL ENERGY STORAGE SYSTEM

The main purpose of a flywheel device is to accumulate rotational kinetic energy, which can then be recovered to the electric system whenever is required. Many examples of flywheel-based energy storage systems are described in the literature, but they can be generally divided in two categories: low-speed, high inertia devices and high-speed, low inertia ones. In any case, the fundamental relationship between angular speed and stored energy is given by equation (4).

$$E_c = \frac{1}{2} J \dot{\theta}_r^2$$

(4)

An important goal of this work is to describe how an SRM should be controlled, in order to be applied in a high-speed flywheel energy storage device. For that purpose, a dynamic simulation model has been written for the software package Simulink/Matlab®, according to the considerations presented in section 2.1. Simulation results are presented in figure 4, showing the dynamic response for a linear speed reference change from 2000rpm to 1000rpm. Two different results are presented, which correspond to speed variations in time intervals of 0.1s and 0.5s. Figure 4 shows the actual shaft speed and the total power that is absorbed from the dc link. As expected, if the speed change occurs in a shorter time interval, a correspondingly higher power can be transferred to the grid. On the other hand, if the power transfer is less intense, it can be sustained for a longer period. These are very interesting characteristics,
indicating that the device can be used with different strategies, e.g. to supply a small amount of critical loads during a power failure, until an auxiliary generator starts to operate, or to compensate large and rapid disturbances in the supply system.

IV. CONTROL OF THE SRM

Figure 5 shows the schematic diagram for one phase of the converter that is used to drive the SRM. Due to the operating principle of the SRM (minimum reluctance), the algebraic signal of the induced torque does not depend on the sense of current flow through the phase windings. Actually the torque signal depends only on the relative position between rotor and stator poles, at a given instant when current is flowing. As depicted in figure 6, if current is flowing in a phase coil before a rotor pole pair gets aligned to the coil poles (along the sense of rotation), the induced torque will be in the same sense as the rotation (motoring torque). Conversely, if current flows after the aligned position has been overtaken, braking or generating torque will be produced. Therefore, the current controller must ensure the current pulses applied to each phase occur before or after the aligned position, according to the algebraic signal of the current reference.

CONTROL STRATEGY

The flywheel shaft speed must be controlled according to the instantaneous active and reactive power demanded by the grid. In this work, the implementation of a two-stage control strategy for the flywheel shaft speed is proposed. Both stages are coupled through a common state variable: the voltage across the dc link capacitor. The main idea is to control the acceleration of the SRM in proportion to the mismatch between the dc link capacitor voltage and a given reference value, as depicted in the block diagram shown in figure 7. If no power flows between the flywheel and the grid, the dc link capacitor voltage then remains regulated at its nominal value. However, if active power is demanded by the grid, the command will act directly upon the grid interface converter, adjusting its voltage or current, according to the kind of connection (series or shunt).

Regarding the example shown in the block diagram of figure 4, power flow control is performed through the alpha-axis component of the converter output current at the grid side. The active power produced by this current is represented by the product between \( i_\alpha \) and \( v_\alpha \). It causes variation of the dc link capacitor voltage, which is compensated by the regulator PI1. Its output is used in turn as a reference for the speed control loop of the SRM, which comprises regulator PI2. There is however another speed regulator (PI3), with the main purpose of adding a small offset to grid converter current, in order to bring the flywheel back to the rated maximum speed after any transients. Its output signal should be limited to values that do not cause excessive power consumption from the grid.

V. PROPOSED APPLICATIONS

In this section, two possible applications of the SRM flywheel energy storage device are presented.

A. Uninterruptible Power Supply (UPS)

The use of an SRM flywheel as UPS is illustrated in figure 8, where the main system components can be identified, namely: bi-directional power electronic converter, switched reluctance machine, flywheel, superconducting axial bearing and control circuit. Depending on the voltage level at the grid side, a step-down transformer may be added between converter 1 and the system bus.
HIGH-SPEED FLYWHEEL SYSTEM WITH SWITCHED RELUCTANCE MOTOR/GENERATOR

VI. IMPROVING SYSTEM PERFORMANCE

According to equation (4), it can be seen that much more additional energy can be stored in a flywheel if its speed is increased while keeping its mass constant than if its mass is increased while keeping its speed constant. However, in high-speed operation many problems may arise such as:

- increased energy loss due to the air resistance,
- increased losses due to bearing friction,
- increased magnetic losses due to higher frequency of stator currents.
- increased mechanical failure risk due to the high rim speed

Magnetic losses can be reduced with an optimization of machine design and careful selection of core material. Windage and friction losses may be reduced using a magnetic bearing. This section will explore these two issues.

A. SUPERCONDUCTING MAGNETIC BEARING

In order to decrease the air resistance, the flywheel system will be housed in a vacuum chamber, with a pressure lower than 1 µbar. The better way to minimize the friction loss is to use a non-contact bearing, like a magnetic bearing. The usual active magnetic bearing introduces an energy loss due to the electric current dissipation, in the bearing coils, and this may be a relevant loss in the thrust bearing. The use of HTS (High Temperature Superconductors) magnetic bearings, mainly in the thrust bearing, allows a very low energy loss in the flywheel system. The new com-

B. Dynamic Voltage Restorer with energy storage

The schematic diagram of a DVR system with flywheel energy storage is presented in figure 9. The operation of this system is now based on adding a compensating voltage in series with the grid voltage.

