Feasibility Study for Small Scaling Flywheel-Energy-Storage Systems (FESS) in Energy Harvesting Systems

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Abstract:

Within recent research studies Flywheel-Energy-Storage-Systems “FESS” with the capacity to store more than 1kWh of energy have been realized in application. Due to the fast charge and discharge capabilities of the flywheels, they are suitable in the stabilization of net frequency or they can be used as a power supply in case of an electrical blackout. This study describes how small FES can be further scaled down, and shows the limits and problems that emerge with the downscaling. It illustrates how the system must be designed to work as an energy storage device for small energy harvesting systems. The biggest problems in the FES Systems are the specific losses that occur due to the smaller scale of the flywheel. Hence the concept of passive magnetic bearings (homopolar bearing with thin copper winding) to reduce losses due to flux is introduced here. A motor/generator concept of an ironless air-coil system with fix coils and rotating magnets would eliminate hysteresis iron losses. The coil-winding must be made out of a bundle of thin copper wires to minimize flux effects in the winding to minimize standby losses. Moreover, to reduce losses, the flywheel must spin in an evacuated housing. Fluid-friction is responsible for the highest specific losses in small dimensioned flywheel devises at environmental atmosphere. New materials as carbon composites can be used for the flywheel design, whereby they increase maximum tolerable angular velocity and efficiency. Given that no friction occurs, the estimated lifespan can be as long as decades, with the flywheel still functioning at full efficiency.

In the course of this thesis, a demonstrator will be created to illustrate this technology and to find out if a simple but efficient system can be created. This demonstrator will be built for a small-medium energy-capacity of 20 Wh and will show if the aircoil motor/generator concept and magnet supported full ceramic bearings are suitable for this device.

Keywords: FESS, flywheel, micro energy storage, Energy Harvester

Introduction

FESS´s are finding an increasing number of practical applications. There are several instances where they were used for short-time energy storage, e.g. Kinetic Energy Recovery System “KERS” in Formula 1 cars, the metro system “Üstra” in Hannover, or for uninterruptable power supply (UPS) in computer-systems in cases of emergency [1]. Miniatures FESS that are applicable in energy harvester systems, with a diameter of 35 mm, have been realized in [2]. Due to the downscaling of manufacturing methods, FESS’s could be realized to an even smaller dimension. Presently, high specific strength materials, e.g. high tensile stress carbon fibers as “T1000”, increased the energy density of flywheels up to 100 Wh/kg (including housing). Due to its enormously high specific strength, prospective materials like Carbon Nano Tubes (CNT) could increase the energy density to about 1800 Wh/kg (without housing, 600 Wh/kg including housing) and thus compete with a new generation of “(nanoporous carbon) electric double-layer supercapacitors” (EDLC) that actually have been developed as a prototype with an energy density of 300 Wh/kg (without housing) [3]. Chemical batteries (Zinc-Air-Battery) have reached an energy density of 450 Wh/kg. However, since they are not rechargeable, available efficient rechargeable batteries as Lithium-Ion-Batteries reach an energy density of up to 200 Wh/kg. Furthermore contactless electro-dynamic bearings for flywheels have been developed [4] that operate at high rotational velocity and replace roller bearings to reduce bearing friction and extend the FESS lifetime. In comparison to chemical batteries FESS’s have a great advantage concerning lifecycles, efficiency, dis/-charge time and power density. Fig. 1 shows the power density vs. energy density of different storage devices.

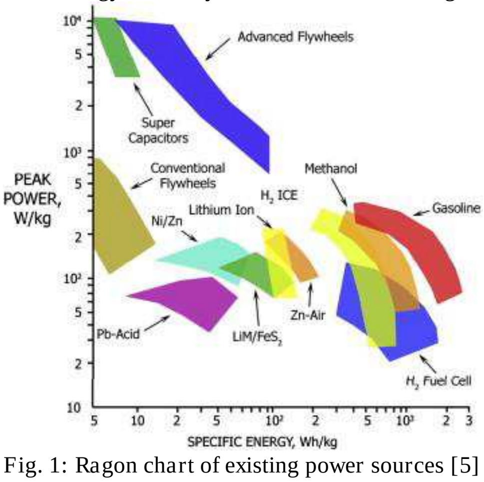

Fig. 1: Ragon chart of existing power sources [5]

