250 kW Flywheel with HTS Magnetic Bearing for Industrial Use

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Abstract. A 250 kW / 5 kWh engineering prototype Flywheel Energy Storage System (FESS) was designed, fabricated and component tested by Adelwitz Technologiezentrum GmbH (ATZ) and L-3 Communications Magnet - Motor GmbH (MM). A heavy - load vertical 0.6 ton rotor is suspended totally magnetically by an HTS radial-passive bearing on the top together with a PM bearing at the bottom. Further features are the flywheel rotor body which is manufactured from carbon fibre reinforced plastics (CFRP) in a multi-rim version and combined with an integrated high-power motor /generator. A 35 W/77 K single- stage Gifford McMahon cryo-cooler is cooling the HTS bearing to a temperature of 45 – 60 K. Functionality and efficiency of the magnetic bearing configurations, rotor control concepts and motor / generator power electric system is considered and established. Bearing stiffness parameters, damping performance, and rotational friction are measured. Testing of further components under vacuum conditions confirmed that low bearing drag and wear - free operation can be attained. The motor-generator operates with a power in excess of 250 kW and an efficiency of > 92%, including the losses of the inverters. A redundant mechanical touchdown bearing system can be activated to restore the rotor position. The separately tested flywheel components are now in the assembling status expecting first machine tests in November 2007. After studying and measuring all FESS parameters in –house the dynamical storage device will be tested in a German E.ON power station under industrial conditions.

1. Introduction
Major motivations for the development of modern flywheels are the requirements of electrical power quality and continuous availability of electricity. We are fabricating a 5-10 kWh/250 kW flywheel energy storage system (FESS) with HTS magnetic bearing funded by the German BMBF. Flywheels are suited for a number of applications and have already been applied for years using mechanical bearings. Historically, Magnet-Motor Co. (MM, today L-3 Communications Magnet- Motor) realized successfully some projects by applying conventional flywheels called “Magnetodynamic Storage Systems”, MDS [1]. Starting in 1988 MDS flywheels of 2 kWh/150 kW were first applied in two communal diesel-electric buses in Munich, Germany. Further diesel-electric demonstration buses followed. In those years experiences could be gained on the operation of flywheels in vehicles, their interaction with the electric propulsion system, the potential of energy saving in buses, reliability and maintenance needs. One important result was that energy savings of 30-35% can be obtained if you regard only the energy balance of the diesel-electric propulsion system including the MDS. With new, more efficient propulsion and MDS components even up to 40% of the propulsion energy could be saved [2]. In 1994/95 a small fleet of 12 trolley buses in the Swiss city of Basel was built, equipped
with MDS units to relieve the overhead network and to recover the brake energy on board. Today these buses have been in operation for more than 12 years. Most of these flywheels have operation hours of more than 50,000 [3]. These flywheel activities of MM give a high degree of technical experience in design, construction and application of flywheel energy storage systems and ensure optimum conditions for the development of flywheel technology with superconducting magnetic bearings.

In stationary applications purely magnetically levitated flywheels offer a number of advantages. Maintenance at the flywheel is only necessary once every few years, losses are minimized and non-contact, very low-noise operation is possible. In the field of magnetic bearings the high temperature superconducting (HTS) bearing is definitely the most fascinating and promising technology. Due to its physical properties it needs no electronic controller and operates self-stabilizing passively. Hence, a number of attempts and developments with HTS flywheels have been performed in past 4 years [4-6]. Three ambitious concepts of larger flywheels use throughout carbon fiber reinforced plastic (CFRP) rotors and radial as well as axial- type HTS magnetic bearings. The storage capacity ranges up to 10 kWh. The analysis of the individual status of the HTS flywheel projects demonstrates the enormous complexity of the systems. Within the different concepts and technical approaches it became evident that most of the technological effort and challenging tasks are associated with the performance of the HTS magnetic bearings. The bearings have not only to carry a heavy- load rotor of several hundred kilograms weight but have to stabilize the fast spinning rotor under all operational conditions and situations.

