Successes and Opportunity in High Speed Flywheel Development

Donald A. Bender, Chief Technology Officer, AFS Trinity Power Corporation, Livermore CA[1]

Over the past several years a number of developers of high speed flywheel systems have overcome long standing technical issues and have produced prototype and early commercial systems with excellent performance. For the purpose of this paper, a high speed flywheel is defined as system in which the rotor operates in a vacuum in order to reduce aerodynamic drag and couples energy to the application through power electronics. Many of these systems use composite rotors and magnetic bearings.

There are a number of challenges that are being successfully met by the flywheel developer irrespective of size or application. These challenges include thermal management, bearing performance, and cost. This paper will discuss how these obstacles have been overcome using the AFS Trinity M3 system as an example.

AFS Trinity M3 Flywheel Power System

The AFS Trinity M3 Flywheel System is a DC power management system using flywheel energy storage. The system consists of: 1) a high-speed carbon- fiber composite flywheel with an integrated motor-generator and magnetic bearings contained inside a sealed vacuum housing; and 2) the associated power electronics and ancillary equipment to deliver a regulated DC voltage output. Prototype systems have been demonstrated with power outputs from 50 kW to 500 kW. Our first commercial product, the will produce 100 kW for 15 seconds at a nominal bus voltage of 600 VDC. The applications for which this system may be configured include UPS/backup, pulsed power applications, and heavy hybrid vehicles. The unit shown below shows the M3 system configured for stationary applications.

M3 Flywheel Power System

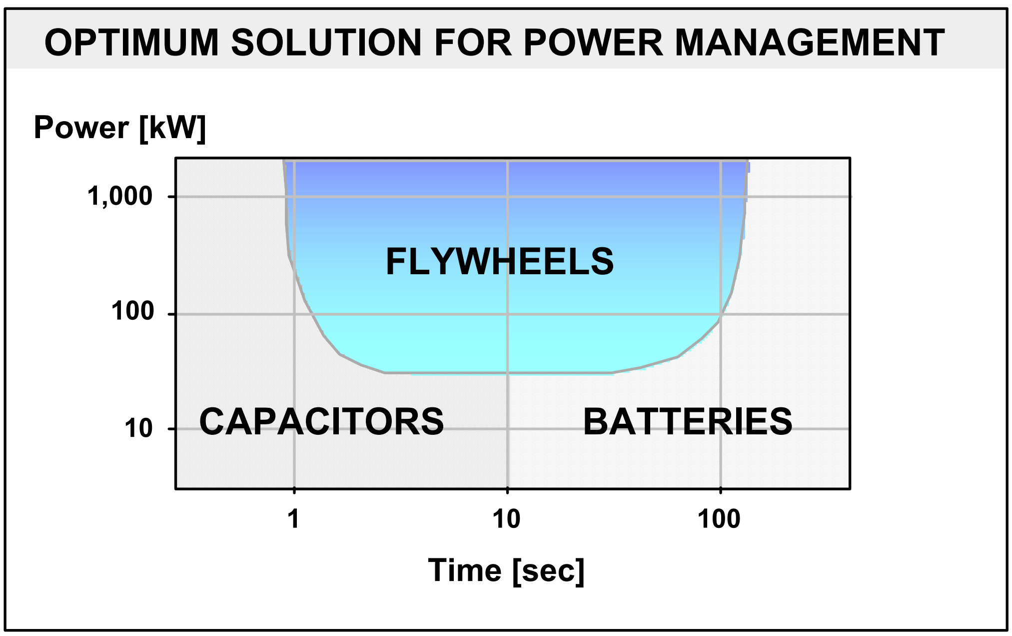
Over the development history of the M3, AFS Trinity have built successive generations of M3 prototypes and have used these systems as a platform for identifying and addressing technical hurdles. The units shown above are classified as engineering prototypes

1 dbender@afstrinity.com

The measured or demonstrated characteristics of the prototype system are as follows:

Power:	100 kW, >15 s
Peak output	> 200kW (higher power electronics not shown)
Usable Energy:	0.42 kWh
Recharge Time:	15 seconds
Efficiency:	1-way efficiency is 95% at 110kW evaluated at DC bus Round trip efficiency ≈ 90% (DC to DC electrical energy efficiency)
Weight:	1,100 lbs. (complete system including interface switchgear)
Rotor weight:	86 lbs.
Footprint:	3.8 sq. ft.
Parasitic Losses:	700 Watts (primarily pumps, fans, inverter switching losses, etc.)
Power interface:	Two wire DC
Control interface:	Keypad, CAN bus

Application Space
For the types of system considered here, AFS Trinity has defined an optimum application space where high performance flywheel can be economically competitive with other forms of energy storage. The application space compares flywheels to batteries and capacitors on the basis of power and discharge time.



Cost Effective Application Space for Flywheels

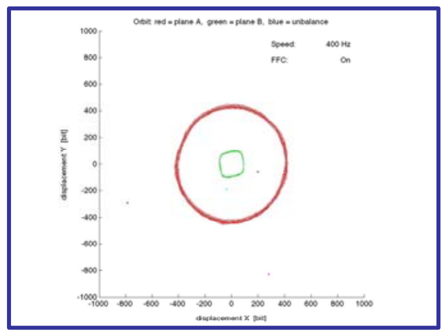
Technical challenges often resolve into issues of cost. In certain applications, the unique performance attributes of flywheels will command a premium price. More commonly, flywheels will represent a superior solution only when they simply cost lest than other forms of energy storage. For long discharge times, increasing energy storage with the incremental addition of rotor material may yield a system that is not cost competitive with batteries. For short discharge times, the increasing size of generator and power electronic components may result in a system that does not compare favorably with capacitors. At low power, balance of system costs make flywheels less attractive. However, in the application space indicated here flywheels can offer major cost and performance advantages over capacitors and batteries.

