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Optimization of a compact flywheel energy storage system with superconducting bearings

PhD theses summary

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Budapest, 2010

1. Introduction and aims of this work

This work is focusing on flywheel energy storage (FES), which is one of the most promising possibilities of future energy storage methods regarding the storage of electric energy. However flywheels were already used by potters of the ancient Egypt, development and construction of a compact, economic system with high efficiency is still a very challenging task.

FES systems (FESS) contain a large moving part (the flywheel itself) and it stores energy in a traditional mechanical way. This has several serious advantages even over high-tech battery and other storage systems such as power density and cycle life.

However there are many possible forms and ways to store electric energy. Fig. 1 shows a comparison of achievable energy density of the different storage technologies.

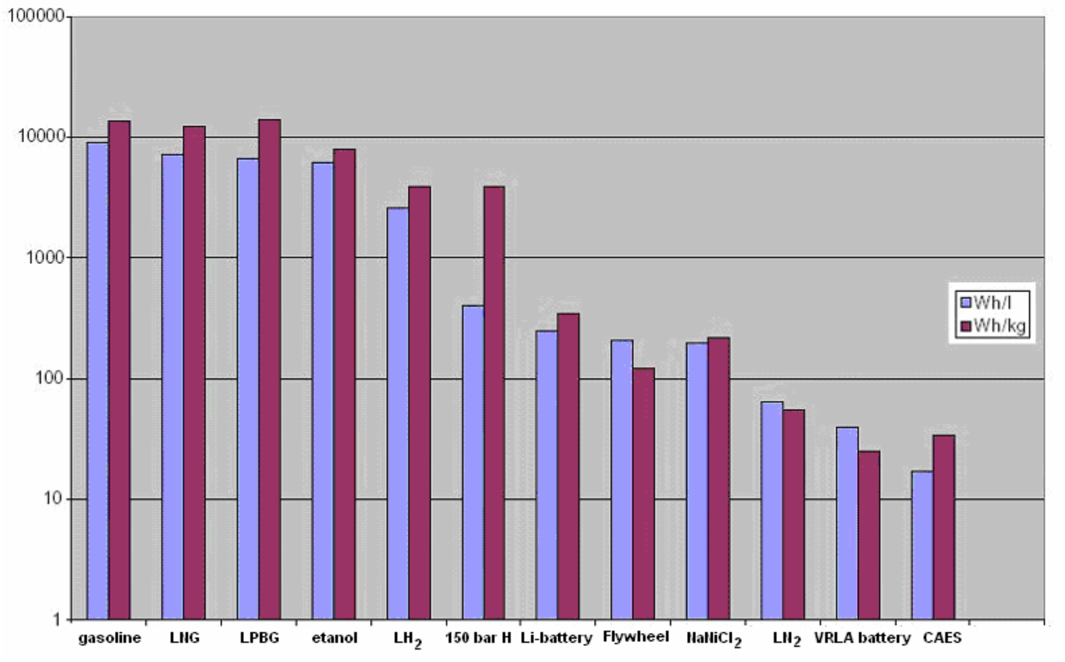

Figure 1. Achievable maximum specific energy density of different energy storage technologies compared to fossil fuels [**1**]

According to the figure above kinetic energy has as impressive achievable energy density. Besides this many advantages such as long lifetimes, insensitivity for discharge levels and environmental impacts, possibility of local or remote monitoring of the key parameters with high precision, small footprint and low impact on environment makes them attractive for many fields of application.

However the figure above shows only the achievable energy density of the flywheel itself, while at system level the achievable energy density is at least about 10 times smaller.

Position of flywheel energy storage regarding the different applications of electric energy storage is shown in Fig. 2.