FESS physical relations

Besides manufacturing complexity of miniature parts, specific losses impede the processes of downscaling. The equation to determine energy content (E) of a flywheel is:

$$E = \frac{1}{4} * m * r^2 * \omega^2 \quad (1)$$

where m represents the mass of the flywheel, r the radius, and ω the angular velocity, assuming a homogeneous flywheel. Smaller flywheels must compensate for their small dimensions with higher rotational speed, to exploit the material limits. Typically the limiting stress occurs in a tangential direction, as given by [6]:

$$\sigma_t = \rho * r^2 * \omega^2 \quad (2)$$

In Equation (2), σ_t denotes the material stress and ρ the density. Comparing eq. (1) and (2) material stress is proportional to energy content at the same mass. This means that the higher the weight specific strength of a material the more weight specific energy can be stored. New materials as carbon fibre reinforced composites have high specific strength and thus are well suited for this task. When CNT will be produced economically they could theoretically increase energy density of a FESS up to 1800 Wh/kg due to an experimental gained tensile strength of around 30 GPa [7]. If, for instance, a 5mm diameter FESS would be built out of CNTs, a rotational velocity of 18 million rpm must be realized to exploit the CNT Strength and thus the higher energy density.

Losses

Smaller flywheels have a worse relation between mass (correlating to stored energy) and surface (correlated to gas friction), and hence the gas friction effect increases. The gas friction (P_{gas}) can be calculated with [8]:

$$P_{gas} = \sqrt{\frac{\pi * M}{2 * R * T}} * p * \omega^2 * r^3 * (r + 2 * h) \quad (3)$$

M: molar mass
R: molar gas constant
T: temperature
p: pressure
h: flywheel height

Importantly, an ultra-high vacuum is extremely important for an efficient run.

For motor/generator concepts, an ironless permanent-magnet excited air coil motor could be an option. This motor type is free from hysteresis iron losses but eddy current losses occur in the copper windings. Miniature flywheels with this type of motor/generator do not need an external power supply for reactive power as in the case of reluctance motors, and can easily be controlled. The eddy currents are mainly related to the rotational velocity, the mass of the copper winding and the diameter of the copper wire (See Eq. (4)) [9]:

$$P_{eddy} = \frac{1}{24} * \kappa * \omega^2 * b^2 * \hat{B}^2 * V \quad (4)$$

κ: electrical conductivity
ω: resetting frequency
b: copper wire diameter
$\hat{B}$: magnetic flux density
V: copper volume

As rotational velocity increases in small FESS's, it is necessary to use bundled copper wires with small diameters to reduce eddy current losses. In [10] a 1 µm thin copper wire has been produced that could stand currents of up to 1011 A/m. With electrical conductivity and magnetic flux held constant, the eddy current losses have no influence on the specific losses, assuming that the copper wire scales react in the same way as the whole FESS does. The permanent-magnets that will be used for power generation, and the bearings system, have very low material strength. Therefore they must be embedded inside the rotor to withstand the high centrifugal forces. Reluctance generators that are often used in FESS's differ from air-coil concepts as they do not incur any standby losses. The need for an external reactive power supply to generate a magnetic field can be a disadvantage, especially in small self-supporting energy harvesting systems.

Finally, bearing losses should be explored: High speed frictionless magnetic bearings can be used as introduced in [11]. These electro-dynamic bearings, using magnets rotating between copper wire coils, generate eddy currents at a certain rotational velocity. Thus a reactive magnetic force lifts and stabilizes the flywheel without any additional controlling device. To reduce eddy current losses at high speed, the copper wires must be as thin as possible to reduce losses, hence as already mentioned above in [10] thin wires should be used. In combination with permanent magnets, an efficient, long-living and high speed FESS is possible. An illustration where a 1.3 kg rotor levitates at frequencies from 4,800 rpm onwards, with only 0.8 W eddy current losses, is given in [11]. Till the electro dynamic bearing starts working, touchdown bearings that only operate on low speeds, like ceramic roller bearings or jewel bearings, can be operationalized. Bearing losses mainly depend on the flywheel mass assuming that the bearing stiffness is designed for high rotational velocity.