Our HTS flywheel project started in 2005 and will be finished in this year 2007. First component results are given previously [7, 8]. This paper reports the overall construction features and component testing for assembling. The performance characteristics of the equipment are analyzed and establish that the HTS magnetic flywheel technology has reached a progress to be considered for industrial application.

2. Configuration of the Flywheel System

2.1. Fundamental design

ATZ and L-3 MM are currently assembling a flywheel energy storage system of nominal 5 kWh storage capacity and an electric power of 250 kW. The rotor with a vertical rotation axis is stabilized magnetically by a superconducting and a permanent magnet (PM) bearing. An increased energy capacity of 10 kWh is obtained at a speed of 10,000 rpm. The integrated permanent magnet motor/generator unit operates with a maximum power of 250 kW as a motor as well as a generator. The diameter of the evacuated flywheel housing is about 1m and the height is also 1m. The weight of the complete flywheel unit is about 1200 kg plus the external periphery such as power electronics and cooling system. Figure 1 shows an overall design view of the HTS flywheel.

Figure 1. Overall design of the HTS flywheel
The HTS flywheel consists of safety housing with three main parts: Carbon fibre rotor, motor/generator and the shaft with top and bottom magnetic bearings. In order to avoid damage to the magnetic bearings a touch-down bearing system acts both as axial and radial excursion stops. The selected configuration ensures consistently smooth touch down behaviour. The low-loss HTS magnetic bearing at the top of the flywheel carries the total rotor load of about 600 kg. In extensive experiments the HTS bearing has been tested regarding load, stiffness and damping performance [5]. A single stage Gifford McMahon cryo-cooler (CTI CP 350) with a nominal cooling power of 40 W@80 K serves for cooling power of the top HTS bearing.

As a concept of compact machine design, the rotor is a hollow cylinder with a concentrically integrated motor/generator, M/G. The efficiency of the motor itself including the power electronics is estimated to 92 - 96 % at maximum torque and at nominal speed of 10 000 rpm. The system stores energy when the M/G operates in motor function and increases the rotational speed of the rotor. Energy will be delivered by the generator mode. The flywheel rotor consists of a central hub containing the carbon fiber rotor and, at both ends, the magnetic bearings and the touch down bearing parts. Design and construction of the rotating hub with connected systems are chosen with respect to maintain a high degree of balance in the presence of centrifugal loads and possible external forces. Large effort was devoted to analyze and control the rotor dynamics. The moment of inertia of the rotor and the maximum rotational speed determine the energy capacity of the flywheel system.

The complete sealed dynamical part of the storage system, especially the magnetic bearing suspension, guarantees low noise operation without vibrations to the surrounding floor level. Therefore, the flywheel could be installed even within buildings.

All flywheel components are assembled in a vacuum housing to reduce air friction. The vacuum condition is maintained by turbo-molecular pump unit. Because of the natural outgassing of composite materials the final vacuum level depends on the operational time, it has been tested to vacuum level of $10^{-3}$ mbar after a few days operation.

2.2. HTS bearing

About design, construction and performance of the HTS bearing we reported previously [8]. All test measurements of components outside the flywheel were performed at LN$_2$ level using indirect conduction cooling. The measured bearing parameters are given in table 1. The nominal HTS temperature was 78 K and about 72 K under sub-cooling conditions. The superconducting cylinder has a size of OD of 230 mm x ID 205 mm x 120 mm assembled of melt textured YBCO bulks. The individual parts of the HTS bearing for the flywheel
are shown as a sketch in Figure 2. A photograph of the flywheel head with the YBCO bearing stator is given in Fig. 3. The top cover and the rotor are removed. While the geometry of the YBCO ring is identical in test and flywheel bearing the melt textured YBCO blocks for the latter were selected from our high quality material stock and glued into a copper ring. The YBCO bulks show trapped field values of 0.9 - 1.1 Tesla at 1.4 Tesla excitation (77 K). The blocks were machined, glued into the massive copper ring with 20 mm wall thickness and milled to a cylinder shape of 205 mm diameter at precision of 0.2 mm. Axial and radial mechanical bearing support is provided by G-10 distance holder between the massive Cu ring and the housing of the flywheel. The holders are designed to withstand radial and axial forces of several tons; simultaneously they have a minimum heat load on the cold bearing.