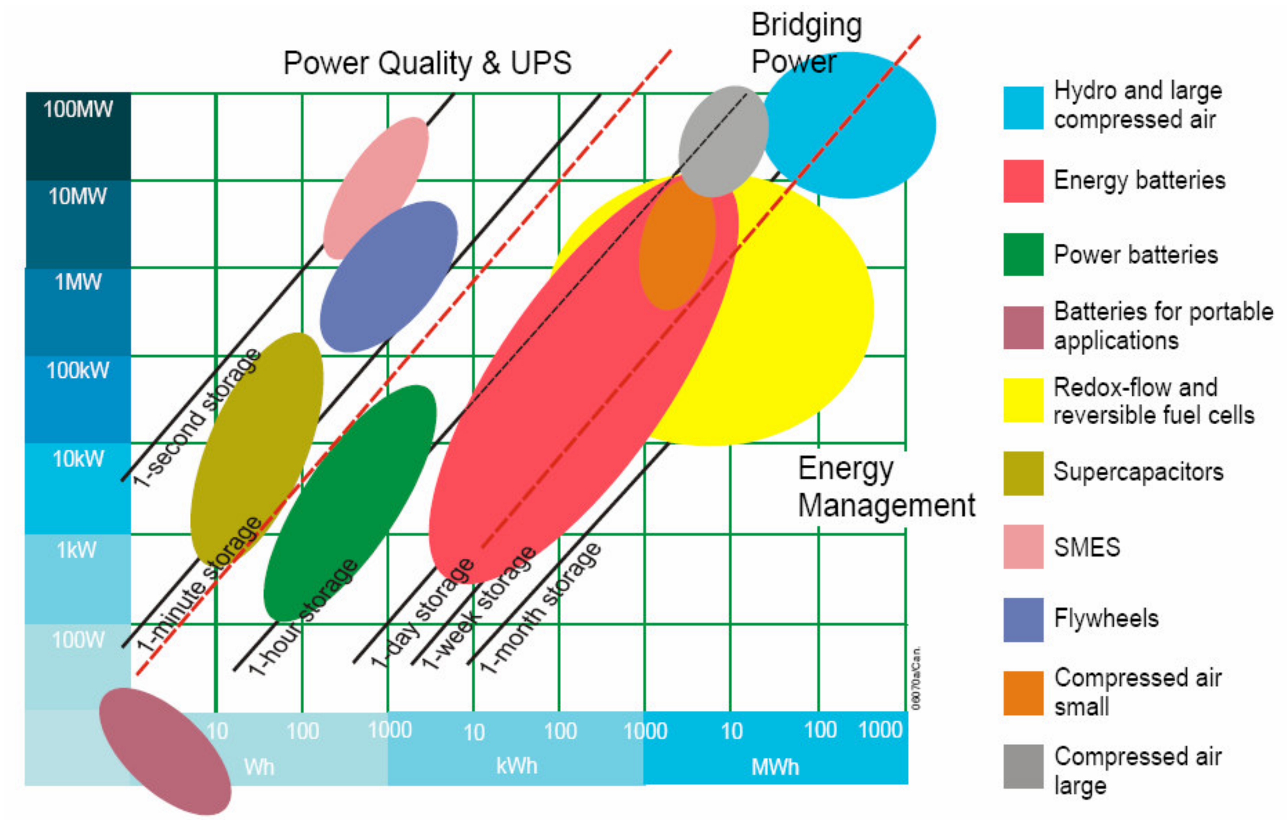

Figure 2. Application areas and position of different energy storage systems in storage of electricity [2]

This shows well that today flywheels can be used for short term (not more than several minutes long) energy storage at their rated power. Hence main application for them is UPS and short term balancing of energy fluctuations.

Dynamic (flywheel based) UPS systems are applied widely with a typical bridging time of 10-60 s. Long term storage is a problem mainly because of the high losses. One percent loss relative to the nominal power of a flywheel system is enough to discharge it within hundred times the bridging time, which is a very short time compared to other storage technologies.

In my studies I wished to verify the achievable energy density with flywheels, and I wished to find a construction, where the no-load losses are significantly smaller than that of conventional flywheels, desirably at a system level.

