

High Power Flywheels With Superconducting Bearings – Design Considerations And Experiences

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Flywheel energy storage systems allow a broad variety of combinations of rotating mass, electrical machine and bearing. So they can be designed in principle very flexible and adopted to different modes of operation. Nevertheless flywheels are typical short time energy storage systems with high specific power ratings. This is underlined also by cost calculations showing that the specific energy costs are comparatively high but the specific costs of power are smaller than with e.g. batteries or CAES systems (Fig1).

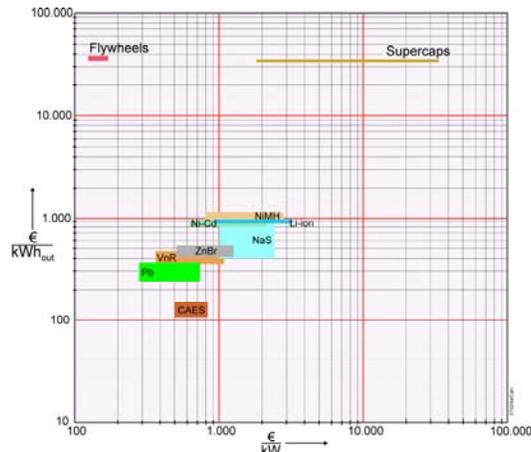
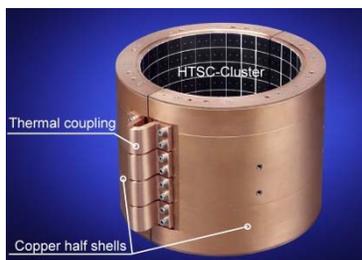


Fig.1: Specific costs of energy storage systems (exemplarily calculated for 1 MW complete systems)

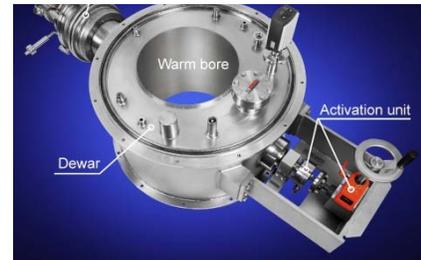
If suspended by superconducting magnetic bearings (SMB), the bearing properties influence widely the design of the flywheel. A SMB offers unique properties with respect to frictionless and inherent stable operation. In fact the same operating safety as with other passive bearings is achieved, if the load stays within the design limits. This is proven by experimental results gained from a 5000 N capacity bearing **Fig 2, 3, 4** recently tested in cooperation with Siemens AG and Nexans Superconductors [1]. The patented construction of the bearing features a design with two movable stator half shells allowing for exact centering of the rotor in the warm bore of the stator. Cooling was achieved by a commercial cryocooler.



2)



3)



4)

Figure 2.: Cu half shells with HTSC monolith cluster

Figure 3.: Rotor of the SMB assembled from NdFeB ring segments, stabilized with CFRP bandage

Figure 4.: Dewar with cold-head and activation device, yet without rotor

The measurements exhibit a linear stiffness with neglectable hysteresis in the force displacement characteristic and after passing the critical speed a very stable rotor position of the only roughly balanced rotor (**Fig 5,6**).

The bearing showed the expected robust behaviour. The quality of the insulation allowed a HTSC temperature of 28 K and after switching of the cooling power supply it took more than 3 hours to reach the critical temperature of the HTSCs. So there is enough time for a safe shut down of the plant in case of long term failure while short time interruptions of the energy supply are bridged by the thermal capacity of the bearing.

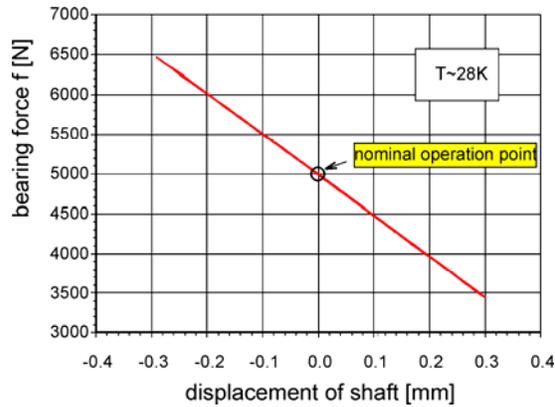


Fig 5: Measurement of static stiffness (n=0)

