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Flywheel energy storage—An upswing technology for energy sustainability

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Abstract

Flywheel energy storage (FES) can have energy fed in the rotational mass of a flywheel, store it as kinetic energy, and release out upon demand. It is a significant and attractive manner for energy futures 'sustainable'. The key factors of FES technology, such as flywheel material, geometry, length and its support system were described, which directly influence the amount of energy storage and flywheel specific energy. It is very suitable to such applications that involve many charge–discharge cycles and little in the way of long-term storage applications including International Space Station (ISS), Low Earth Orbits (LEO), overall efficiency improvement and pulse power transfer for Hybrid Electric Vehicles (HEVs), Power Quality (PQ) events, and many stationary applications. Design margins, fault protection and containment were considered as three good approaches to solve safety issue. Vacuum enclosures or helium–air mixture gas condition were discussed for solution of windage energy loss. In short, with the aid of new technologies the cost of FES can be lowered and the FES will play a significant role in securing global energy sustainability.

Keywords: Flywheel energy storage; Specific energy; Flywheel factors; Applications; Issues

1. Introduction

It is now accepted that the present production and use of energy pose a serious threat to the global environment and consequent climate change [1]. Accordingly, more and more countries are examining a whole range of new policies and technology issues to make their energy futures 'sustainable' [2]. Clearly, as nonrenewable energy source become more scare, the world is set to make major changes to its energy supply and utilization systems. One significant manner using energy storage unit is very attractive and expected to show up. Flywheel is proving to be an ideal form of energy storage on account of its high efficiency, long cycle life, wide operating temperature range, freedom from depth-of-discharge effects, and higher power and energy density—on both a mass and a volume basis [3–6]. Flywheel energy storage (FES) can have energy fed in the rotational mass of a flywheel, store it as kinetic energy, and release out upon demand. The first real break-through of FES was the seminal book by Dr. A. Stodola in which flywheel rotor shapes and rotational stress were analyzed [7]. The next big milestones were during the 1960s and 1970s when NASA sponsored programs proposed energy storage flywheels as possible primary sources for space missions and FES was proposed as a primary objective for electric vehicles and stationary power back-up [8]. In the years immediately following, fiber composite rotors were built and tested in the laboratory by US Flywheel Systems and other organizations [9,10]. With the development of strong lightweight materials, microelectronics, magnetic bearing systems interest in the potential of flywheels was flourishing. The present designs at US Flywheel Systems (USFS) have been tested and showed power densities at its designed speed 110,000 rpm will exceed 11.9 kW/kg with in-out efficiency of 93% [7]. The University of Texas at Austin has subjected a composite flywheel spinning at about 48,000 rpm to more than 90,000 charge–discharge cycles with no loss of functionality (see Fig. 1) [11]. At the same time a FES delivering 360 MJ energy and 2 MW rated power was also developed by the University of Texas at Austin Center [12].

The objective of this paper is to describe the key factors of flywheel energy storage technology, and summarize its applications including International Space Station (ISS),

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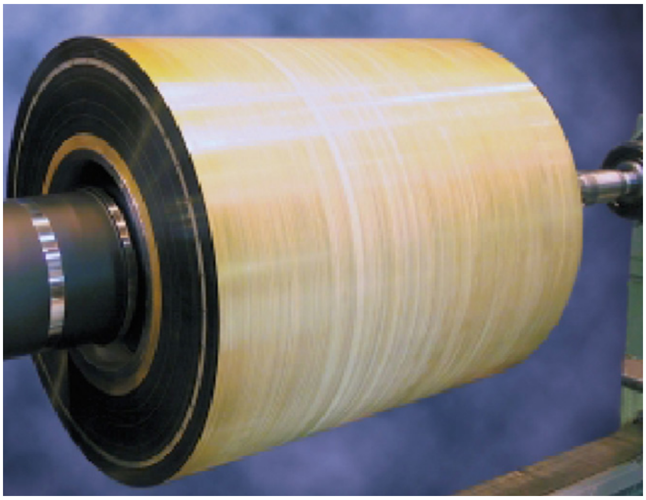

Fig. 1. A flywheel rotor at the University of Texas at Austin's Center.

