CHALLENGES AND SOLUTIONS FOR THE USE OF FLYWHEEL ENERGY STORAGE IN HIGH POWER APPLICATIONS

By:

J.D. Herbst
M.T. Caprio
A.L. Gattozzi
C. Graf

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Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

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John Herbst, University of Texas Center for Electromechanics j.herbst@mail.utexas.edu
Matthew Caprio, University of Texas Center for Electromechanics – Austin, Texas
Angelo Gattozzi, University of Texas Center for Electromechanics – Austin, Texas
Carl Graf, University of Texas Center for Electromechanics – Austin, Texas

The University of Texas at Austin Center for Electromechanics (UT-CEM) is currently developing and testing a 2 MW, 130 kWh flywheel energy storage system as a critical element of the Advanced Locomotive Propulsion System (ALPS) Program.[1] The hybrid electric locomotive propulsion system consists of two major sub-systems: a gas turbine prime mover directly coupled to a 3 MW high speed synchronous generator and a 480 MJ flywheel energy storage system. Figure 1 is a simplified block diagram showing the major components of the propulsion system; the shaded elements are being actively developed by the ALPS program.

The ALPS energy storage system consists of a high speed energy storage flywheel, a 2 MW high speed induction motor/generator, and a high frequency bi-directional power converter. In the course of developing the energy storage system for this demanding mobile application, UT-CEM identified and developed effective solutions for several critical technical issues which have challenged the use of high speed flywheels for high power energy storage applications. Ongoing work on other UT-CEM programs is also relevant to high power flywheel energy storage applications [2,3]. Although these designs were typically developed for a more challenging mobile environment, they are also appropriate for stationary installations.

UT-CEM has been conducting research on energy storage in rotating machines since its inception in 1975. Advances in composite materials have shifted the focus to higher performance composite structures for inertial energy storage applications. Energy storage in a rotating mass can be expressed as:

$$E = \frac{1}{2} J \omega^2$$

where, E = stored energy in joules
J = polar moment of inertia in kg-m^2
ω = rotational velocity in radians per second

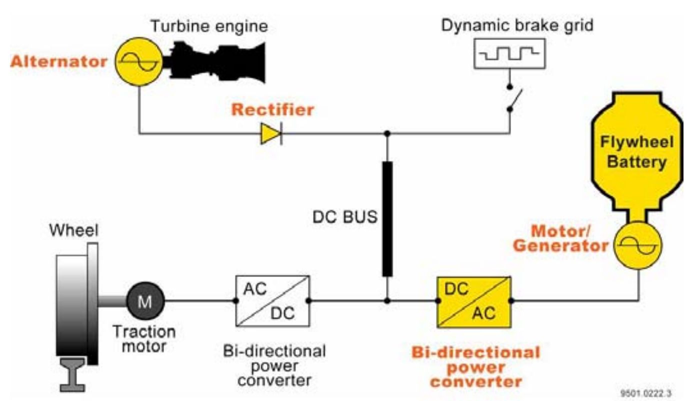

Figure 1. Simplified block diagram of ALPS system

The relationship of stored energy to the square of the rotational velocity drives the design of high energy density flywheels to operate at the maximum rotational speed. Although the exact relationship depends on the flywheel design, in general, the maximum rotational velocity and specific energy (joules/kilogram) of a flywheel are proportional to the allowable working strength divided by the density of the rotor material:

$$\omega_{max} \sim \sigma_{working}/\rho$$

where, ω_{max} = maximum rotational velocity
$\sigma_{working}$ = allowable working stress and,
ρ = material density

This relationship makes high strength, low density graphite epoxy composites the ideal material for high specific energy flywheels. The tangential velocity or tip speed of the rotor in meters per second is the product of rotor outer radius in meters and the rotational velocity in radians/second. This figure of merit can be used to compare the performance of rotors with different diameters and operating speeds.
Advanced composite materials have extremely high strength in the fiber direction, but have relatively low strength in directions transverse to the primary fiber orientation. To manage the high tangential tensile stresses in rotating composite structures, the fibers are predominantly oriented in the circumferential or hoop direction. However, the relatively low transverse tensile strength of the composite make control of radial (transverse) tensile stresses a critical issue in the design of composite flywheels. The outer portion of a flywheel experiences a higher tangential velocity (and hoop stresses) than the inner rings, leading to larger radial growth and the development of radial tensile stresses in the structure. The designer's challenge is to bridge the higher growth at the OD with the limited growth at the diameters closer to the shaft. UT-CEM has developed and successfully demonstrated two approaches to managing non-uniform radial growth and the associated radial tensile stresses: compressive pre-stress and growth matching composite arbors.


