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Research paper

A comparative study between optimal metal and composite rotors for flywheel energy storage systems

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ABSTRACT

Most recent research on flywheel rotors has focused on high-speed composite rotors as the storage element of the flywheel energy storage system (FESS). Literature research indicates that this is primarily due to the high specific energy of composites compared to metals. However, a quantitative comparison of the performance of flywheels made from these materials has not been conducted. This paper aims to answer the question - 'Are composite flywheels better suited for energy storage than metal flywheels?'. This study uses three different performance indices: kinetic energy; specific energy; and, energy per cost, to compare the corresponding rotor designs. A plain-stress, linear elastic mathematical model of the flywheel rotor described by Krack et al. (2010) is used for analysis. Different optimization formulations corresponding to performance indices chosen based on the FESS application are then solved to study optimal FESS designs. The study indicates that for applications where the energy-per-cost is to be maximized, metals are superior to composite rotor materials. On a total energy basis, metals and composites are on par with each other. Composite rotors are however, superior for applications requiring high specific energy. A hybrid rotor, with a metallic energy storage element and a thin composite burst-rim, is also optimally designed and found to be a viable solution, because it offers the cost benefit of metal rotors, as well as the burst-safety provided by composites.

1. Introduction

In order to improve the reliability and robustness of the grid, short duration energy storage is of critical importance to electric utilities. Flywheels have become a feasible storage choice for typical short duration applications, such as frequency regulation (Silva-Saravia et al., 2017), voltage leveling (Cardenas et al., 2001) and fault ride-through support (Daoud et al., 2016) of intermittent sources like wind and solar farms (Arani et al., 2017). As the integration of intermittent renewable resources in the grid continues, a proportional increase in energy storage capacity will be required in order to comply with existing and future grid codes for safety, reliability and profitability. The increasing use of flywheel energy storage systems has resulted in a subsequent resurgence of research in the area of flywheel analysis and optimization in order to achieve more reliable and cost effective designs.

Some flywheel specifications for prototype storage installations across the world are listed in Table 1. The table depicts the type of flywheel rotor, power capacity, energy storage, mass, speed, self-discharge and round-trip efficiency of various manufactured flywheels. These flywheels have been installed for a variety of applications, ranging from frequency regulation, voltage support and resilience, which need short duration storage (in minutes or seconds), to reserve capacity, which needs longer duration storage (in hours). Some manufacturers have chosen to use composite rotors, while others use metal rotors. Thus, it is necessary to understand all the factors that may affect the choice of rotor material, and consequently, the optimal design and performance of the storage system.

The performance of a flywheel energy storage system (FESS) can be improved by operating it at high speeds, by choosing high strength materials, and by optimizing the shape and dimensions of the flywheel rotor (Arnold et al., 2002). The use of multiple-rim composite rotors can further increase the energy content, by optimizing the number of composite rims, the sequence of materials used in the rims, the amount of interference between the rims, and their relative thickness (Arnold et al., 2002; Genta, 2014). The properties of composite materials, such as high strength in the fiber direction, low density, and flexibility in tailoring of material properties make them a promising choice of rotor material. On the other hand, metal flywheels have advantages such as ease of manufacturing and lower cost. Standby losses occurring in FESS components, such as the bearings and electrical machine, scale with the speed of operation, thus the decreased operational speed in metal flywheels also reduces losses occurring in the system.

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Table 1
Flywheel storage solutions deployed at utility scale applications.

Flywheel model	Rotor type	Power capacity kW	Energy storage kWh	Mass kg	Specific energy Wh/kg	Speed rpm	Self-discharge W	η %	Ref
Beacon Power, LLC (BP400)	Carbon composite	100	25	1133	22.06	8000–16000	4500	85	(Beacon Power Webpage, 2017)
LEVISYS	Carbon composite	10–40	10	–	–	–	–[a]	–	(LEVISYS Webpage, 2017)
Stornetic GmBH (EnWheel)	Carbon composite	22–80	3.6	–	–	<45000	–	–	(Stornetic GmBH Webpage)
Flywheel Energy Systems Inc.	Composite	50	0.75	135	5.55	15500–31000	500–1000	86	
Powerthru / Pentadyne	Carbon composite	190	0.528	590	0.89	30000–53000	250–300	–	(Powerthru Webpage, 2017)
Calnetix (VDS-XE)	4340 Aerospace steel	300	1.11	821	1.35	24500–36750	–	–	(Calnetix Webpage, 2017)
Amber Kinetcis (M32)	Low-carbon Steel	8	32	2268	14.10	<8500	65	88	(Amber Kinetics Webpage, 2017)
Temporal Power	Steel	100–500	50	3500	14.28	<10000	500	85	(Temporal Power Webpage, 2017)
ActivePower	Steel	50–250	0.958	272	3.55	7700	2500	–	(ActivePower Webpage, 2017)
ABB (PowerStore)	Steel	100–1500	5	2900	1.72	1800–3600	12000	–	(ABB Powerstore Webpage)
Piller	–	2400	5.833	–	–	1500–3600	–	–	(Piller Webpage, 2017)
Energiestro	Concrete	5	5 kWh	1700	2.94	–	–	–	(Energiestro Webpage, 2017)

[a] Three weeks standby time.

