Abstract. A 5 kWh / 250 kW engineering prototype Flywheel Energy Storage System (FESS) was designed and assembled in a joint project ATZ with L-3 Magnet- Motor Corp. The 0.6 t rotor is magnetically stabilized between a 1 ton magnetic HTS bearing on top and a new PM bearing. Based on the measured bearing load (max. 10000 N), Stiffness (3-4 kN/mm axial, 1.8 kN/mm radial) and rotor eigenfrequency (~ 6.5 Hz) optimum operating conditions are obtained. For industrial use the flywheel periphery is described and evaluated.

A comparison and evaluation showed, both the composite rotor as well the HTS magnetic bearing are utilized more efficient in systems with larger energy storage capacity. This can provide UPS function as well as power quality (load levelling) economically and correspond to industrial requirements and demands. In a third phase starting in 2009 the parameters for larger energy storage capacity 25 – 50 kWh are calculated, investigated and the basic elements studied.

1. Introduction

In the last decade several flywheel energy storage projects by integrating superconducting magnetic bearings are performed up to a R&D status [1-5]. Load, stiffness, damping and the resulting rotor dynamics and stabilization are the key issues of the concepts. ATZ has been cooperated with L-3 Communications Magnet Motor (L-3 MM) following a MDS (Magneto Hydrodynamic Storage) flywheel concept. More than 20 MDS devices during the previous decade have been produced by MM. In the conventional version the flywheel rotor is supported by mechanical bearings (a PM bearing typically relieves the axial load). With mechanical bearings short-term electricity storage has been shown beneficial, e.g. in a mobile application of urban buses. In contrast, in long-term storage the total loss per day is 60% or more of the stored energy, mostly due to friction of the mechanical bearings.

To improve the long-term storage capability of the flywheels the concept of a hybrid flywheel with total magnetic stabilization was developed and designed. The project started in 2005 with a 5 kWh / 250 kW flywheel energy storage system (FESS-5). Two magnetic bearings support and stabilize the 0.6 t rotor.

In 2007 the technical concept of the HTS bearing on top and the PM bearing below the motor/generator was re-designed. Calculations and measurements on a dummy rotor lead to conclusions that the expected magnitude of the real 0.6 ton rotor resonance vibrations with an amplitude of 3- 5 mm which would be too large. To limit the rotor movement two dynamical damping systems are attached at both ends of the vertical rotor shaft. Fig. 1 shows the ATZ/L-3 MM HTS FESS without the vacuum and electronic system. Some parameters and conditions are given in table I.
The HTS flywheel (FESS) unit has a vertical rotation axis. The rotor is a hollow cylinder and is made primarily of carbon fiber compound. To make the system very compact the motor/generator (M/G) unit is integrated concentrically in the hollow cylindrical rotor. The system stores energy when the M/G unit works as a motor and increases the speed of the rotor. It delivers electrical energy when the M/G unit is switched to generator mode thus reducing the rotor speed. The rotor's mass moment of inertia and its maximum permissible rotation speed determine the energy capacity of the MDS. The power capability is determined by the specifications of the M/G unit and the electronic converter system controlling the M/G unit. The M/G unit is a permanent magnet excited machine operated with compact high-performance IGBT-inverters. It is especially developed for the application in flywheels. The machine is optimized for low no-load losses and a very high electric efficiency of 92-95% including the losses of the inverters. The electric performance is obtained both in motor as well as in generator operation.

As a result the round trip efficiency of the FESS-system is about 85-90%. The power consumption of auxiliaries as the vacuum pump is not included in this calculation. An important feature for many applications is the extremely high cycling capability. The expected cycle lifetime is in the range of $10^6$ to $10^7$ cycles.

### Table I: FESS Parameters

| Parameter         | Value       |
|-------------------|-------------|
| Diameter          | 1.05 m      |
| Height            | 1.25 m      |
| Mass + frame      | 1200 kg     |
| Max. speed        | 1000 rpm    |
| No -load loss     | < 1 kW      |
| Vacuum            | $\sim 10^{-3}$ mbar |
| Cooling HTS       | 35W/80 K GM |
| Cooling           | Water/glycol|

2.2 HTS Magnetic bearing

The HTS component of the flywheel is the superconducting magnetic bearing on top of the FESS device. This HTS magnetic bearing together with PM bearing holds the rotor during operation. The rotor has no mechanical contact to the housing diminishing mechanical losses and wear. The properties of the 200 mm HTS magnetic bearing have been measured previously [4] where the PM
The force density of the one-ton bearing at a temperature of 70 K was determined to be 13 N/cm² axially and 6.5 N/cm² radially. These parameters are limited by the available magnetic flux density of the PM configuration of about 0.45 T in the bearing gap. Doubling the magnetic flux would increase the force density by a factor of four. One possibility to increase the magnetic flux of HTS bearings is the use of HTS coils. These coils winded with superconducting wires (second-generation wires 2G) we are investigating for the application of high gradient structures.

2.3 Cooling of magnetic bearing

For cooling the HTS bearing 40/35 Watt/1.8 kW Gifford McMahon (GM) cryo–cooler was adapted by a flexible copper braid. A complete test program with 20 cold-warm cycles was performed to gain reliable experiences with thermodynamics. At zero thermal loads the cold head goes to a temperature of about 35 K. Within the assembled bearing the measured temperature on the YBCO surface was 48 K generating high Jc values with excellent magnetic properties of the superconducting bulk ring. The low temperature causes less hysteresis and relaxation effects of the levitation forces and stiffnesses (Fig. 3). Between the GM cold head and YBCO ring at largest distance the temperature gradient was less than 1 K. Following Fig. 4 the cooling procedure serves a safe operation of the bearing. After switching–off the cryo-cooler at 48 K the HTS temperature due to heat losses increases rather slowly and pass the 77 K level in about 90 minutes. In an emergency case this large time window allows a safe switch-off procedure of the electric and dynamic rotor system.