Figure 2. 480 MJ composite flywheel rotor

As can be seen in the picture of the ALPS flywheel rotor (fig 2) , large composite flywheels are typically constructed of a series of concentric rings. By assembling the concentric rings with radial interference, a state of radial compressive pre-stress can be developed in the inner rings which limits the radial tensile stresses in the structure at operating speed. As the size of the composite structure increases, the forces required to pre-stress the rings and overcome interface friction can become extremely high. Work on the 480 MJ ALPS flywheel led to advances in interface materials and assembly techniques which enable effective radial compressive preload to be built into large composite structures. First, the composite rings are assembled with a tapered interference fit to minimize the push distance required to achieve a given radial interference. Second, an interface layer specifically designed to reduce the coefficient of friction is applied to the outer surface of the rings. Finally, a fluid with time varying viscosity characteristics is used to lubricate the interface during the press fit procedure. Using these techniques, the effective coefficient of friction can be repeatably controlled to less than 0.01, enabling large composite structures to be assembled with reasonable axial forces.

Another approach to non-uniform radial growth is the use of growth matching arbors. These funnel shaped structures (fig.3) are designed to match the radial growth of the flywheel rim with minimal radial growth at the shaft radius. Although metallic arbors have been used in flywheel applications, fatigue life considerations typically limit them to lower tip speeds. UT-CEM researchers have developed a unique analytical tool, CEMWIND, to support the design, analysis, and fabrication of complex composite arbor structures. The software code takes geometric inputs from the designer and evaluates manufacturing issues such as bridging and tow slippage.

The code also creates an input file for a structural finite element analysis in ABAQUS; FEA results can then be used to calculate fiber direction and transverse stress and strain as well as stiffness characteristics for rotor dynamic analysis. Using this approach, UT-CEM successfully demonstrated a composite arbor flywheel design which holds the current world record for tip speed in a composite structure suitable for energy storage applications. These advanced designs achieve extremely high performance while minimizing the amount of composite material in the flywheel – a critical driver in the overall cost of the energy storage system.

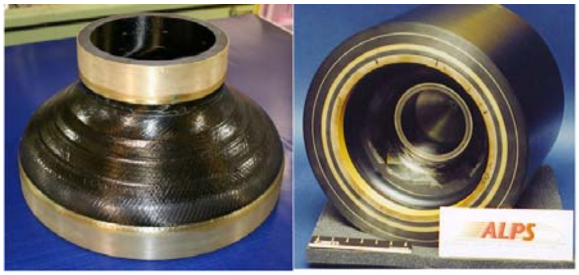

Figure 3. Composite arbor and dual arbor test rotor

For advanced high energy density flywheels, it is crucial to create designs which are robust, reliable and operate with well characterized design margins. Through the course of several pulsed alternator and flywheel programs, UT-CEM has developed techniques to ensure safe, reliable operation of high speed flywheels. Composite materials and structures do not have the long history of development and material property data bases available for conventional engineering materials. A critical step in flywheel safety is the use of prudent design margins in flywheel structures which have minimal susceptibility to catastrophic cascade failures. This approach allows the designer to limit failure considerations to the outermost flywheel rings and to control the amount of energy stored (and potentially released) in those outer rings. The next step in defining design margins for composite structures is to fully characterize the strength of the materials under the applied loading conditions and operating temperatures.

