FLYWHEEL BASED BATTERY CHARGER

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ABSTRACT

A review of flywheel energy storage technology was made, with a special focus on the progress in automotive applications. We found that there are at least 26 university research groups and 27 companies contributing to flywheel technology development. Flywheels are seen to excel in high-power applications, placing them closer in functionality to supercapacitors than to batteries. Examples of flywheels optimized for vehicular applications were found with a specific power of 5.5 kW/kg and a specific energy of 3.5 Wh/kg. Another flywheel system had 3.15 kW/kg and 6.4 Wh/kg, which can be compared to a state-of-the-art supercapacitor vehicular system with 1.7 kW/kg and 2.3 Wh/kg, respectively. Flywheel energy storage is reaching maturity, with 500 flywheel power buffer systems being deployed for London buses (resulting in fuel savings of over 20%), 400 flywheels in operation for grid frequency regulation and many hundreds more installed for uninterruptible power supply (UPS) applications. The industry estimates the mass-production cost of a specific consumer-car flywheel system to be 2000 USD. For regular cars, this system has been shown to save 35% fuel in the U.S. Federal Test Procedure (FTP) drive cycle.

1. INTRODUCTION

The flywheel is an old means of storing energy and smoothing out power variations. The potter's wheel and the spinning wheel are examples of historical uses of flywheels. The focus in this review is on applications where flywheels are used as a significant intermediate energy storage in automotive applications.Several tradeoffs are necessary when designing a flywheel system, and the end results vary greatly depending on the requirements of the end application. Examples exist of power flywheels, such as the ABB short-circuit generator (built in 1933 and still in use today), which can deliver a stunning 4000 MVA and short-circuit currents of 100 kA rms for short durations of time [1]. On the other side of the spectrum, one can find a lightweight energy flywheel with a rotor specific energy of 195 Wh/kg [2], which is comparable to that of Li-ion batteries.

Perhaps the most important tradeoff in a flywheel energy storage system is between high power or high energy. A high-power application is relatively simple seen from a flywheel design perspective. A standard high-power electric machine is fitted with some extra weight to sustain the power for a long enough time. A focus on high energy means that the requirements on the mechanical properties of the rotor puts limits on the power transfer units or suspension. Energy flywheels are a main area of research, since this opens up possibilities for new end applications.

Some end applications, for example a flywheel power buffer in a hybrid bus or a Formula 1 flywheel, will release the stored energy relatively soon after charging. This requires an optimization focus on the round trip efficiency (sometimes called AC-AC efficiency), computed as the fraction ~~of input and~~ available output energy:

1.1. Rotor: Mass vs. Speed

The usable kinetic energy stored in a flywheel is the speed interval over which it is allowed to operate:

$$E = \frac{1}{2} J \; !^2 \quad = \frac{!_{max}^{\;2} \quad !_{min}^{\;2}}{2} \underset{Z}{} r^2 dm \qquad (3)$$

where J is the moment of inertia about the axis of rotation; ! is the rotational velocity and dm is a small mass element at a distance r from the axis of rotation. A heavy steel rotor is optimized for high inertia; more energy is attained in a linear fashion by adding extra weight. Steel rotors are usually solid (solid rotors can be shown to be optimal in an energy density sense for isotropic materials [3]). High power is fairly straightforward to attain on high-inertia machines.

Kinetic energy grows quadratically with speed; for a rotating body, this implies that energy for a mass element grows quadratically with radius and rotational speed. Unidirectionally-wound carbon composites exhibit extreme strength in one direction, which implies that a thin rotating shell is optimal, since most of the centrifugal stress is developed in the circumferential direction [3]. By placing mass close to the periphery, it is better utilized (a higher speed at a larger radius results in higher kinetic energy per mass element). Flywheels optimized for high-speed operation are usually of higher energy density, although the high speed can impede power transfer capabilities.

1.2. Bearings: Magnetic vs. Mechanical

The choice between magnetic and mechanical bearings depends on the application; see Table 1. Volume and weight constraints suggest the use of mechanical bearings. However, vacuum operation and low loss requirements suggest the use of magnetic bearings. Magnetic bearings require backup systems for handling delevitation events (planned and unplanned), and although these are maturing [4], industrial standards are yet to be rigidly defined.

