

DESIGN AND DEVELOPMENT OF A 100 KW ENERGY STORAGE FLYWHEEL FOR UPS AND POWER CONDITIONING APPLICATIONS

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ABSTRACT

The design and development of a low cost 0.71 KW-HR energy storage flywheel to provide 100 KW for 15 seconds is described. The flywheel target market as related to the selection of the power and duration for the flywheel is also defined. The key subsystems in the flywheel system are described to show how the flywheel system is successfully integrated into a mechanical system. Test results are then presented.

The flywheel is designed for high power, short discharge applications in the UPS and power quality markets. It can output up to 100 KW for a 15 second duration, targeting diesel generator set (gen-set) ride through applications as well as load leveling applications. The flywheel operates at a peak speed of 35,000 rpm, pulling power down to a minimum speed of 20,000 rpm. The tests conducted on the system have verified expected peak power output, energy storage capacity, maximum operating speed, and steady state thermal performance.

INTRODUCTION

Flywheel UPS systems are establishing their presence in the power quality market by offering a lower life cycle cost, being more environmentally friendly, and providing enhanced reliability and efficiency over battery based systems. The high initial cost of the flywheel systems available today has limited their ability to penetrate the available UPS market; however, certain companies introducing flywheel UPS systems have demonstrated that these systems offer clear technological benefits over battery systems for specific markets, and that selective markets are willing to pay premium prices for these benefits. Although lower life

cycle costs, environmental advantages, and enhanced efficiency are substantial benefits offered by energy storage flywheel based UPS systems, it is clear that in order for them to achieve a market share of any significance, their initial cost must be competitive with existing battery based systems.

Applications that can realize immediate benefit from this alternative UPS system include:

- *Integration with standby gen-sets.* A short, high discharge power flywheel UPS can allow these systems to be used with no interruption in user power.
- *Continuous power conditioning and power quality improvement applications.* Unlimited charge/discharge cycles, allowable deep discharge, minimum environmental installation requirements, and fast recharge rates of flywheel UPS systems offer significant benefits for this application.
- *Load leveling for standby or continuous gas turbines.* A developing market that has many of the same requirements as the prior applications, where efficiency is improved with elimination of short, high power loads on the turbine.

Other applications in development where flywheel systems offer significant long term cost and efficiency benefits include:

- Load leveling for microturbines
- Load leveling for fuel cells
- Energy storage for micro-grids (islanding)
- Stop and go power recycling for metro/subway stations
- Stop and go power recycling for multi-elevator buildings

In order to enter the UPS market, a flywheel UPS must be cost competitive with equivalent battery based systems. While life cycle cost savings are important to the customer, this typically does not weigh significantly in current year budget constraints of customers for capital equipment purchases. A successful flywheel UPS must therefore be initially cost competitive with competing systems, offer clear performance advantages in the target markets, be significantly lower life cycle cost, and be environmentally friendly to appeal to a broader global market.

FLYWHEEL DESIGN

The patent pending flywheel system, presented in Figure 1, was developed to address the needs of the UPS market where a flywheel power source could offer significant benefits and to be competitive with the purchase price of battery based systems. An output power of 100 KW was chosen to meet the 100 KW to 300 KW middle market range for diesel gen-set ride through applications. The flywheel UPS will support the critical load requirements of the user until the gen-set starts and provides full back-up power. The 15 second duration was based on a maximum anticipated gen-set start-up time of 8 seconds and a two times safety factor to provide adequate time for a 3-5 second delay for short power outages and avoid nuisance starts by the gen-set.



Figure 1. Energy Storage Flywheel

The flywheel system incorporates a high speed permanent magnet motor/generator, a five axis active magnetic bearing system with associated controls, and a high strength steel hub, as show in Figure 2, for high operating tip speed. The flywheel is sealed for operation in a vacuum

environment to minimize windage losses created by the high speed rotor. The rotor losses are dissipated via radiation to the housing and stationary components surrounding the rotor. To minimize rotor heating, low loss permanent magnet homopolar magnetic bearings and a permanent magnet motor generator are utilized. The steel hub was chosen over composite technologies to allow for higher rotor operating temperatures, support the system with proven materials, and target low cost manufacturing. While composites offer higher energy densities allowing smaller hub designs, size and weight are not as critical as cost for the target industrial applications.