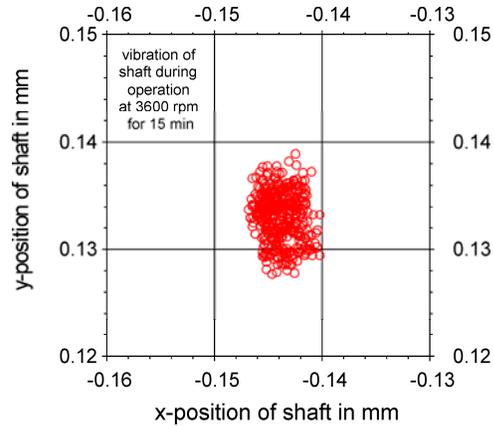


Fig. 6: Rotorposition at 3600 rpm (unbalanced)

Even a short touch down into an auxiliary displacement limiting bearing did not affect the stability of the bearing and after the disturbing forces are removed the bearing returned to stable operation again. Experience shows that this nearly is impossible with active magnetic bearings (AMB), especially if the control system of the AMB is disturbed by EMC effects or a sensor or microprocessor failure. This confirms the decision to use superconducting bearings especially for rotors with high energy content as they are encountered with heavy fast rotating machines or even high speed flywheels for energy storage.

As bearing topologies cylindrical and planar configurations are possible. With external rotors a cylindrical bearing exhibits the best properties with respect to speed while with internal rotors planar bearings offer more favourable properties for high speed applications, because their structural and magnetic properties can be decoupled. For the “DynaStore” project, funded by the German department of economics, targeting at an efficient energy content of 10 kWh and rated power of 2 MW a design with an electric machine integrated into the rotor hub of the flywheel rotor was chosen.

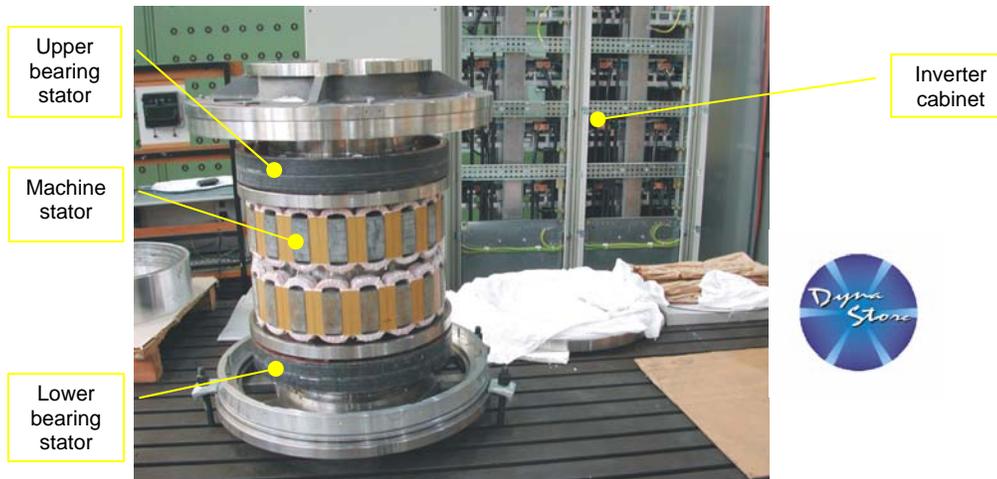


Fig. 7: Test setup of the flywheel stator for electrical testing and operation under 1 bar conditions

So in consequence for the external rotor a suspension with cylindrical bearings turned out to be the best design approach. As a flywheel usually has a vertical axis activation in this case is very simple and can be done by axial movement of the rotor into its operating position after the superconductors are cooled down to operating temperature.

Damping is another essential property to pass safely through low resonance frequencies of the flywheel or for damping of the excentricity forces of the electrical machine and requires additional devices in the bearing arrangement, because due to the high quality of modern superconducting bulks, nearly no inherent damping of the HTSC material is available. The relative damping of the material can be estimated to 0.1 %. As simulations

of the startup of the flywheel show a relative damping of 1..3% will be sufficient to pass safely through the critical modes.



