DEVELOPMENT OF AN AMB ENERGY STORAGE FLYWHEEL FOR COMMERCIAL APPLICATION

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Abstract

An AMB supported, 140 kW energy storage flywheel has been developed to provide 15 seconds of ride-through power and UPS service in conjunction with a diesel generator set. The flywheel, which operates in a vacuum, is supported by AMBs to minimize bearing losses, and has a high power motor/generator coupled to an efficient power conversion module. Beta units are scheduled to be released to six customer sites in July of 2005. The flywheel has been updated incrementally from an earlier configuration that was reported in the literature. The changes are discussed here and include: 1) increased flywheel mass to allow full power delivery over a longer period of time with less speed differential, 2) replacement of the radial magnetic bearing with a three axis bearing that provides passive axial lift to support the increased rotor weight within the same magnetic bearing envelope, 3) a new backup bearing mount to improve the dynamic performance of the flywheel on the backup bearings, and 4) an AMB controller/amplifier has been selected which has long production history and is well suited to volume applications.

Keywords: energy storage flywheel; magnetic bearings; UPS

Introduction

A flywheel energy storage system has been developed for industrial applications offering advantages over other forms of energy storage like chemical batteries and ultracapacitors. Key advantages offered by flywheels are: 1) life unaffected by frequent deep charge/discharge cycles, or by high charge/discharge rates, 2) minimal maintenance, 3) relative insensitivity to high ambient temperatures, 4) less floor space and higher power density, and 5) none of the environmental concerns with eventual disposal. Flywheel based systems are particularly advantageous in UPS systems when combined with diesel or turbine generator sets (gensets) to protect against prolonged outages. Energy stored in the flywheel is used for events lasting less than 3 seconds, where for longer events the flywheel supplies ride-through power for an additional 12 seconds while the genset is being brought on line to provide long-term power.

The flywheel system consists of two major subsystems: 1) the flywheel module, which includes the flywheel, motor/generator, and a five axis active magnetic bearing system, and 2) a three-phase bi-directional IGBT bridge (converter) used for both motoring and generation. Details of the converter were reported in [1]. The design and preliminary testing of the Alpha or demonstration version of the flywheel module were reported in [2]. A number of incremental improvements were identified during testing of the Alpha unit. These improvements have been incorporated into the Beta units that will be tested at customer sites. First, the flywheel mass was increased from 160 lb to 240 lb. The increased energy storage allowed an increase in power delivery time and a reduction in the required speed differential, simplifying the power electronics. Second, the radial magnetic bearing design was replaced with a three-axis design that uses a passive axial pole to support the extra weight. Third, the backup bearing mount was modified to improve the dynamics of the flywheel during an emergency coastdown event. Extensive testing has been performed on the backup bearing system to validate its performance. Additionally, as part of the overall cost reduction and reliability improvement effort, an AMB controller/amplifier was selected which has long production history and is well suited to volume applications. These enhancements are reported here in detail.

1 The Energy Storage Flywheel

The Beta flywheel module, shown in Figure 1, is designed to store a total energy of 1.25 kWh at 36,000 rpm and deliver 140 kW for 15 seconds (0.58 kWh). The configuration and basic features are the same as for the Alpha flywheel described in [2] so only a brief description is provided here for background. The vertically mounted rotating assembly uses a steel flywheel placed below a separate motor/generator on the same shaft. This partially integrated configuration was chosen to allow integration of an existing, proven motor/generator with a robust flywheel design. Similar configurations have been well tested and proven to be reliable [3]. While the flywheel hub has a fairly high Ip/It, the rigid body Ip/It for the entire flywheel rotor is quite low due to the size of the high-power density motor/generator. This feature helps to simplify the magnetic bearing control. The motor/generator utilizes a two-pole permanent magnet rotor. The magnet is captured radially by a thick inconel sleeve, which also provides the structural connection to the rest of the flywheel rotor.

