Flywheel Energy Storage System with AMB's and Hybrid Backup Bearings

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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 AMB to minimize bearing losses, and has a high power motor/generator coupled to an efficient power conversion module. As part of the flywheel module a backup bearing system to the AMB was developed and tested.

Index Terms – **Flywheel, AMB, Backup Bearing, Hybrid Ball Bearing**

I. INTRODUCTION

A flywheel energy storage system (FESS) has been developed for industrial applications offering advantages over other forms of energy storage such as chemical batteries and ultracapacitors. This system utilizes a flywheel module composed of a high speed rotor levitated on active homopolar magnetic bearings. Integral on the rotor is a permanent magnet which is used in conjunction with a wound stator to act as a motor to increase rotor energy and as a generator to remove energy. The module operates in a vacuum to minimize windage losses, thereby maximizing operating efficiency.

The module operates as part of a FESS with power conversion electronics, system controller, user interface, and supporting systems. The flywheel module forms the core energy storage portion of the product. These FESS's are currently in operation at test sites following extensive in-house testing that validated performance. This paper focuses on the design and testing of the mechanical bearing system used as a backup to support the high speed rotor in cases of the primary bearing system, magnetic bearings, failure or fault.

II. THE ENERGY STORAGE FLYWHEEL

The flywheel module, shown in Fig 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). Active magnetic bearings provide suspension of the rotor during normal operation. A magnetic bearing controller (MBC) is powered firstly by power available at the user site, and secondarily by power from the flywheel generator.

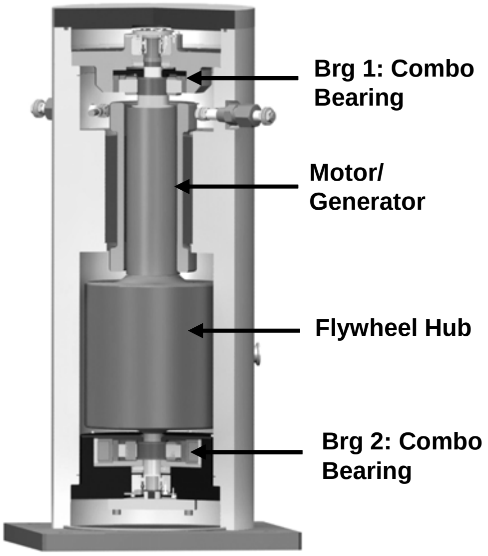

Fig 1. 140kW Flywheel Module

Mechanical ball bearings using steel races, ceramic balls, and vacuum compatible grease are used for support during non-operation of the active magnetic bearings and for emergency spin down of the rotor if the magnetic bearings are not able to provide rotor levitation. These bearings are mounted in a compliant mount that provides both stiffness and damping. The bearing mount is designed such that the stiffness and damping provided minimize loading on the bearings during operation.

As reported by Hawkins [1], 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. Extensive testing has been performed on the backup bearing system to validate its performance. During development the backup bearing mount was modified to improve the dynamics of the flywheel during an emergency coast down event.

The flywheel rotor weighs 109 kg. While a five axis active magnetic bearing system levitates the rotor, the upper radial bearing utilizes a passive axial lifter to offset approximately half the rotor weight, thereby reducing the required force from the axial magnetic bearing. This passive support is also present when the magnetic bearings are not active, thereby reducing the axial load on the backup bearings.

As described by Hawkins [1], the thrust backup bearing is located in the lower, or bottom, end of the flywheel module, as shown in Fig 2. The passive lifting element is on the opposite, or upper, end of the flywheel module. While subject to differential thermal growth effects that can change its operating clearance, the axial air gap is relatively large and the flux is provided by a permanent magnet, thus significantly reducing force changes as a result of gap changes. This allows for a fairly consistent passive lifting force during all operating conditions.

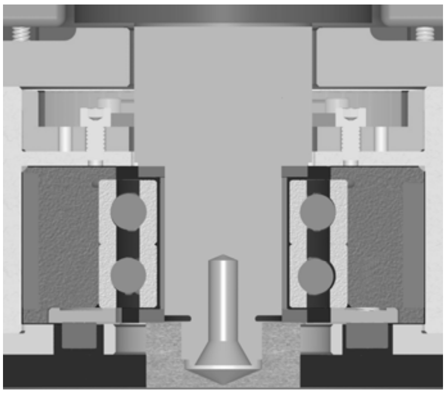

Fig 2. Thrust Backup Bearing Arrangement

When the primary magnetic bearing system does not sustain rotor levitation, the rotor drops onto the backup bearings. To prevent continued operation during this event, a fault signal from the magnetic bearing controller is sent to the FESS controller, whereby the FESS goes into shutdown mode. The duration of operation on the backup bearings is then dependent on the type of shutdown present.

A typical verification test for a backup bearing system is to deactivate the magnetic bearings at operating speed, causing the rotor to drop onto the backup bearings and spin down to rest. For the flywheel the duration of spin-down can vary as it can be loaded or unloaded during spin-down. There is a substantial body of work in the open literature that investigates AMB rotors on backup bearings. Hawkins [2] developed a rotordynamic simulation that included a nonlinear backup bearing clearance effects to analyze shock response in a magnetic bearing system. Several authors have also described full five axis drop tests for test rigs or machines for industrial service. Kirk [3] and Swanson [4] have presented numerous test results and analysis from a full scale, AMB rotor drop test stand. Caprio [5] presented results for drop testing on a large, vertical energy storage flywheel. However, all of these drop tests are for machines considerably heavier and slower than the flywheel described here, and all but [5] are for EM bias magnetic bearings. Thus the available literature was not able to provide much insight to aid in guiding the design of the backup bearing system and its expected results.