Researchers have predominantly used the specific energy as a performance measure to compare flywheel designs. Genta (2014) compared flywheel materials using their specific energy at burst speeds, which is given by the relation:

$$e = \frac{E}{m} = K\left(\frac{\sigma_u}{\rho}\right) \tag{1}$$

where e is the specific energy, E is the total energy, m is the mass of the rotor, σ_u is the ultimate strength and ρ is the density of the material. The shape factor K depends mainly on the flywheel geometry. Using Eq. (1), the specific strengths of some isotropic materials, Carbon Steel (Fe 34), Aluminium Alloy 2024, Titanium Alloy and Maraging Steel were found to be 12, 46, 63 and 66 Wh/kg respectively, and those of composites such as unidirectional Glass, Kevlar and Graphite reinforced plastics were 180, 230 and 240 Wh/kg respectively. This indicated that the theoretical maximum specific energy of composites was greater than that of metals, by a factor of 4–5 on average.

As described by Genta, however, there are some precautions to be taken when using this method to compute the specific energy. When orthotropic materials such as composites are used to fabricate flywheel rotors, the ultimate strength, σ_u, must be indicative of the failure mode of the composite rotor. Also, rotor designs with shape factors > 0.5 have bi-directional stress distributions, which cannot be handled by filament wound composite rotors with unidirectional laminates, since their tensile strengths transverse to the fiber direction (i.e., in the radial direction) are very low. Thus, designs with shape factors ≤ 0.5 must be chosen, or an alternative manufacturing method must be used, which would result in a multi-directional composite, with a better transverse tensile strength, albeit a lower hoop strength. Metal rotors, on the other hand, can be fabricated to have high shape factors, leading to improved performance. Thus, the shape factor depends on the choice of rotor material.

Liu and Jiang (2007) estimated the theoretical maximum energy density of different flywheel rotors using (1), and found the specific energy of Maraging steel, Kevlar and T700-Graphite fiber composite flywheels to be 47, 370 and 545 Wh/kg respectively, when using a fixed shape factor of 0.5, corresponding to a rotor of constant thickness. The flywheel shape used for this comparison is unfavorable for metal rotors, since they can be manufactured with complex shapes to improve the shape factor K. Bitterly (1998), calculated the specific energy of the flywheel using the relation:

$$e = 1.57E-5\left(\frac{\sigma_\theta}{\rho}\right)\xi_{Stress}\xi_{Design} \tag{2}$$

where, σ_θ is the hoop stress, ρ is the material density, ξ_{Stress} and ξ_{Design} are safety factors for stress and design. They reported the theoretical maximum energy density e^{max} of 4340-Steel and Kevlar-49 flywheels to be 31.7 and 350 Wh/kg, using (2), with safety factors of 100% to estimate the energy density. Neither of these methods accounted for the different failure modes in composites, and thus could not be used to reliably compare the specific energy of metal and composite rotors.

Arnold et al. (2002) modified the shape factor to account for material anisotropy and stress-state multiaxiality and compared the specific energy of a slightly anisotropic and a strongly anisotropic material using the original and modified shape factors. They found that, for the strongly anisotropic material with a volume fraction of 40%, the calculated specific energy varied from 327.86 to 113.74 and to 115.36 Wh/kg when using the original 'hoop only', a modified 'radial-only' and 'multi-axial' shape factors respectively. Thus, the use of multi-axial shape factors could account for the geometry and operating conditions of the rotor more accurately. Also, this study showed that the shape factor of the type used in previous literature resulted in an over-prediction of the specific energy in the case of anisotropic materials such as composites.

The data from Table 1 indicates that there is a balanced mix of composite and metal flywheels currently being manufactured, despite evidence from previously published work that the specific energy of composites is much higher than that of metals. This leads to the following two hypotheses, which will be investigated in this paper.

The first hypothesis is that the specific energy is not the only performance index which is important while selecting the rotor material, and that there might be other factors influencing the choice of materials during the design process. In utility or grid applications, the total energy and cost might be the most important performance indices; whereas, in mobile applications, the weight or space occupied by the FESS might be a major constraint, and thus the specific energy or energy density might be the most important performance indices. There is, therefore, a need to compare optimal flywheel designs based on different criteria, depending on the application. Krack et al. (2011b,c) optimized the energy per cost of fixed volume multi-rim composite annular disk-type flywheels, by varying the operating speed and relative thickness of the composite rims, using normalized costs of rotor materials. This approach can be extended to the current work to select the best rotor materials for the optimal flywheel for the application.

The second hypothesis is that the use of a simple geometric shape factor to estimate the specific energy of a material might not accurately predict the specific energy of a rotor made of that material, especially when anisotropic materials are used. Thus, a mathematical model of the rotor is needed, which will account for material anisotropy and failure modes. When this model is used to optimize the flywheel, a more realistic value of the specific energy of the rotor can be obtained, which can then be used to choose the appropriate rotor material. An additional advantage of using an optimization formulation to determine the performance of the rotor materials is that, practical constraints other than material failure can also be checked. For example, constraints on the radial tensile stresses at the interface of multi-rim press-fitted composite rotors ensure that the composite rims do not detach due to differences in the radial expansion of the various rims.

This paper proposes to use an optimal flywheel rotor to compare and select rotor materials. The 1-D plane-stress axisymmetric