The magnetic bearings are positioned immediately above the motor/generator and immediately below the flywheel. The magnetic bearings use a homopolar, permanent magnet bias topology. Homopolar refers to the direction of the bias flux, which is oriented either uniformly into or uniformly out of the shaft at any circumferential location. This topology significantly reduces rotor eddy current losses compared to conventional designs. The upper bearing is now a combination bearing with three axes, two radial control axes with 555 N radial capacity and one passive axial axis with a 500 N capacity. This bearing, described in more detail in Section 2.2, is a new design that provides an additional axial axis with passive axial lift. The lower bearing is a three-axis combination radial/thrust bearing with a 555 N radial capacity and 1100 N axial capacity.

Rolling element backup bearings are placed outboard of the magnetic bearings. The backup bearing system consists of a duplex pair of angular contact ball bearings at each end of the shaft. The lower backup bearing also acts as a backup thrust bearing due to the inclusion of thrust collars on the rotor.

2 Flywheel Design Changes from Alpha to Beta

2.1 Increase in flywheel mass
The most significant change to the system in going from Alpha to Beta was to increase the mass of the flywheel. The original Alpha flywheel had a mass of 73 kg and total energy storage of 0.75 kWh at 36,000 rpm. The design allowed delivery of 100 kW for 15 seconds (0.42 kWh) as the flywheel was pulled down to 20,000 rpm. Discussions with distribution partners pointed to the need to increase the power delivery to 140 KW (0.58 kWh) to allow utilization with 150 KVA UPS systems operating at a 0.9 power factor load. In addition, it was desired to increase the minimum speed during a discharge to reduce the voltage swing in the generator, thereby reducing the peak current requirement of the electronics. Decreasing the peak current reduced system cost by allowing the use of power electronics components rated for lower current. Both of these goals were accomplished by increasing the axial length of the flywheel hub from 152 to 250 mm, thus increasing the flywheel mass to 109 kg. This change increased the energy storage at 36,000 rpm by approximately 50%, allowing the lower operating speed to be increased to 24,000 rpm while still delivering the added energy required.

By maintaining the same hub diameter used with the Alpha flywheel the original stress factor of safety was maintained. The operating margin of the steel is greater than 2:1 over the strength limit of the material, eliminating the necessity for containment. Further efforts have been conducted both in analysis and testing to validate this, including: (1) obtained independent analysis/validation of design stress levels, design margin and cycle life, (2) implemented an extensive material testing and inspection program for every rotor, (3) implemented overspeed testing to 120% speed for all rotors, and (4) validated onset of yield in the rotor at 52,320 rpm in spin pit testing.

Of course, increasing the size of the flywheel impacts the system rotordynamics and control design as well as the bearing capacity requirements. Figure 2 shows a comparison of the conical rigid body mode and the first two bending modes. The conical rigid body mode now has less speed dependence because the rigid body I_p/I_t was reduced by increasing the hub length. The first bending mode dropped from 733 Hz to 681 Hz at zero speed, but is less gyroscopic. Because there is less gyroscopic change in the conical mode and the backward and forward bending modes, the control design was simplified. The second bending mode changed little because it is a mode primarily of the combo bearing shaft that does not significantly involve the flywheel hub.

2.2 Conversion of radial bearing to a three axis bearing with passive axial lift.
The axial load capacity of the combination bearing in the Alpha flywheel design was 1100 N, comfortable for the original flywheel but inadequate for the 109 kg Beta flywheel. One obvious choice would have been to increase the thrust capacity of the combination bearing (lower); however, that would have pushed down the second bending mode frequency, adding unnecessary complexity to the control design. Instead, the upper radial bearing was replaced with a combination bearing, providing three axes of load support instead of two. This combination bearing is similar to the radial bearing in that it utilizes a single homopolar control stack. The permanent magnet bias field now returns through a single axial pole on the upper face. The mechanism is clearly demonstrated in the magnetic finite element analysis result of Figure 3. The axial axis of this bearing provides a passive vertical lift force of 500 N at nominal air gap. A large air gap, 2.0 mm, limits the additional axial negative stiffness to 358,000 N/m and makes the passive lift force relatively insensitive to changes in rotor length. This is important since at thermal equilibrium (135C) and normal operating speed, 36,000 rpm, the helper pole gap decreases by 0.75 mm. Thus, as the rotor heats up, the force that must be provided by the thrust bearing decreases.