Table 1. Comparison between mechanical and magnetic bearings.

Mechanical bearings	Magnetic bearings
High stiffness per volume	Larger footprint for a given stiffness
Known technology	Industrial standards not yet mature
Must be rated for unbalance forces at high speeds	Can allow the rotor to spin around the natural axis at high speeds
Higher standby losses at high speeds	Very low standby losses
Lubricants evaporates during vacuum operation	Good for vacuum operation
May require active cooling systems	Practical full magnetic levitation requires active control

1.3. Power Transfer: Electric vs. Mechanical

Table 2. Theoretical potential for flywheels with contemporary and future materials.

Material	Ultimate tensile stress (MPa)	Density (kg m 3)	Rotor energy density (Wh/kg)
Aluminum 7075	572	2810	28
17-7 PH Stainless steel	1650	7800	29
Titanium Ti-15V-3Cr-3Al-3Sn ST 790 °C	1380	4760	40
Advantex E-glass (glass fiber)	1400	2146	90
Toray T1000G composite	3040	1800	234
Toray T1000G fiber	6370	1800	491
Vapor grown carbon nanofibers [25]	2920	2000	202
Single wall carbon nanotube (low end) [25]	50,000	1300	5341
Single wall carbon nanotube (high end) [25]	500,000	1300	53,418
Multi-walled carbon nanotubes (low end) [25]	10,000	1750	793
Multi-walled carbon Nnanotubes (high end) [25]	60,000	1750	4761

2. Understanding the Flywheel Niche

There are primarily four properties that make the flywheel attractive for use as energy storage:

- High power density;
- Long cycle life;
- No degradation over time and;
- Easily estimated state-of-charge.

Taking advantage of the first two properties leads to systems with high and very frequent flows of energy. One example of this is using the flywheel as a buffer for smoothing frequent fluctuations, e.g., in the grid.

Taking advantage of the first and fourth properties leads to systems with high, but rare flows of energy, but where correct information regarding the state-of-charge of the storage system is critical. One example of such a system is the uninterruptible power supply (UPS). In a battery system, the aging processes can increase the internal resistance, while an SoC estimation from the measured voltage does not reveal this [26].

2.1. Depth-of-Discharge

The cycle life of flywheels is not directly related to depth-of-discharge; however, this is the case for batteries. This is important when defining the niches for flywheel energy storage.

Batteries degrade when cycled, when discharging at high rates and at high temperature [26]. The degradation affects energy capacity and power capacity, the latter through an increase in internal resistance. For an application with a requirement of 106 cycles, a battery pack can only be run at a depth-of-discharge of 3% (as seen in Figure 2), which implies that a battery that is 33-times larger must.

The statistics of the discharge depths is very important when considering end applications for energy storage. Assume the following two cases.

2.1.1. High Variations on the Required Cycle Energy

This case is applicable for the regular car owner. The average trip distance for a car in Europe is only 15 km [28], but people want to have the capacity to drive 500 km or more. The average number of trips per day is also less than three. The electric car manufacturer Tesla Motors markets their car as having a range of 434 km, with Li-ion batteries as the only energy storage [29]. Depending on the depth-of-discharge, the max range cycle life is around 2000 cycles (driving the max range every day for six years). However, since the average use case for people is much less than that, the typical depth of discharge is only 3.5%. That means that the battery lasts for 1,000,000 average cycles or longer than the lifetime of the car (from a depth-of-discharge aging point of view).

$$\frac{1;000;000 \text{ cycles}}{3 \text{ average cycles per day } \; 365 \text{ days}} = 936 \text{ years} \qquad (5)$$

In essence, the electric car buyers are not buying a high-capacity battery only for the maximal range, but for limiting the depth-of-discharge, so that the battery lasts the entire lifetime of the car.
2.1.2. Few Variations on the Required Cycle Energy
The second case is characterized by small changes in the required energy per cycle. Many applications fit into this niche:
- Power buffers in drive lines where the power density is low in the prime energy carrier

3. RESULT

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4. CONCLUSION

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