Fig 8: Vacuum container and essential rotor parts ready for assembly

In most of the published bearing proposals damping devices were neglected, but conventional hydraulic or friction based dampers are not applicable with contactless and oil free bearings running under vacuum. So different designs to provide system conform contact free damping effects were developed by IMAB. These are based on eddy current dampers using a comparative construction as with the superconducting bearing (fig. 9) or can be integrated into the motor by a special layout of the winding.

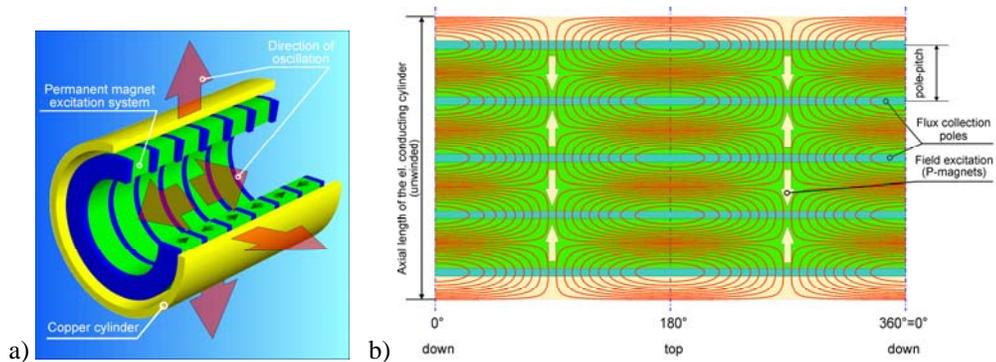


Fig. 9: a) Principle arrangement of a bearing damper with copper cylinder and flux collecting poles, b) Eddy current distribution in the circumference of the damper cylinder (unwinded representation)

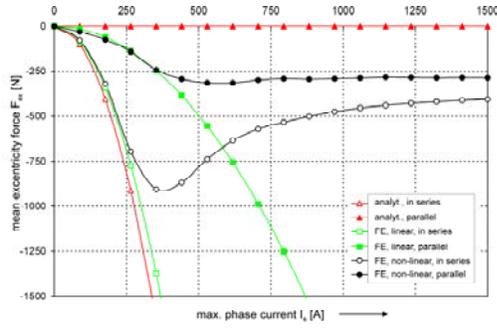


Fig.10: Damping of excentricity forces by parallel winding paths. Nonlinear calculation is given by the lines with white (series connection) and black dots (parallel connection)

An easy to achieve damping effect is provided by parallel paths in the motor windings. Preferably they help to stabilize the rotor against excentricity forces. The exemplary nonlinear FE calculation for a switched reluctance machine shows the damping effect taking saturation into account (fig 10) [3].

The calculation of the eddy current dampers can be done with sufficient accuracy by quasistationary complex field calculation. Assuming a Cartesian representation of the field problem, the 3 D Problem is reduced to a 2 D problem but the basic design rules can be derived.

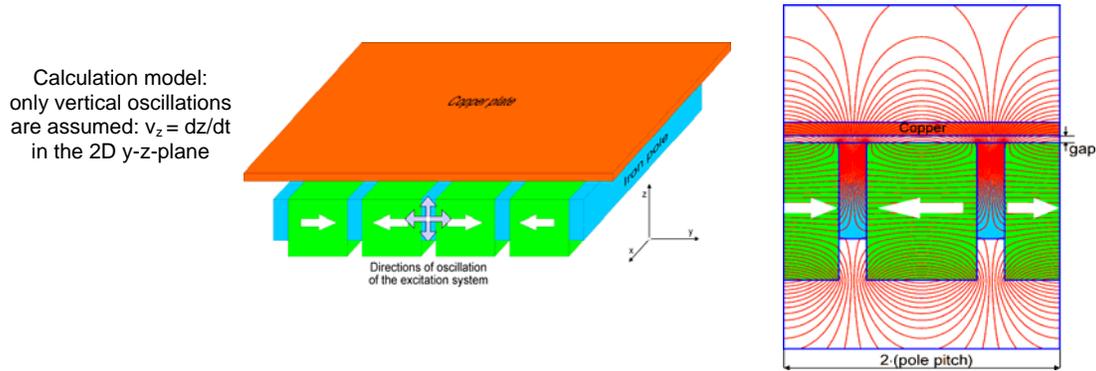


Fig. 11: Electrodynamic generation of damping forces $F = k \cdot dz/dt$

The damping force F_z is produced as a Lorentz force from the current density S_x and the flux density B_y in the copper plane with the effective area a :

$$F_z = I_x B_y = S_x a B_y \text{ with } F, v = f(t) \text{ and } I, S, B = f(y, z, t) \quad (1)$$