2.3 Modified backup bearing support design
The thrust end (lower end) backup bearing system is shown in Figure 4. The backup bearings are angular contact bearings, preloaded face-to-face into a resilient mount. Radial flexibility is provided between the mount and housing, where a hard stop limits radial deflection. The net radial stiffness is 5.0e6 N/m, resulting in a lowest radial natural frequency of 40 Hz.

The backup bearing system has undergone extensive testing, including 43 full-to-zero speed drop tests, and at least twice as many drops in different parts of the speed range. In test runs, spin-down time was gradually extended until the rotor was coasting down unassisted in approximately 2.75 hours. The tests were planned to evaluate a number of characteristics, including: 1) rotordynamic performance on the backup bearings, 2) bearing life, and 3) rotor thrust washer material.

Figure 5 shows time history and orbit data from a representative drop test. A 0.1 second time slice taken at 32,700 rpm spin speed is shown. From the time history, the primary whirl orbit is 0.25 mm at 45 Hz. The spin vector is in the $-z$ coordinate direction so this motion is a forward whirl. Also visible is the 545 Hz synchronous amplitude of 0.025 mm. The characteristic dynamic behavior in all tests was consistently a full circle forward whirl at 35-45 Hz around the backup clearance. This whirl frequency, which is determined by the backup bearing mount stiffness [4], does not change with speed for speeds above 2400 rpm, regardless of spin speed. This is an important result because the low whirl frequency reduces the load reacted by the backup bearings. In the testing performed to date, the life of the bearing itself has not been a limiting factor.

The rotor thrust washer is subject to sliding friction with the backup bearing inner race as the rotor whirls at the 40 Hz whirl frequency. The metal thrust washer used initially consistently wore approximately 0.05 mm during a thirty minute spin down. Several different materials and coatings

were tested, and of those, the one with the lowest coefficient of friction gave the best performance, lasting through six 2.75 hour spin downs with less than 0.025 mm total wear.

2.4 Production magnetic bearing controller

The development and testing of the Alpha flywheel was done with a development controller as described in [2]. The development hardware, based on the TI TMS320C6201 DSP, is very powerful and provides extensive control and feature flexibility. However, this hardware implementation was expensive for the cost sensitive industrial flywheel application. Therefore, a production magnetic bearing controller, Figure 6, was chosen. This controller is based on the TI TMS320F240 DSP and has been optimized for low cost. Moreover, several thousand units of this basic controller have been produced and it has an extensive reliability record.

The original version of this controller was designed for conventional heteropolar magnetic bearings with current bias. The flywheel uses permanent magnet biased magnetic bearings and needs bipolar amplifiers. A relatively simple design change was made to the amplifier board to add this functionality. Additionally, the manufacturer upgraded the amplifier board to higher power capability for this application. The final control box configuration has passed UL tests and is now UL listed.

Field commissioning was completed in May and the system has since been accumulating running hours in test. The control approach used was similar to that described in [2], but was made simpler by the use of center-of-gravity coordinates. A generalized synchronous cancellation scheme [5] was used to limit synchronous bearing loads and transmitted vibration.

Conclusions

An energy storage flywheel developed for UPS application has undergone extensive testing in preparation for field testing at Beta sites.
1) The system is capable of delivering 140 kW for 15 seconds, with a rotor speed swing from 36,000 rpm down to 24,000 rpm.
2) A new three-axis bearing that provides two radial control axes and passive axial lift was successfully developed and tested for this application. This bearing uses the same envelope as the previous two-axis radial bearing.
3) A new backup bearing mount was developed that has excellent dynamic characteristics. Extensive testing of the backup bearing system has resulted in a configuration that has gone through 6 full-to-zero speed rotor drops, each with 2.75 hour spin down times.
4) A production quality magnetic bearing controller has been successfully commissioned with the flywheel.