Many works have been published about the optimization of performance and energy consumption of DVR systems [(Choi et al., 2000), (Haque, 2001), (Zhan et al., 2001)].

In this work, the control strategy proposed in [(Castellões e Aredes, 2001)] is applied. The development of a hybrid device that combines both the properties of DVR and UPS, as described in [(Weisbach et al., 2001)], will be dealt with in a future work.
composite material, with wound carbon and glass fibers embedded in epoxy resin, allows rim speeds over 1 km/s [9].

The main SRM advantage is that there are no losses in standby mode, with no excitation current in the stator. But, the magnetic losses in the rotor have to be minimized in order to avoid overheating. In a vacuum chamber the heat transfer is very poor, mainly by radiation and gas conduction, there are no convection. The low speed flywheel system avoid this problem, but the energy/mass relationship for the high speed flywheel make it competitive with the chemical batteries and another energy storage systems. The Kinetic Energy Storage System that is being proposed is showed in figure 10. The system is composed of a composite flywheel, a SRM, a thrust Superconducting Magnetic Bearing (SMB) (figure 11) and radial Active Magnetic Bearing (AMB). The AMB plays a role in the system stabilization when the speed is increased throughout the critical speeds. The critical speeds are the speeds where the system reaches a normal vibration mode resonance. The AMB will work only when it is necessary, not all the time.

The superconducting magnetic bearing will be prepared with seeded melt textured YBCO (YBa$_2$Cu$_3$O$_{7-δ}$) blocks and NdFeB permanent magnets. The YBCO blocks will work at the boiling liquid nitrogen temperature (77 K) and will be field cooled in order to optimize the levitation force and the stiffness of the SMB [10].

**B. CORE LOSSES**

A simple method to estimate the iron loss in electrical machines has been presented by Atallah et al [11], and is proposed to be applied to SRM in the present paper.

The total iron loss ($P_t$) may be calculated by the sum of hysteresis loss component ($P_h$), eddy current component ($P_c$) and anomalous loss or excess loss component ($P_{exc}$) as shown in equation (5)

$$ P_t = k_h B_m^2 \sigma d \frac{d^2 f}{dt^2} \int \left( \frac{\partial B}{\partial t} \right)^2 dt + k_c f \int \frac{\partial^2 B(t)}{\partial t^2} dt \left[ W/kg \right] $$

where $k_h$ and $k_c$ are the hysteresis loss constants, $f$ is the frequency, $B_m$ is the peak flux density, $\sigma$ is the material conductivity, $d$ is the lamination thickness, $\delta$ is the material mass density and $k_e$ is the excess loss constant. Equation (5) relies on the calculation of the magnetic flux density in every section of the machine. For this purpose, this work uses a commercial finite element program [8]. The iron loss density is calculated on an element-by-element basis in the way described by Mueller et al. [12]. Two magnetic materials are being considered, an standard FeSi steel used in machines and an amorphous magnetic alloy which has a higher magnetic permeability. The losses characteristics of both material are shown in figure 12. From those curves the various constants of equation (5) can be derived.

The effect of the material on core losses can be seen in Table I, which shows calculated iron losses for a design considering 0.5 mm laminations of FeSi and another with 0.022 mm laminations of amorphous material. The machine is running at 3600 rpm. As expected the amorphous material yields a much lower value for iron losses. The finite element analysis is also a useful toll in order to identify regions of high loss density as can be seen in figure 13, which loss density distribution over a machine cross section.

![Figure 10: Flywheel energy storage system with superconducting magnetic bearing and SRM.](image)

![Figure 11: Superconducting magnetic bearing.](image)

<table>
<thead>
<tr>
<th>Geometry A</th>
<th>Geometry B</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeSi</td>
<td>67.6 W</td>
</tr>
<tr>
<td>Amorphous</td>
<td>1.26 W</td>
</tr>
</tbody>
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**Figure 12:** Iron loss data for FeSi and amorphous material.
The effect of material on the performance of the machine can be seen in figure 14, which shows torque calculations using the Finite Element Method (FEM) for both machines. The machine is supposed to be running at 3600 rpm and is excited with phase current of 2 A. It can be seen that the amorphous alloy also gives a higher torque for the same electric loading.

The machine performance can also be improved with an optimization of its design. This can be seen in Table I, which presents calculated results for an alternative design where the stator poles are wider at the bottom as shown in Figure 14. Table I shows that this geometry gives a reduction in the iron losses. However, this geometry results in a slight decrease on the available torque. A design optimization, which takes both effects into account, is underway and will be presented in a future work.

VII. CONCLUSIONS

Due to its elevated robustness and reliability, The SRM seems to be a good choice as a driving machine for flywheel energy storage devices. This work has presented the conception of an SRM flywheel system, considering many design aspects such as material choice, mathematical modeling and control strategy. Two possible applications have been described, where the use of such a kinetic energy storage system can contribute to the enhancement of power quality in electric energy systems.

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