Using Ohms law for moving media the current density is derived from

$$S_x = -\sigma \cdot v_z B_y \quad (2)$$

yielding the proportionality

$$Fz \propto \sigma \cdot v_{\max} B^2 \quad (3)$$

For the low frequencies expected here force and velocity are in phase, what was proven by a transient field calculation. Further calculations taking the strong field gradients (Fig. 11) of the excitation system into account give characteristic curves (Fig. 12) for the influence of air gap and thickness of the copper shield. Before calculating the curves the optimal pole pitch was calculated for each air gap value. With help of the curves and proportionality of eq. 3 the damping forces can be derived for arbitrary configurations.

Separate dampers, backside use of the excitation magnet field or dampers integrated into the warm bore (squeeze field damper) have been studied yielding several patent applications.

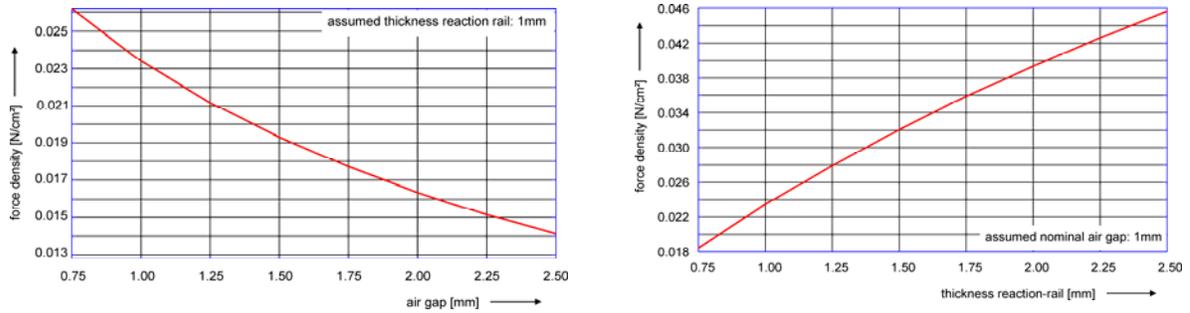


Fig 12: Excitation field and influence of air gap and thickness of copper plate on the damping force
 $(v_{z,\text{mean}}=2/\pi \cdot \omega \Delta z_{\text{max}}; f=13.5 \text{ Hz}; \Delta z_{\text{max}}=0.27 \text{ mm}; \sigma_{\text{Cu}}=50 \cdot 10^6 \text{ S/m})$

To investigate the effect of a space saving squeeze field damper measurements were conducted with varying frequencies, air gaps and under influence of the trapped field in the superconductor. For this validation a model arrangement of P-Magnet, copper plate and HTSC was excited with an electrodynamic shaker (Fig. 13).

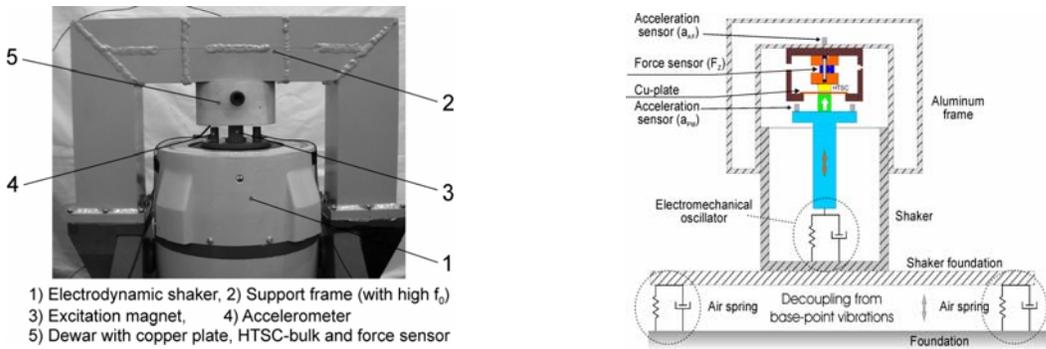


Fig. 13: Validation of the calculation models by damping measurements with electrodynamic shaker