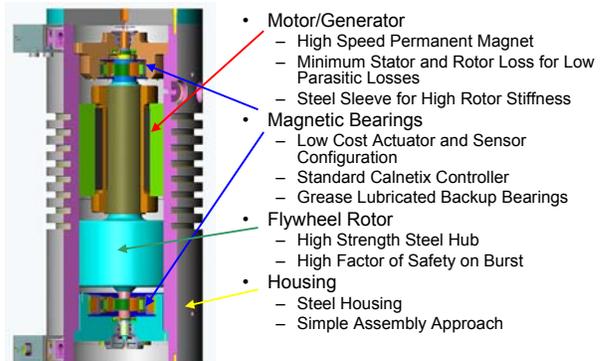


Figure 2. Energy Storage Flywheel Components

The flywheel steel housing aligns and supports the bearings and the motor/generator. Alignment is critical to prevent contact between rotor and stator components. Vacuum sealed connectors are used for power leads from the motor/generator, and vacuum feed-thrus are used for magnetic bearing power, sensor signals, speed sensor, and temperature sensors. A vacuum sealed infrared sensor provides non-contact temperature measurement of the rotor hub during operation. Additional vacuum seals are located at the top and bottom of the flywheel. A vacuum hose valve provides a connection to a vacuum pump required to lower the vacuum level in the flywheel to approximately 4×10^{-3} Torr during operation.

Motor/Generator

The motor/generator consists of a unique stator and rotor assembly that are designed to operate effectively in a vacuum environment. The stator assembly is designed to minimize rotor losses that are difficult to remove in a vacuum

environment. The motor/generator is designed for stator cooling via convection heat transfer to the housing. The permanent magnet rotor is highly integrated with the flywheel hub, as shown in Figure 3. The magnet retaining sleeve, made of high strength nonmagnetic alloy, also functions as the main stiffness member for the entire flywheel rotor assembly.

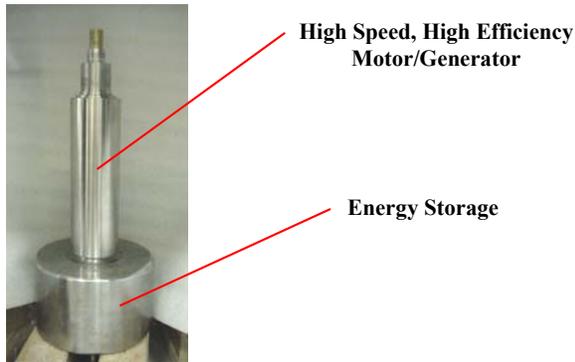


Figure 3. Flywheel Rotor

A similar configuration of motor/generator is used on the University of Texas Transit Bus Flywheel system¹, as well as in high speed industrial machines currently in production at Calnetix. The design is proven for applications of up to 450,000 rpm and has shown to be stable in high temperature environments. Manufacturing methods and techniques are well understood for accurate production cost estimation.

The motor/generator characteristics, presented in Table 1, are designed specifically for this application. Its unique features provide many system benefits that include: (1) extremely low rotor losses, (2) very low magnetic spring rate with minimal bearing loading due to eccentricity, and (3) robust rotor construction suitable for highly integrated or standalone applications. These benefits, demonstrated for flywheels, extend to other high speed applications such as turbo compressors and turbo alternators.

Table 1. Flywheel Motor/Generator Characteristics

PARAMETER	VALUE
Machine Type	Permanent Magnet Synchronous
Operating Speed Range	20,000 to 35,000rpm
Over Speed	110%
Rated Output Power	100kW over the entire speed range
Designed Bus Voltage	800 VDC
Nominal Back-EMF	270 Vrms L-L @ 20,000rpm
Nominal Torque Constant	0.17 N-m per amp-rms
Number of Poles	2
Number of Phases	3
Winding Configuration	Y connected
Winding	
▪ Inductance L-L	140 μ H
▪ Resistance L-L	23 milliohms (at 20C)
Cooling Scheme	Passive

Magnetic Bearings

For rotor support in the primary axes as presented in Figure 4, magnetic bearings and vacuum compatible grease lubricated ball bearings were evaluated. Although magnetic bearings are more expensive than mechanical bearings, they possess unique advantages in operation and longevity for the system. These advantages include extremely long life with no maintenance, tolerance to unbalance, minimum rotor losses, and low power consumption. While keeping costs minimized is a critical function of this design, the magnetic bearings are considered critical to meet the operational life of the system.

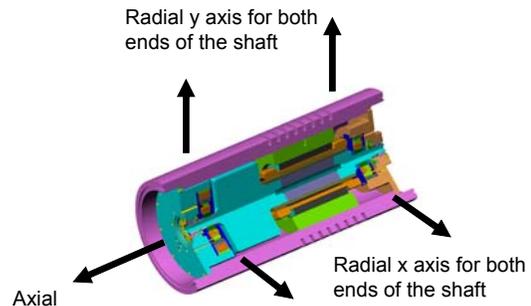


Figure 4. Flywheel Bearing Axes

Rotor components for bearing and sensor targets, composed of electrical steel laminations, are interference fit on the rotor, becoming integral to the rotor construction. The bearing rotor journals are sized to provide the necessary magnetic field path for static and dynamic load response of the bearing. Stresses for these components based on operating speed and fit are designed to provide an infinite fatigue life for the components. Once fit onto the rotor, a final

machining operation aligns the bearing journals to the rotor centerline.