References

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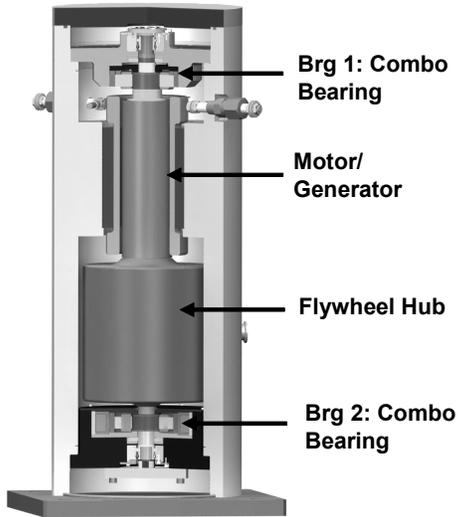
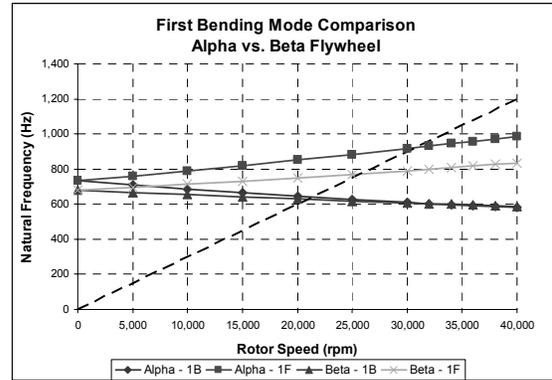Figure 1. 140 kW Beta Flywheel

Figure 2. 1st bending mode comparison, Alpha vs. Beta flywheel
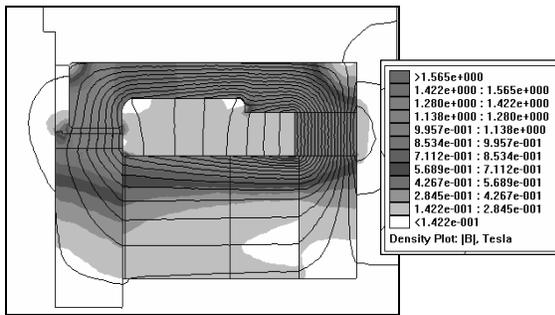
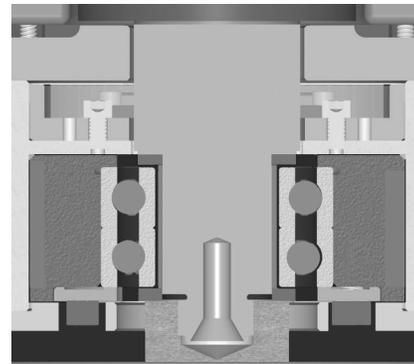

Figure 3. Bias Flux Distribution

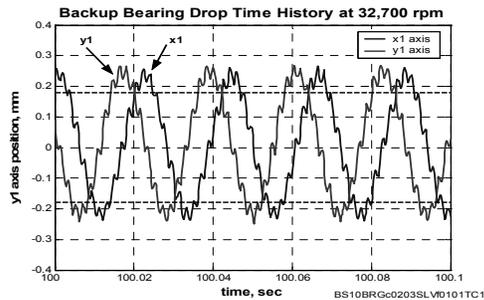Figure 4. Backup Bearing Arrangement (Thrust End)

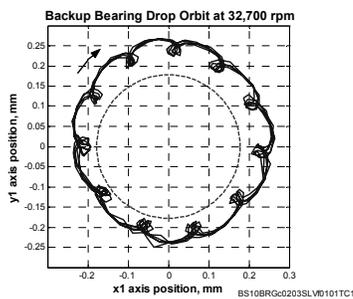Figure 5a. Sample backup bearing drop time history

Figure 5b. Sample backup bearing drop orbit (bottom)

Figure 6. Production controller mounted in flywheel cabinet.