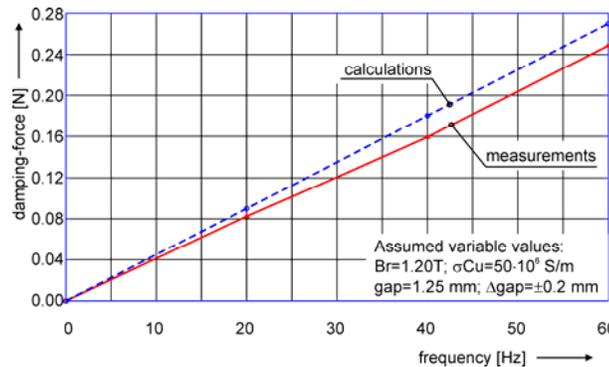


Fig 14: Damping forces (mean value of: $abs(f(t))$) depending on frequency and air gap, (damper plate: Cu- $\varnothing=65 \text{ mm}$, $th_r=2 \text{ mm}$)

The fundamental bearing properties stiffness and damping provide very strict boundary conditions for the design of the flywheel rotor and its inertial values. As superconducting bearings are principally soft bearings, the two rigid body modes have comparatively low Eigenfrequencies which are further reduced by the magnetic eccentricity effects of the unbalanced magnetic pull [3]. Due to the gyroscopic effects the critical speed of the rigid body modes is dependent on the rotor speed and split up into forward and backward modes especially for disc type rotors. The central quantity describing these effects is the ratio of polar J_p to equatorial inertia J_a . The influence of this ratio is illustrated in the Campbell diagrams of fig. 15.

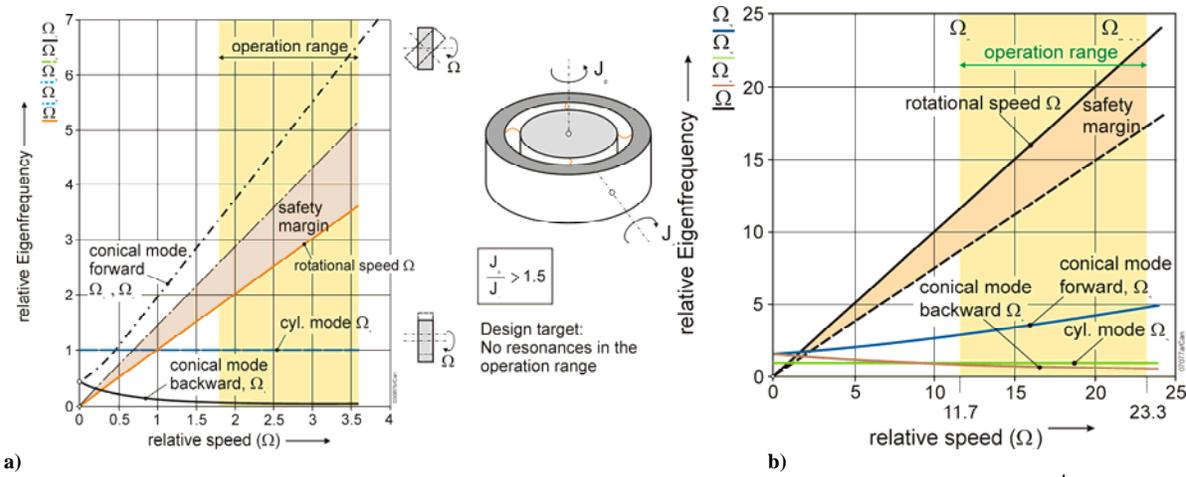


Fig.: 15: Exemplary Campbell diagrams for a disc type (a) and a cylinder type (b) rotor (safety margin $\sqrt{2}$)

So the first task is to keep the area of operation free from the higher elastic modes as described in [2] and as a second task we have to keep a sufficient distance to the critical speeds of the forward rigid body modes to avoid close to resonance operation. Alternatively a design of a long cylindrical rotor can be chosen what requires passing of the critical speeds of forward and backward conical mode and that of the cylindrical mode as well (Fig. 15). In the operating area a sufficient distance to the frequencies of the forward conical mode should be assured. In consequence there must be an area of forbidden designs between disc type and cylindrical rotor flywheels where the ratio of polar inertia J_p and equatorial inertia J_a is close to unity (spherical Tensor).