Bearing Performance
The flywheel designer has two options for suspension: ball bearings or magnetic bearings. Ball bearings have well known performance attributes and operating restrictions. For speeds less than 10,000 RPM low loss can be attained and bearing life is such that inspection or replacement intervals are in the range of 3000 – 8000 hours.

Many different types of magnetic bearing have been considered for use in flywheels. These include fully active systems with 5-axis positioning control, superconducting bearings that use flux pinning for stabilization, and hybrid systems that use a combination of magnetic and mechanical suspension.

The combination of composite rotors and magnetic bearings pose a number of interesting challenges. For one thing, the on-rotor losses attributable to the magnetic bearing must fall well within the thermal budget for the rotor. In addition, composites experience a great deal of radial growth as the rotor changes speed and the degree of unbalance may be larger and more highly variable than is typical in metal rotors. This gives rise to synchronous disturbance (vibration) which must be rejected by the bearing for quiet operation and long life.

The active magnetic bearing solution employed in the M3 is non-contact and has high reliability, low loss and low cost. Bearing hardware and diagnostic output from the bearing system are shown below.



Actuator Stator **Diagnostic Output**

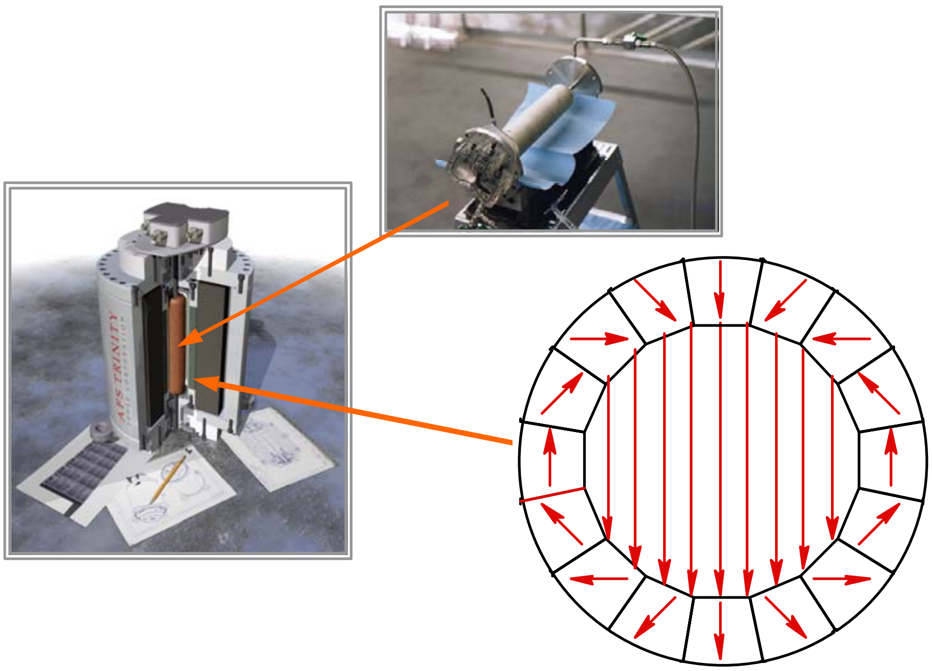
AFS Trinity Active Magnetic Bearing

Thermal Management
In order to make efficient use of rotor material, the machines considered here will have rotor surface speeds well in excess of 300 m/s. These rotors will operate in vacuum to avoid severe aerodynamic drag. For energy storage in the range of 0.5 – 10 kWh, the rotors will be fairly compact. A compact rotor with high surface velocity will also have high spin speed and the best suspension for this type of rotor will be magnetic bearings. A rotor supported on magnetic bearings has only one mechanism available for the removal of heat and that is radiation transport to the surrounding housing.

Radiation heat transport is driven by the difference in absolute temperature to the fourth power between two facing surfaces. This mechanism is very effective when a large temperature difference is available but that is not the case for a flywheel system intended for use in an industrial environment. A typical design point for ambient temperature may be 50°C. In order for the flywheel designer to use the most cost effective composite rotor materials, the maximum allowable rotor temperature may be in the range of 70-80°C. For a flywheel storing 1-2 kWh of extractable energy, this may mean that the thermal load on the flywheel rotor cannot exceed 20 W.

Thermal load on the flywheel rotor arises from aerodynamic drag, eddy current and hysteresis losses from the motor, and bearing losses. Attainment of low on-rotor losses has been a major challenge for all developers of advanced flywheels. In general, aerodynamic losses may be addressed simply by maintaining a rough vacuum in the rotor enclosure. On-rotor losses attributable to the magnetic bearing can be addressed through careful design of the bearing actuators and the strategy implemented in the AMB controller. For a high power flywheel system, the largest on-rotor heating mechanism is often associated with the motor/generator.

The approach take by AFS Trinity involves an ironless motor/generator which has no permeable material in the core and therefore no core losses. The architecture employs a dipole Halbach array pioneered for use in motor/generators by Dr. Richard F. Post at the Lawrence Livermore National Laboratory and licensed to AFS Trinity.



Ironless Permanent Magnet Motor Generator
Litz Wire Stator (top), Halbach Magnetic Array (right)

In addition to having no core loss, the system nearly eliminates hysteresis and eddy current losses within the rotor.

ACKNOWLEDGEMENTS

The work reported here was funded in part by the Department of Energy and the California Energy Commission. AFS Trinty would like to express its appreciation to these agencies and to Sandia National Laboratory and Calstart/Westart