A testing process has been developed for circumferential filament wound structures that closely matches the loading configuration in high speed flywheels. Internal pressure is used to load composite specimens instrumented with multiple strain gages; the test tracks load/strain characteristics as well as ultimate strain-to-failure. Hydroburst test results are used to qualify resin/fiber combinations and manufacturing procedures and, along with the appropriate statistical processing, are used to define allowable operating stresses and overall operating margins in the composite structures. The hydroburst test procedures have been validated with excellent agreement between material test results and failure strains in controlled flywheel burst tests. Understanding material strength is only the first step – one must also characterize and control manufacturing and assembly processes from start to finish. Hydroburst specimens are fabricated and tested for each lot of material and ring fabrication is tracked throughout the filament winding process with a focus on maintaining consistent quality. Careful control of component dimensions and monitoring of axial and circumferential strains during the press fit assembly process ensures adequate radial preload is achieved. In addition to material strength characterizations, UT-CEM has also conducted fatigue testing of composite flywheels, demonstrating over 112,000 full charge/discharge cycles, with no measurable loss in preload or burst strength.

As a final element of the defense-in-depth strategy, UT-CEM typically incorporates some form of structural containment into the design of the flywheel housing. Containment features are extremely critical in applications where the flywheel must be installed in a vehicle or where personnel or critical equipment would be at risk in the unlikely event of a ring burst. A lightweight composite containment system has been developed to manage the energy released by an outer ring failure, containing the radial and axial burst forces and dissipating the remaining rotational energy in a controlled fashion to limit loading on the flywheel housing and mount structures. The composite containment liner design for the ALPS program was developed with support from Argonne National Laboratory, leveraging their expertise in transient structural analysis for nuclear reactor containment designs. The composite containment design approach and analytical approach have been validated with a series of controlled burst tests.

Critical elements of this flywheel system design philosophy have been compiled into ANSI/AIAA Standard S-096-2004 “Space Systems – Flywheel Rotor Assemblies”.

Another critical technology for high energy, high power flywheel energy storage is the development and demonstration of high load capacity, low loss active magnetic bearings. To maximize efficiency and enable operation at high rotational velocities, most high energy density flywheels operate with non-contacting magnetic bearings. For the demanding dynamic environment of mobile applications, UT-CEM has worked with industrial partners to develop permanent magnet bias, homopolar magnetic bearings and advanced controllers. [4]

The mechanical design of magnetic bearings for flywheels may involve specialized considerations relative to other applications. For example, the scale of the ALPS flywheel rotor demands unique rotordynamic requirements of the radial magnetic bearings, thereby influencing their mechanical design. Due to the flexibility of the flywheel rotor shaft, the radial bearing lamination stacks are required to contribute significant bending stiffness in order to precisely locate certain bending modes above and below the operating speed range. To this end, specialized lamination stacking and installation techniques were developed to increase packing factor and effective lamination modulus. Additionally, axial preloading features were incorporated into the design of the radial bearing lamination stacks to further contribute to bending stiffness.

Minimizing the internal losses of bearing magnetic materials is also critical in flywheel applications. As most flywheels operate in a vacuum enclosure, thermal management of the rotor bearings is challenging. The ALPS flywheel for example relies solely on radiation cooling of the rotor bearings, and therefore required lamination materials that balance mechanical strength (to accommodate the spin loading) with low losses for thermal management purposes. Additionally, manufacturing techniques were developed to machine the final outer surfaces of the rotor bearings with minimal impact on the eddy current losses.

Magnetic bearings require a set of backup or touchdown bearings to support the rotor during fault conditions or when the magnetic bearings are not active. Prior to the ALPS program, the design of touchdown bearing systems for large composite flywheels had not been well validated by experimental data. UT-CEM conducted controlled drop tests onto the touchdown bearings of the ALPS flywheel to confirm analytical predictions of rotor dynamic behavior and ensure safe operation and shutdown during magnetic bearing fault conditions. [5] Although the testing revealed some unexpected rotor dynamic behavior, the ALPS experiments confirmed the predicted limits on rotor whirl frequencies and led to the development of secondary bearing control systems to arrest forward whirl and significantly reduce forces during a shutdown on the touchdown bearings.