Low Earth Orbits (LEO), overall efficiency improvement and pulse power transfer for Hybrid Electric Vehicles (HEVs), Power Quality (PQ) events, and many stationary applications, which involve many charge–discharge cycles and little in the way of long-term storage. Eventually, three solutions for safety issues and two approaches for windage loss were also discussed.

2. Key factors of FES

2.1. Flywheel material

There are two basic classes of flywheels based on the material in the rotor. The first class uses a rotor made up of an advanced composite material such as carbon-fiber or graphite. These materials have very high strength to weight ratios, which give flywheels the potential of having high specific energy. The second class of flywheel uses steel as the main structural material in the rotor. This class not only includes traditional flywheel designs which have large diameters, slow rotation, and low power and energy densities, but also includes some newer high performance flywheels as well.

The amount of energy stored, E, is proportional to the mass of the flywheel and to the square of its angular velocity. It is calculated by means of the equation

$$E = \frac{1}{2} I \omega^2 \quad (1)$$

where I is the moment of inertia of the flywheel and ω is the angular velocity. The maximum stored energy is ultimately limited by the tensile strength of the flywheel material. The maximum specific (per unit mass) energy density E_{sp} that can be stored in a flywheel may be written as

$$E_{sp} = K_s \frac{\sigma_m}{\rho} \quad (2)$$

where σ_m is the maximum tensile strength of the flywheel material, ρ the density of the flywheel, and K_s is the shape factor. The dependence of E_{sp} on material properties, i.e. proportional to tensile strength an inversely proportional to density, shows we should use a kind of material which has high tensile strength and low density. Fiber composites are the materials of choice for flywheel energy storage systems. Table 1 shows theoretical flywheel energy comparison when $K_s = 0.5$. The highest tensile flywheels are not made of steel, but of fiber-reinforced composites. As well as rotating faster and storing more energy than steel flywheels, these composite flywheels are much safer if the maximum safe speed is exceeded, since they tend to delaminate and disintegrate gradually from the outer circumference rather than explode catastrophically [13].

Table 1
Physical parameter of commercial fibers

Rotor material	σ_m (GPa)	ρ (kg/m^3)	E_{sp} (Wh/kg)
E-glass	3.5	2540	190
S-glass	4.8	2520	265
Kevlar	3.8	1450	370
Spectra 1000	3.0	970	430
T-700 graphite	7.0	1780	545
T-1000 graphite (projected)	10.0	–	780
Managing steel	2.7	8000	47

2.2. Flywheel geometry

The geometry of an energy storage flywheel is generally chosen in such a way as to maximize the energy density and/or the specific energy [8]. Consider first optimization of the moment of inertia. This would involve placing the mass as far from the axis of rotation as possible and/or increase the density in order to increase I. Since σ_m is given by

$$\sigma_m = \rho r^2 \omega^2 \quad (3)$$

Flywheels can readily be designed which make optimal use of the material strength. By using Eq. (2) the specific energy E_{sp} can be calculated for various rotor designs in terms of a shape factor, K_s for isotropic materials; see Table 2. The shape factor, K_s is a measure of the shape efficiency of the rotor in the stress-limited case.

The case of anisotropic materials, such as carbon composite, is not as straight forward, may be illustrated by the following example. For ideal composite rotors, the analysis is more complicated because the maximum stress depends not only on the rotor shape, but also on the composite material system(s), fabrication process, loading conditions, and other factors such as failure modes. The maximum tangential stress, S_m in a long

Table 2
Shape factor for various flywheel geometry

Flywheel geometry	Cross sectional/pictorial view	Shape factor K_s
Flat unpierced disc		0.61
Thin rim		0.50
Rim with web		0.40
Flat pierced disc		0.31