Considering the small achievable damping this area can be properly defined by a safety margin of $1/\sqrt{2}$ below and $\sqrt{2}$ above the critical speed of the conical mode. From the considerations regarding the inertial properties follow directly that favorable designs especially for high power ratings of the flywheel feature an electrical machine integrated into the rotor hub. The choice of machine type depends widely on the operational requirements as rotor losses, stand-by losses, response time or efficiency. With respect to stand by losses and start up time a reluctance machine with double saliency (Switched reluctance machine, SRM) was chosen.

For a flywheel with 2 MW rated power and 10 kWh effective energy a three step calculation had to be done: First designing of the electrical machine yields mass and inertias of the machine and the inner rotor construction, second designing the complete flywheel gives the overall values of mass and inertias and third calculating the Campbell diagram gives information about the resonance situation during startup and operation of the flywheel. For high speed designs the pole pair number was reduced with respect to the stator iron losses.

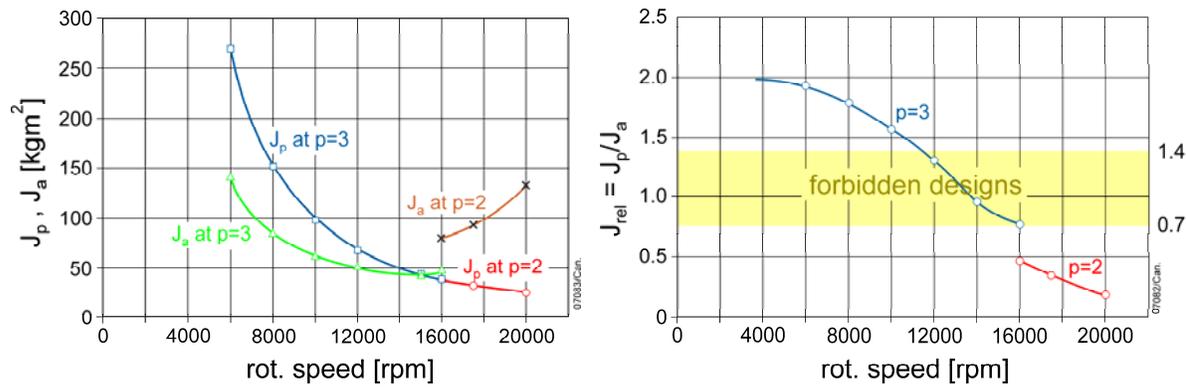


Fig. 16: Absolute inertias and inertial ratio for a flywheel design with 2MW, 10 kWh, the two branches of each graph depict pole pairs of 2 and 3

It has to be noted that a safety margin of $\sqrt{2}$ to the frequency of the forward conical mode obviously yields the same margins also for the area of the forbidden designs in the graph of the relative inertias.

Conclusion

Superconducting bearings show especially for flywheel rotors with high energy content some favourable properties due to their inherent stable and thermal robust behaviour. Experiences with a 5 kN capacity HTSC bearing confirmed these properties. These bearings are of low stiffness and neglectable damping what requires special attention in the design process. Damping can be provided by appropriate design of the motor windings or adding additional electrodynamic dampers. The damping properties of electrodynamic dampers in the region of operating frequencies of high power flywheels have been investigated and validated by model experiments. With a small damping the passing of the critical speeds of the rigid body modes is easily possible. A smooth operation of the flywheel is achieved if there is enough distance to the resonance frequency of the forward conical mode and if there are no elastic modes between the upper and lower operating speed. These design rules are exemplarily illustrated at a 2 MW, 10 kWh flywheel design for UPS and power quality applications.

Literature:

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