The concentrically arranged permanent magnet counterpart of the HTS cylinder consists of axially stacked PM rings with OD of 200 mm x ID 150 mm x 8 mm in size each, with Fe shims in-between providing a high radial magnetic flux gradient. With 2.5 mm the air gap and the magnetic distance of the bearing is relatively high to provide enough margins for the HTS bearing to develop its retraction forces. Axial stiffness values of 2-4 kN/mm have been measured at temperatures from 78 K to 72 K. Radial values are measured to 1.8 kN/mm. The estimated damping performance shows temperature dependence similar to reciprocal of $J_c$ and varies from 5 % at 48 K to about 10 % at 77 K. Under rotation an averaged AC and hysteresis friction moment of the HTS bearing of 5x $10^{-4}$ Nm was determined.

The flywheel HTS bearing is connected with a Gifford McMahon (GM) cryo-cooler of the type CTI CP350. The single stage GM cooler was tested having a cooling performance of about 35-40 Watt @77K.

| Table 1. HTS bearing parameters |
|----------------------------------|
| Bearing type | Radial type |
| Diameter x height | 205 x 120 |
| Magnetic area | 768 cm² |
| Superconductor type | YBCO, melt textured |
| HTS size/number of elements | 65 x 35 x 13 / 55 pcs. |
| Rotor configuration | 200 mm PM rings |
| Bearing housing | Fe / Al / G-10, vacuum |
| Magnetic gap | 2.5 mm |
| Free rotor movement | 2.0 mm |
| Cooling YBCO | GM cooler, 40 W@77 K |
| HTS bearing weight | 55 kg |
| Maximum load, axial | 10800 N / 3 mm displacement |
| radial | 4700 N / 3 mm displacement |
| Stiffness, axial | 4.5 kN/mm |
| radial | 1.8 kN/mm |
| Speed (test) | 3200 rpm |
| Thermal loss | 12-15 W @ $10^{-3}$ mbar |
| Rotational friction | -5 x $10^{-4}$Nm |

2.3. Passive PM bearing

The PM bearing is located at the bottom of the flywheel. The PM bearing at the bottom of the flywheel (see Figure 6) supplements the HTS magnetic bearing. The bearing is of the radial – type with 8 stationary PM rings of the size 120 mm x 100 mm x 10 mm. The corresponding rotating 8 PM rings with geometry 92 mm x 72 mm x 10 mm are mounted on the nonmagnetic rotor shaft. The PM rings
consist of Neodymium-iron-boron (NdFeB) having Grade N33H with a nominal magnetic energy (BH) product of 33 MGOe. Magnetic rings are stacked axially on pressure with SN-NS-SN pole orientation and locked mechanically by end rings. All PM rings are sitting on mounting sleeves of high tensile strength. The PM rings were stacked together using a heavy lathe to provide the forces exerted by the magnets while pressing on the sleeve. The relative position of the poles of the rotor and stator PM rings determine the magnetic forces in axial and radial direction at the nominal gap of 4 mm. The bearing operates under large gap conditions. Stiffnesses of the PM bearing are calculated by FEM. The finite element calculation gives a radial stiffness of about 80 N/mm per pole (2 stator and 2 rotor rings). The corresponding negative axial stiffness is about 160 N/mm. In Fig. 5 we compare the FEM calculation with the experimentally determined axial forces. While the negative axial forces and stiffness between calculations and experiment for small rotor shifts < 5 mm are identical the force values at larger rotor PM displacement deviate from each other.