Scaling

To see how downscaling affects rotational velocity, energy content and losses, the following parameters are set:

Scaled parameters: (See fig. 2)
outer flywheel diameter d_o = 1 - 100 mm
inner flywheel diameter $d_i = 0.5 * d_o$
height $h = 0.5 * d_o$
vacuum: $1*10^{-4}$ mbar
copper wire diam. air-coil $b = d_o/500$; min.: 1 µm
Tangential stress: Spring steel 1.7108: 1.4 GPa, Titanium alloy TiAl6V4: 1.1 GPa, Toray T1000: 3 GPa [12] and CNT TS: 30 GPa [7])

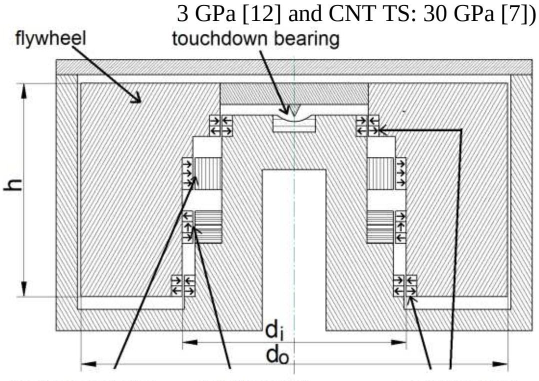

Fig. 2: Schematic diagram of FESS

Resulting values:
Rotational velocity n, halftime-period τ, energy content E
Energy density: Steel: 13 Wh/kg, Titanium 14 Wh/kg, T1000: 110 Wh/kg, CNT: 600 Wh/kg

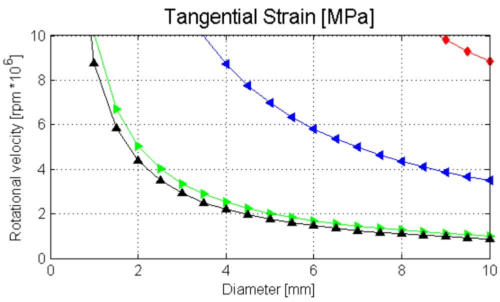

Fig. 3: Resulting rot. velocity of flywheel vs. diameter

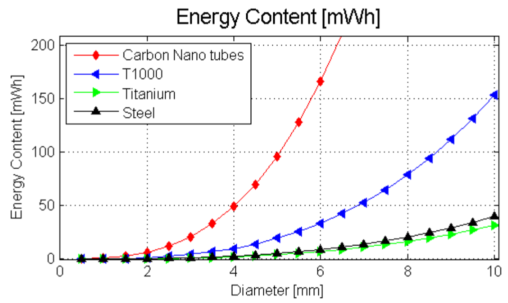

Fig. 4: Energy *content of scaled FESS's*

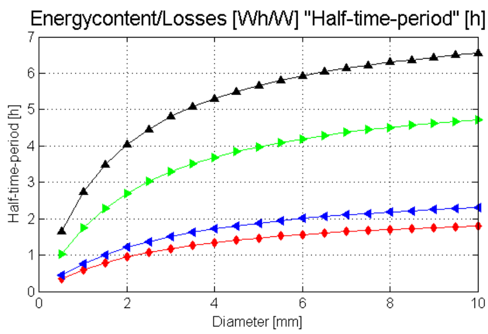

Fig. 5: Halftime-period τ reduces with smaller dimensions

The losses have been calculated from eq. (3) and (4) together with bearing losses. Bearing losses are calculated by assuming a relationship of weight to power of 0.6154 W/kg [11], and independent of rotational velocity. Due to the high strength of carbon fibre materials, the energy content for an identically sized FESS is much higher than for metal flywheels. The high rotational velocity of carbon fibre flywheels causes higher gas-friction and eddy current losses in the copper coils so that it has a stronger effect on the losses than the specific flywheel weight. This is why the halftime periods of the composite FESS are much shorter.

Conclusion

Under the above mentioned aspects, composite flywheels are suitable if the charge and discharge timespan is short and the required energy is relatively high. Metal FESS's could be a good option for cheaper energy storage if charge/discharge timespans are longer and energy content does not have to be as high as in composite flywheels. Since a good equation for downscaled 3-phase air coil motor/generators couldn't be obtained yet, a power plot (power [W] vs. diameter [mm]) was not possible here. But referring to fig. 1, power densities of more than 5000 W/kg in bigger FESS have been achieved. The efficiency of charge/discharge cycles of this type of motor, generally at about 90 %, is extremely high. Even after years, the FESS's still maintain the same efficiency.

Outlook

If techniques are developed to produce carbon nanotubes in a cost efficient manner and in larger filaments, they could increase energy density by a factor of 5 compared to actual FESS's. High life expectation, fast charge and discharge and cheap mass production could help FESS's to be used as energy storage devices of the future, like in cases of power backup, fast acting energy harvesting applications etc.

At the IDS Hannover, a demonstrator will be built with an energy content of 20 Wh, a permanent magnetic supported ceramic bearing system, a high strength aluminium rotor and an air coil motor/generator (power peak 1 kW). If a successful run could be achieved, a micro scaled FESS with carbon flywheel and magnetic bearing system could be realized.

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