Flywheel energy storage however in spite of the easy storage theory is a very complicated system, and its design makes it necessary to know a combination of fields of engineering and physics. The most important among these are:

- vacuum physics (to decrease windage losses)
- cryogenics (to keep temperature of some main parts under -180 °C)
- physics of superconductors (levitation forces and damping)
- design of electrical machines (energy converter)
- design of electrical drives (network connection, motor and generator operation)
- flow theory (calculation of windage losses both in continuous media and free molecular flow)
- structural mechanics (flywheel design)
- rotor dynamics (to determine vibrations and losses caused by them)

The detailed study of all these features was naturally not possible in this worked, hence I chose to examine and optimize the flywheel, the superconducting bearings and the energy converter.

I studied possibilities of different flywheel shapes, regarding achievable maximum energy density and incorporation of the generator without causing mechanical problems.

I found a similarity of constant stress profiles, which makes it easier to design such structures.

Analyzing the losses of the system I found that the losses of the energy-converter should be decreased significantly (to be in the order of the bearing and windage losses). I proposed an ironless, disc-type construction, which is suitable for flywheel applications regarding compactness, power density, reaction time and the above strict expectations on losses can be achieved as well.

A made a detailed analytical optimization of such machines, and I gave a recommendation of main geometrical ratios and electrical parameters for different optimums such as maximum power density and minimum losses.

I have also designed and constructed several experimental machines of this kind, and it was verified in practice that losses of this construction can be at least an order of magnitude less that conventional machines compared to the rated power.

2. Research method

During my research I have started to study all components on the basis of the know analytical equations. On the basis of them I made design methods and theoretical models, which I verified by numerical methods (in most cases by finite element methods) and by experimental models and measurements.

I found the similarity of constant stress discs by the help of finite element methods for example.

Studying anisotropic flywheels I set up an equation system for multi-layer flywheels, and I made a design program, which can analyze such flywheels and hence accelerates highly the design (especially the determination of tolerances at boundaries of different layers). This made possible also to design superconducting bearings made of multi-layers of permanent magnets.

Design of the electrical machine was based on the traditional Hungarian Liska-Asztalos method, which I developed further to fit this special construction. For calculation of no-load losses I used a widely accepted approximation formula.

For design of superconducting bearings I used the direct solution of the Maxwell equations with special boundary conditions. The results were refined by finite element methods following these pre-calculations. The approximate method can be used well for demonstration and educational purposes.

Measurement results of the experimental models were used to verify and improve theory when it was necessary. This way I could find a good description of spin-down curve of simple superconducting bearings as well as I could confirm the low-losses of the construction I suggested.

The hardest part of my PhD work was definitely the experimental side. I had to set a flywheel lab to measure the experimental components and their joint operation. This was also made successfully however there is still a lot of development is possible both on the device and the measurement side.

3. Summary of new scientific results

1st thesis (energy-converter):

I have optimized double-rotor, disk-type permanent magnet synchronous machines with an ironless stator, and I have set up the background theory. I gave recommended key parameters to achieve optimums of different basis such as maximum power density projected to the active volume and minimum losses projected to the square of the apparent power.

(a) I have defined two ratios, the pole and the magnet ratio. I have shown that maximum torque/active power can be achieved if the magnet ratio is $a_{m,\,opt} = \frac{\mu_{mr} - \sqrt{\mu_{mr}}}{\mu_{mr} - 1}$, where μ_{mr} is the relative permeability of the applied permanent magnet material. Leakage should be kept at a low level to apply this formula. [9]

(b) I have introduced current density and fill factor into the general design equation as design parameters. I have shown how to choose the ratio of the inner and outer active diameter of the machine, and for the case of non-overlapping, concentric winding how to choose the ratio of the coils and the poles to achieve different optimums such as maximum power density projected to the active volume and minimum losses projected to the square of the apparent power. These optimum were shown for different phase numbers as well [9].