![Figure 5. Force distribution of radial concentrically PM bearing element](image)

![Figure 6. Schematics of the bottom radial PM bearing](image)

The total forces of the lower permanent magnet bearing are in radial direction about 800 N at 1.5 mm radial displacement stabilizing the rotor with a stiffness of 560 N/mm while in axial direction a negative stiffness of 1.1 kN/mm is directed upwards against the rotor’s gravity.

### 2.4. CFRP Rotor

The diameter of the actual flywheel rotor is about 1 m at a height of about 0.5 m. The flywheel rotor consists of glass and carbon fiber composite material. The high strength carbon fiber reinforced composite material (up to 3200 MPa) is used in the outermost layers which characterizes an advanced multi-rim type rotor. Fabrication of multi-rim rotors is more complicated compared to a homogenous cylinder-type rotor. On the other hand a multi-rim rotor shows a more evenly stress behaviour which is equivalent to a higher specific energy density. The fabricated concentric rings of glass and graphite fiber can be either press fit or shrink-fit at the interface or separated with compliant interlayer’s for radial stress relief during operation. The rotor is attached to a metallic shaft in the centre that is supported at opposite ends by magnetic bearings.

Fabrication of flywheel rotors is based on filament winding know-how whereby carbon or glass fibres are drawn through a resin bath and wrapped in the hoop direction on a heated mandrel. The temperature of the mandrel and the winding speed has to be carefully controlled to avoid quality problems. The final rotor has a typical fiber volume fraction of about 65 percent, while void fractions are typically less than four percent. A picture of the CF rotor is shown in Fig. 7.

Rotor’s energy is proportional to the square of the angular velocity, and hence proportional to the square of the rim speed. This property causes the effect that a 75% of the rotor energy is stored
between the maximum speed and half of its top speed. The same quadratic dependency is valid for the stress distribution in the rotor. The centrifugal force depends on the square of the peripheral velocity \( \omega^2 r^2 \), with the angular speed \( \omega \) and the radius \( r \). A cylindrical shell as a typical flywheel geometry has a hoop stress equivalent to \( \rho \omega^2 r^2 \).

It should be interesting to remark that rotor designing and scaling can be simplified by calculating the stress distribution for a given rotor size in an optimum geometry and then introducing a geometrical scaling factor. In fact, especially by scaling up, shrinking and thermal residual stresses caused in the rotor fabrication has to be considered also. In principle, the geometrical scaling factor can be multiplied by a variable parameter in a corresponding way to preserve the chosen material criteria. For a given maximum hoop stress the radius of the rotor could be increased \( r_{sc} = q r \) by a scaling factor \( q > 1 \). Simultaneously, the angular speed of the rotor should be inversely proportional to the speed of the original rotor \( \omega_{sc} = \omega/q \) to keep the hoop stress unchanged.

2.5. Motor/Generator
The flywheel power capability is determined by the specification of the motor / generator unit and the power electronics. The M/G is permanent magnet excited machine with an external rotor with a power performance of 250 – 300 kW. The M/G unit is controlled and operated by a compact and high efficient power converter system shown in Fig. 8. The motor/generator configuration has been developed especially for the flywheel electric system and is optimized for low loss operation with 92-96 % efficiency. Simultaneously, the flywheel power electronic allows a high load/deload cycling rate for power quality and load levelling purposes. Electric stability requirements in these fields are an increasing demand because many electronic devices are sensitive to level and quality of grid electricity. In this application for example, the flywheel can take care of high quality electric grid power.