Figure 4. Rotor of high speed induction motor/generator

For electrical energy storage applications, transfer of energy into and out of the flywheel requires a high speed motor/generator. Load leveling applications can involve essentially continuous duty cycling from the flywheel and motor/generator. This can be contrasted with a UPS application where the flywheel typically operates at rated speed in a standby mode for long periods of time and then is discharged over a relatively short time to support a controlled shutdown or transfer to a backup power system. To support load leveling and braking energy recovery for the locomotive propulsion system UT-CEM developed a 2 MW squirrel cage induction motor/generator designed for continuous duty operation between 7,500 and 15,000 rpm. The ALPS induction motor/generator rotor (fig. 4) incorporates several novel design features to reduce stresses in the critical bar-to-endring joints and achieve the required fatigue life for this demanding application. [6] To manage the stresses from high speed operation, the patented rotor design features zirconium copper bars and a self-supporting high strength copper-beryllium end ring assembled to the shaft with an interference fit [7]. Keyhole stress reliefs in the endring isolate circumferential tensile stresses from the bar-to-endring solder joint. An integral cylindrical sleeve on the endring increases the area of the solder joint and, in conjunction with a spacer/balance plate, distributes the shear stresses associated with non-uniform radial growth and thermal expansion. The use of high strength heat treated materials in the rotor required the development of advanced soldering processes which ensure repeatable, high quality joints with a well controlled temperature profile in the components.

High charge/discharge power and continuous duty operation greatly increase the loading on the thermal management system and operation in a vacuum (to allow for high speed with low windage losses) and on non-contacting magnetic bearings can make it extremely difficult to reject heat from the flywheel rotor. For the multi-megawatt continuous duty ALPS application, a non-integrated flywheel design was developed, isolating the motor/generator heat loads from the flywheel rotor. While separation of the energy storage and electromechanical energy conversion elements increases design flexibility by allowing the designer to more effectively match the energy storage and power requirements of a given application, this approach required the development of a low leak, low loss high speed shaft vacuum seal. The shaft seal must be capable of managing the cyclic torsional loading of the flywheel while tracking shaft motion within the magnetic air gap and onto the touchdown bearings. The high performance vacuum seal has been successfully bench tested to over 20,000 rpm and demonstrated to over 14,000 rpm on the ALPS flywheel.

Flywheel batteries require a power conditioning system to interface the flywheel with a dc bus or 60 Hz utility power grid. For high power, high speed flywheel batteries, the required operating frequencies typically exceed the ratings of conventional motor drives. For the ALPS program, UT-CEM developed a 250 Hz, 2 MW bi-directional power converter (fig. 5) to interface the flywheel with the locomotive's 1,960 Vdc traction bus. To minimize harmonic losses and improve the output current waveforms, a 4 kHz switching frequency (>15 times the fundamental operating frequency) was selected.

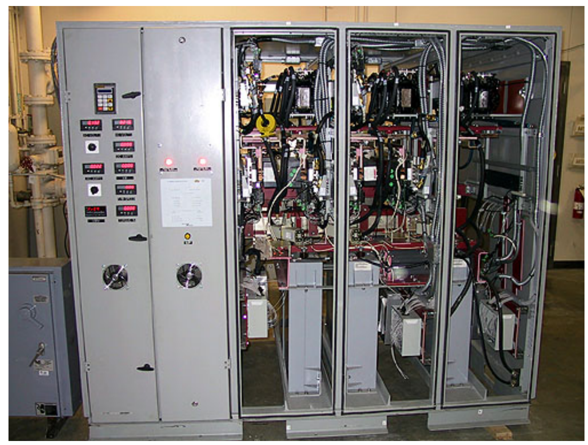

Figure 5. 2 MW continuous dury ARCP converter

Taking as an overall performance figure the frequency-power product (Hz*kW), the converter is at least an order of magnitude larger than typical commercial traction drives. This fact, coupled with the stringent space restrictions of a locomotive environment, leads to severe thermal management issues. To resolve these challenges, the converter was designed using the auxiliary resonant commutated pole (ARCP) concept in order to minimize switching losses and still retain the pulse width modulated (PWM) waveforms. In the ARCP topology, the commutation of the main switches relies on the resonant cycle of auxiliary circuits, which imposes additional timing relationships on the switching signals that are not required from conventional PWM controllers. Minimal switching losses are achieved by commutating the switches when there is a condition of either zero voltage across or zero current through them. Development of this advanced power converter topology is an enabling technology for the use of high power, high frequency motor drives for flywheel batteries.

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