The flywheel system utilizes patented homopolar permanent magnet bias active magnetic bearings², shown in Figure 5, for rotor radial and axial support. The magnetic bearings suspend the rotor in a magnetic field, responding to static forces as well as dynamic forces. The upper magnetic bearing provides two axes of support, whereas the lower combination bearing³ provides three axes of support, including the axial or vertical axis. To minimize bearing power requirements and losses, the flywheel is oriented in a vertical arrangement, thereby requiring the combination bearing axial axis to support the full rotor weight of 185 lbs. The four radial axes are therefore only required to support loads due to installation tilt, misalignment, and dynamic loads from external forces and rotor unbalance. Of these, synchronous dynamic forces due to unbalance are eliminated with the use of open loop cancellation in the magnetic bearing controller. Conventional inductive position sensors monitor shaft position, feeding signals to a digital signal processor based controller. Current amplifiers take the controller output and drive current to the actuators for each axis to impart forces on the rotor to maintain the desired position.

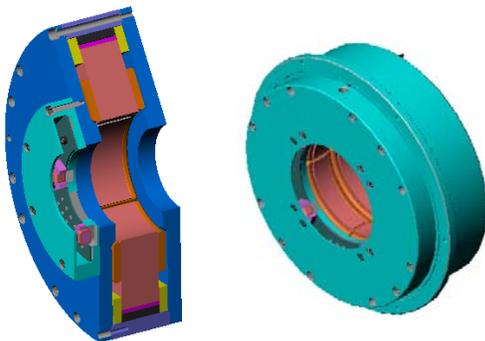


Figure 5. Magnetic Bearings

The magnetic bearings provide peak a capacity of 250 lbs of axial force and 125 lbs of radial force in each of the radial axes. Operating loads for the system at full speed of 35,000 rpm with no externally imparted loads are less than 10 lbs per radial axis. This leaves significant margin available for mounting tilt and external forces, such as earthquakes.

The standard Calnetix magnetic bearing controller shown in Figure 6 contains a digital controller, sensor demodulator, and current amplifiers. The position signals are fed to the control module, which runs a digital filter compensation program to produce a command signal for each power amplifier. The basic compensator for the flywheel is a single input, single output (SISO) proportional integral derivative (PID), having an integrator to provide very high stiffness against static shaft loads, proportional gain to provide the baseline positive stiffness to support the shaft rigid body modes, and a lead-lag filter to provide damping for the shaft rigid body modes. Additional cascaded biquad filters follow the basic PID to further shape the frequency response and to insure stability of all system bending modes.

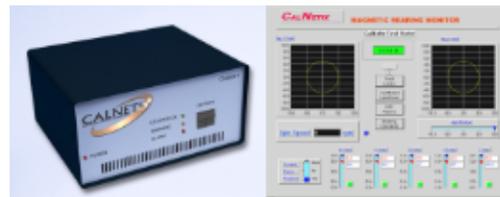


Figure 6. Magnetic Bearing Controller and Graphical User Interface

Several other control enhancements are used to provide robust performance and to minimize system losses.

These include:

- 1) Gain scheduling: Adjusting the compensator as a function of spin speed. This is needed for a gyroscopic plant, such as a flywheel, which changes significantly with spin speed.
- 2) Adaptive Open Loop Cancellation: This is also called Synchronous Vibration Control (SVC) and involves placing a feed forward control loop around the basic compensation. The SVC scheme can be used to minimize either synchronous displacement or synchronous control current. In the flywheel it is used to minimize synchronous current, reducing transmitted vibration and parasitic power losses. The substantial reduction in power consumption available with this technique was demonstrated by Hawkins⁴.

- 3) Multi-Input, Multi-Output (MIMO) Control: This allows cross-coupling between different control axes for difficult to stabilize plants. This can be implemented either as additional cross-coupled PID channels or as a full state-space matrix. In this flywheel, cross-coupled PID channels are used because they are effective and less computationally intensive.

Steel Hub

A high strength grade of AISI 4340 steel was selected for the rotor hub material. Stress levels in the hub are targeted to provide a factor of safety on burst of greater than 2.5:1, as defined in SAE, J1456⁵. Meeting the criteria used for automotive engine flywheels eliminates the need for the housing to be sized for rotor burst. In this initial unit the steel housing is over two inches thick. In addition, until burst testing is conducted, the flywheel is operated within a burst cell during high speed testing.

Stored energy is based on the mass of the flywheel and its operating speed. Usable energy is what is removed from the flywheel by the generator. In this system the useful energy removal occurs between full operating speed of 35,000 rpm down to 20,000 rpm. This speed range is determined by the generator design, the power electronics and the allowable voltage swing. The variations in material characteristics and in manufacturing must be taken into account in determining the allowable voltage swing.