The electric M/G unit has only electrical connections. No rotating components have to be directed outside the electric unit. The effective cooling of the motor stator and the power inverter system is performed using a closed loop liquid circuit. A standard liquid/air heat exchanger transfers the corresponding heat load to the surroundings.
2.6. HTS bearing cryogenics

In the present flywheel a 40/35 Watt/ 1.8 kW Gifford McMahon (GM) cryo-cooler is adapted to the flywheel head as shown in Figure 2. The cold head of the GM cooler is connected to the rigid copper ring by a flexible copper adapter. Under zero thermal loads the cold head is running to a temperature of about 33 K. Because of the importance of reliable cooling the HTS bearing we performed a complete test program and gained experiences with flywheel bearing head. The cold parts of the HTS bearing are thermally insulated by developing low thermal conductive axial and radial mechanical support structures made of G-10. The axial warm support has been tested up to loads of 4 tons at a minimum heat transfer. Radiative thermal shielding is carefully designed and realized by layers of superinsulation foils (MLI, CRYOLAM). In the present flywheel with the open HTS bearing about 60 % of the thermal load is caused by the warm rotor in vicinity to the YBCO stator.

![Figure 9: Cool-down behaviour of the HTS flywheel bearing; Insert: Temperature increase after GM-cooler switch-off](image)

Thermal shielding is therefore mandatory for the YBCO ring to reduce thermal heat load. Figure 9 represents a typical cool-down curve of the HTS bearing. The superconducting level and a temperature of 77 K are approached after 12 – 13 hours. A final temperature on the YBCO surface was 45 – 50 K which is excellent for the magnetic properties of the superconducting material. Between the GM cold head and the opposite part of the YBCO ring the temperature gradient was less than 1 K, giving evidence to a homogeneous temperature field around the HTS ring. After switching-off the cryo-cooler at 45 K the HTS temperature increases rather slowly and passing the 77 K level in about 90 minutes (insert of Figure 9). In an emergency case this large window gives enough time to run-down and switch-off the flywheel system.

2.7. Rotor dynamics

Rotor motion relative to the stator involves three oscillation modes: radial translation mode at critical speed, precession mode, and the nutation mode. If one considers that the moment of inertia around the rotational axis C (Figure 7) is substantially higher than the corresponding parameters of the orthogonal axes A and B, nutation frequency will not be excited by rotation (C/A > 1). Calculations show that precession frequency will appear mainly when the motor armature is submitted to a slew manoeuvre. Amplitudes of the rotor due to tilting motion of the principal axis of the moment of inertia (C axis) or unbalance have been calculated. Amplitude of the tilting mode appears during slew acceleration. Further on, rotor dynamics calculations show a resonance of the flywheel at very low speed (Eigen-
frequency). To overcome this, rotor damping and special precautions were taken. The range of nominal rated speed is considerably higher than the resonance frequency which means that the flywheel will operate in overcritical condition. The asymmetry forces of the motor/generator act mainly on the permanent magnetic bearing at the bottom of the flywheel and are calculated to be only a fraction of the centering and stabilizing forces of that bearing.

3. Conclusion and outline

The 10 kWh / 250 kW flywheel is presently at ATZ and at L-3 MM in a final assembling status. All tests on components were successful. The reported parameter examination of components shows the designed specifications. The radial – type superconducting bearing is able to suspend the 0.6 ton CFRP rotor while the bottom PM bearing stabilizes radial dynamic forces. With 13 N/cm² axially and 6 N/cm² radially the HTS bearing force density was designed at optimum. Successful thermal insulation of the HTS bearing cold parts is confirmed by cryogenic cycling program whereby the superconducting bearing was cooled down to 45 – 60 K dependent on the heat load of the rotor and using an 40W/80 K GM cryo-cooler Thermal break-down of cooling restores the magnetic bearing force for a time of more than one hour.

The flywheel system presented here is based on a modular concept of existing and challenging new technologies. It allows a scaling-up in energy and power without changing compact design and technical concept. In November 2007 the HTS flywheel will be scheduled to E.ON Company located in Ingolstadt, Germany and will be electrically connected to the power network of the UPS facility of the power station there. It is planned to test the flywheel over 1 year for UPS function.

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4. References

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