(c) I have confirmed by approximate calculations and measurements that in case of double-rotor, disk-type permanent magnet synchronous machines with an ironless stator specific no-load losses can be decreased at least by one order of magnitude compared to conventional machines, and hence the loss components of the no-load losses considering the whole rotor (the bearing part as well), can fall into the same order of magnitude. [1], [2], [3], [4].

2nd thesis (flywheel shape):

I have shown that for constant stress discs made of homogeneous, isotropic, and linearly elastic materials the ratio of the maximum equivalent stress and the calculated stress (according to the model neglecting the change of the thickness) is only dependent on the minimum slope of the profile function.
According to the above, a corrected energy density value can be given for discs made of any homogeneous, isotropic, and linearly elastic materials.
By comparing the equivalent energy densities of constant stress discs and constant thickness discs it can be stated that maximum achievable energy density of constant stress discs are lower than that of constant thickness discs if the minimum slope of the profile function of the constant stress discs are smaller than -0.6 [6].

3rd thesis (superconducting bearings):

(a) I have worked out a general model to describe dynamic behavior of simple superconducting bearings on the basis of physical phenomena. This model can describe both quantitatively and qualitatively the measured spin-down curves, and the experienced λ-effect around the critical speed. Different forms of the model for different circumstances (such as free molecular flow or continuous medium) were given. [1], [5], [7], [8].

(b) I have set up an analytical approximate calculation to determine the levitation of axial flux superconducting bearings. The calculation is based on the direct solution of the Maxwell-equations [2].

4. Most important publications for the theses

[1] Kohári Z, Schmidt I, Veszprémi K: Korszerű lendítőkerekes energiatárolók fejlesztése, Research report, EON-Északdunántúli Áramszolgáltató Zrt., BME VET, 2008

[2] Kohári Z, Schmidt I, Veszprémi K: Korszerű lendítőkerekes energiatárolók fejlesztése, Research report, EON-Északdunántúli Áramszolgáltató Zrt., BME VET, 2010

[3] Kohari Z: Test results of a compact disk-type motor/generator unit with superconducting bearings for flywheel energy storage systems with ultra-low idling losses, paper accepted, ASC 2010, expected publication IEEE Trans App Sup, 2011

[4] Kohari Z: Test results of a compact superconducting flywheel energy storage with disk-type, permanent magnet motor/generator unit, IEEE Trans App Sup, 19 (3), pp. 2095-98, 2009

[5] Kohari Z, Tihanyi V, Vajda I: Loss Evaluation and Simulation of Superconducting Magnetic Bearings IEEE Trans App Sup 15 (2) pp2328-31, 2005

[6] Z Kohari: Possibilities of kinetic energy storage, Elektrotechnika 101:(1) pp10-14, 2008 (in Hungarian)

[7] Vajda I, Kohari Z, Porjesz T, Benko L, Meerovich V, Sokolovsky, Gawalek W: Operational Characteristics of Energy Storage High Temperature Superconducting Flywheels Considering Time Dependent Processes, Physica C – Superconductivity, 372:(3) pp1500-1505, 2002

[8] Kohari Z, Vajda I: Spin-down Measurements and Loss Calculation of Multi-layer, Multi-pole HTS Magnetic Bearings, SUPERCONDUCTOR SCIENCE & TECHNOLOGY 18:(2) ppS105-S110, 2005

[9] Z Kohari: Axiális fluxusú gépek tervezése, Elektrotechnika, 2010, handed in

5. Scientific statistics

Publications:13 Independent references:15 Summarized impact factor:7,004

6. Litreture used in this summary

1 John T. S. Irvine The Bourner lecture: Power sources and the new energy economy, Journal of Power Sources, Volume 136, Issue 2, 1 October 2004, Pages 203-207

2 „DynaStore” – Energiesparender Schwungmassenspeicher mit HTSL Lagerung für dezentralen Einsatz”, kutatási jelentés, 2007