POWER ELECTRONICS

The charging (motoring) of the flywheel energy storage system is effectively accomplished through precise control of the state-of-the-art semi-conductor switches. The fact that the system operates in vacuum mandates mitigation of the current harmonics present in the windings of the stator, as there exists no effective method of heat dissipation. Fast switching Insulated Gate Bipolar Transistors (IGBTs) are the best choice for silicon switches that are turned on and off to closely approximate a sine wave through Pulse Width Modulation (PWM). The correct waveform is the most important weapon in reducing harmonics, along with controlling current ripple through faster switching.

A true double-conversion Uninterruptible Power Supply (UPS) topology which uses the flywheel

as the back-up power source can be seen in Figure 7. As depicted in the figure, the line input (utility or another back-up source) is first rectified. The rectification is necessary to feed the IGBT bridge (converter) on the output which is used to re-create the sine wave free of quality problems. The input bridge also boosts as necessary to achieve the AC output voltage of typically 480V or 400V. During normal operation, the flywheel bridge uses the DC bus voltage to generate a sinusoidal input to the flywheel to motor up and maintain speed necessary to achieve the stored energy. In case of loss of line input, the flywheel bridge immediately goes into regeneration mode and the flywheel discharge begins. The output bridge which feeds the critical loads of the UPS is now fed through the rectified and boosted voltage from the flywheel bridge. Upon restoration of input power, the flywheel bridge will once again charge up (motor) the flywheel.

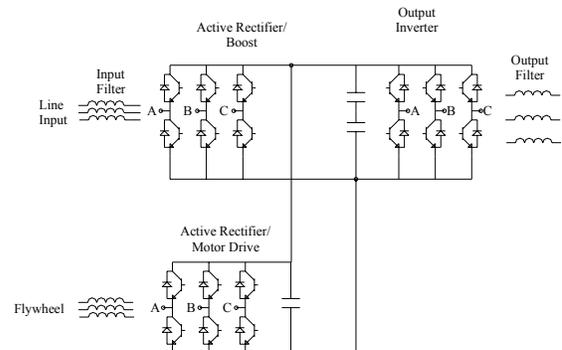


Figure 7. Power Electronics Topology

The modularity of the bridges shown on Figure 7 enables the flywheel energy storage system to be used in a variety of applications. The right combination of converters (bridges) will allow the use of the flywheel energy storage system as an AC or a DC source.

FLYWHEEL TESTING

Testing was conducted at Calnetix facilities in Torrance, California and Cerritos California, and consisted of high speed operation via motoring and spin-down loading using a resistive load bank. Initial testing was focused on the operation of the magnetic bearing system. Once integrated into the system with rotor and stator components, the bearing system levitated the rotor. Appropriate stability margins were first verified for operation, where initial levitation confirmed the control compensation determined

in the analysis with no tuning required. Low speed spin-up via a sensed motor drive was performed to validate bearing currents (or effectively forces) and rotor position as the rotor transversed the two rigid body modes of the rotor. Once bearing performance was confirmed, the system was spun up to its full operating speed of 35,000 rpm.

Motoring was performed with a sensed, six step PWM drive. Concerns of rotor heating due to the harmonics generated were evaluated. Additional inductance was placed on the output of the motor drive to the flywheel motor/generator to minimize this ripple. It is expected that a sine wave drive with higher switching frequency will significantly reduce the amount of inductance necessary for low rotor loss operation.

Energy measurement during power extraction verified the useable energy storage capacity of 0.44 KW-HR of the system. Power output of 100 KW was demonstrated in multiple discharge cycles. Parasitic power for standby operation at peak speed was measured at less than 600 W. This loss is minimized with the operation of the system at a vacuum level of 4×10^{-3} Torr. for reduced windage losses. Thermal testing has verified operating temperatures for the motor/generator in a vacuum environment are below rated temperature for all critical components. Rotor hub temperature measurements taken during testing indicated the system maintained a safe operating temperature at steady state and following multiple discharge/recharge cycles.

During operation with the use of the magnetic bearing open loop cancellation, currents and rotor displacements were minimal due to unbalance. With additional unbalance the currents can be kept small but displacement will grow, as the rotor mass centerline is farther from the geometric centerline.

CONCLUSIONS

The flywheel UPS presented offers significant advantages in the market for high power, short duration power applications. With its low cost, unlimited power cycling life, and ability to fully discharge over short time frames with no impact on life, it offers significant benefits for ride-through, power conditioning, and load leveling applications. Testing of the flywheel has

demonstrated its performance in meeting the energy and power requirements for these applications. Further integration with the power electronics will demonstrate a completely integrated UPS for direct application to these applications.

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