2.4 Composite rotor

The rotor in Fig. 5 is a hollow cylinder winded of glass and carbon fiber rings. It is dedicated to a speed of 12 000 rpm. Spin tests in an external set-up are performed up to 14 400 rpm. The rotor has a diameter of 1 m and a height of 0.5 m. The rings are arranged concentrically with the carbon fiber re-impregnated (cfpr) material towards the outer periphery where the stresses are the highest. The composite rings are mounted on a central shaft connecting the rotor with the M/G and the two bearings. Either some of the rings are press fitted together in pairs to impose some pre-compression in the radial direction. The ring-pairs are separated from each other by elastomeric interlayer’s preventing the transmission of radial stresses from one ring-pair to the next. Alternatively, all composite rings can be press-fitted or shrink-fitted to the neighbours, again with the carbon fiber rings in the outermost layer. The multi-rim rotor structure shows a more evenly stress behaviour. At a rotor speed of 10 000 rpm the maximum rim speed is about 550 m/s which corresponds to 40 Wh/kg specific energy. These values are 50% lower than the theoretical speed of the rotor but are considered industrial “fail-safe” standard.
2.5 Motor / Generator M/G
The M/G unit is permanent magnet excited multi-pole motor/generator operated for example with 06
single 4-quadrant IGBT-inverters and has only electrical connections. The rated power is 250 kW. No
gearing is necessary. By integrating this unit in a vacuum housing, the losses due to air friction are
very low. The cooling of the stator of the M/G unit and of the inverters is a closed loop liquid circuit,
which means advantageously that no dirt can penetrate into the cooling system. A standard liquid/air
heat exchanger or liquid/water heat exchanger transmits the losses to the surrounding air. It is
advisable to run the FESS in a cycle operation mode between 100% and 50% of the speed (10,000 –
5,000 rpm) independently of the technical possibility. In a UPS operation mode the flywheel may run
down to 25% of the speed. As the rotational energy of the flywheel has a quadratic dependence on the
speed the useable energy in an UPS (uninterruptable power supply) operation mode is $7/8$ of the stored
energy.

Losses through friction are minimized by the magnetic bearings and the low vacuum. The total
losses are estimated to be less than 900 W at full idle. Power consumption of auxiliaries as the vacuum
pump is not included. The operational vacuum is maintained by continuous evaporation with a
vacuum pump in the < $10^{-3}$ mbar level.

2.6 Power Electronics
The power coupling between flywheel and DC line (750 V) is linked by power electronic system units.
These electronics consists of 3 single 4-quadrant IGBT inverter which operate the 12 phases of the
flywheel. The switching frequency of the inverters depends on various parameters and is up to
operational frequency of 20 kHz. Current-and voltage-measurements as well as a diagnostic routine
are integrated in the power electronics. The necessary inverter control system for the direct motor or
generator operation of the FESS is part of the power electronics. Operational directives are given by a
superior control electronic system.

In case of a malfunction of the FESS system or of an external malfunction (even in case of a
disconnection of the system from the DC-power-link) the speed of the FESS is reduced to standstill by
switching the M/G coils directly to a brake device. For breaking the FESS no auxiliary power is
needed.

The power electronics and the periphery are highly variable and can be adapted at the local conditions.
A close installation of all the components is preferred. The power consumption of the auxiliaries is
about 4.0 kW totally.

3. Flywheel scaling
In general energy storage can avoid a large amount of costs of down-time and repair time for high-tech
industries resulting in greater economic productivity. On the other hand, energy storage
coupled with solar and wind farms would allow the industry to sell blocks of electric power at
premium prices more effectively.

The way from R&D to a pilot type flywheel energy storage system is accompanied by technical and infra-
structure factors. Surprisingly, it is dominated by the discussion about the optimum storage capacity and the
available power per unit. The calculation of Fig. 6 shows the power versus time behaviour of different electricity storage capacities. A power reserve of 0.5 MW, e. g. to bridge the time for starting large diesel engine generators requires a flywheel capacity > 20 kWh.

To get a higher flywheel storage capacity one has two basic scaling factors: The size and mass of the rotor and the speed. The present FESS rotor has a geometrical shape of a hollow cylinder which gives fundamental benefits. The compactness and robust character of volume-saving concentrically motor / generator design inside the...
Hollow rotor. This structure provides simultaneously high aspect ratio and the option of storing energy per rotor mass in larger systems. The here provided concept of the rotor stabilization allows substantial larger energy storage devices of > 20 kWh having M/G power levels of 0.5 – 1 MW.

4. Conclusions and Outlook
ATZ and L-3 Magnet Motor developed and assembled a magnetically stabilized flywheel energy storage system of 5 kWh/ 250 kW with HTS bearing. Analyzing the properties and performance the present FESS the energy capacity of 5 kWh is not optimal. To increase the storage capacity to 25 – 50 kWh per unit two factors determine the storage capability: Increasing the rotor mass of inertia \( (E \sim \Theta) \) and/or increasing the rotor speed \( (E \sim \omega^2) \). Of the two possibilities we postulate in the near future to increase the rotor mass although the stored energy grows here linearly only. One principal feature is the limitation of the rotor speed \( (v_{\text{rim}} = 1200 \text{ m/s max.}) \). Safety standards require 60 - 70% of burst speed.

As a conclusion, the magnetic stabilization of a 2 ton rotor is under investigation. For this a HTS bearing concept with improved force density > 40 N/cm² is analyzed and investigated.

5. References
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