Three key magnetic bearing failure/fault types that initiate shutdown mode were identified and used as the basis of development and testing to validate backup bearing performance.

1) MBC fault: During this type of failure, the FESS commands a powered shutdown, with the FESS discharging power to cause the rotor to spin down within 10 minutes. The rotor is assumed to be on the backup bearings (though not necessarily the case in most instances), with a 10 minute operating time on the backup bearings. For this to function the FESS must be connected to a UPS and the UPS under load, thus allowing the flywheel to push power to the load. Most UPS's will allow such a condition, whereby the FESS raises the dc voltage on the UPS bus to be the dominate power supply to the UPS load. During this condition the flywheel energy is discharged at a constant current, either at a level the UPS load can support or at a maximum level set in the FESS controller. This level is maintained all the way to 5,000 rpm, where then the FESS isolates itself from the UPS and coasts down in speed to zero rpm.

2) Loss of primary AC power: This fault will activate an auxiliary power system - the critical power supply (CPS). The CPS takes in the Bemf voltage from the flywheel, goes through an AC-DC converter, and powers the MBC. The MBC is normally power by the auxiliary AC power available in the FESS. The MBC is designed though to accept both AC and DC power, thus allowing the DC power from the CPS to support the MBC when AC is not available. This use of flywheel power allows the rotor to maintain levitation until approximately 8,000 rpm. At this speed the flywheel rotor drops to the backup bearings for the remainder of the spin down. Typical operating time on the backup bearings is 30-40 minutes.

3) Multipoint failure: For example, failure of the CPS/MBC and the FESS controller at the same time. This failure would a spin-down on the backup bearings with no assistance to minimize time on the backup bearings. This spin-down takes between 2.5 to 3 hours on the backup bearings from full speed to zero speed. This case, while the most remote, is the most extreme in terms of backup bearing wear. While in the other cases the most of the bearing configurations proved successful, in this case many did not survive.

One further failure type is the failure of the backup bearings themselves during case 3. While not detailed in this paper, this destructive test was prepared by cutting the phenolic backup bearing cages in multiple locations prior to assembly in the flywheel. The flywheel rotor was dropped at full speed for an unassisted spin down. The damaged bearing set failed during the first 2 minutes of operation. In this case the rotor came down in speed in approximately ½ hour and eventually seized on the rotor shaft. While this damaged the flywheel module rotor and stator, the flywheel module stayed attached to its mounting with no external damage. Thus the most extreme failure has been tested.

III. BACKUP BEARING TESTING

Testing was conducted based on the failure/fault cases defined above and has shown the backup bearing system is acceptable for use in the FESS. A series of rotor drop/spin down tests includes over 40 full speed-to-zero speed drop tests on multiple units, and over 200 drops in different parts of the speed range. Initially, testing was done with accelerated spin downs – where the rotor speed was pulled down to zero in about 4 minutes by electrically loading the flywheel generator. In subsequent test runs, this time was gradually extended until the rotor was coasting down unassisted in approximately 2.75 hours. The tests were planned to evaluate performance of a number of characteristics: 1) rotordynamic performance on the backup bearings, 2) bearing life, 3) rotor sleeve material, and 4) rotor thrust washer material. As reported in [1], a compliant backup bearing mount was used to lower support stiffness and to supply limited damping to maintain bearing loads at an acceptable level during spin-down.

The test setup utilized a prototype MBC capable of manually de-levitating the rotor while recording the magnetic bearing position sensor signals. This high frequency data could then be studied to determine whirl frequencies and spin characteristics prior to bearing failure. During testing it was noted that prior to a bearing failure the thrust position changed dramatically very quickly. Based on this observation, an automatic re-levitate feature was incorporated into the MBC code. This feature uses an axial position threshold to trigger re-levitation, allowing the MBC to quickly in re-activate the magnetic bearings and preserve the ball bearings right at the point of failure. This allowed for a more accurate study of the ball bearing failure mode and determination of modifications for improved performance.

Fig. 3 presents test data taken from a representative backup bearing operational test. This particular data set is a 0.1 second time slice taken at a spin speed of 32,700 rpm. The primary whirl orbit is forward whirl at 45 Hz with a much smaller synchronous component. The characteristic dynamic behavior in all tests was consistently a full circle forward whirl at 35-50 Hz around the backup clearance. This is an important result because the low whirl frequency reduces the load reacted by the backup bearings. This primary whirl frequency is driven by the bearing support stiffness as discussed by Caprio [5]. The small loops in Fig #3 represent the synchronous orbit which is about 0.012 mm (0.0005 in) at this speed.

Numerous configurations of the backup bearing system were tested, which included five different bearing sets, seven different combinations of sleeve materials, and five different braking scenarios. Some bearing/sleeve combinations gave better results than others and the best combination has been chosen as part of the manufacturing and testing. Although the current configuration has shown adequate results, further improvements are still considered. The myriad of configurations will be narrowed down and more focus will be dedicated to the current backup bearing system in this paper.

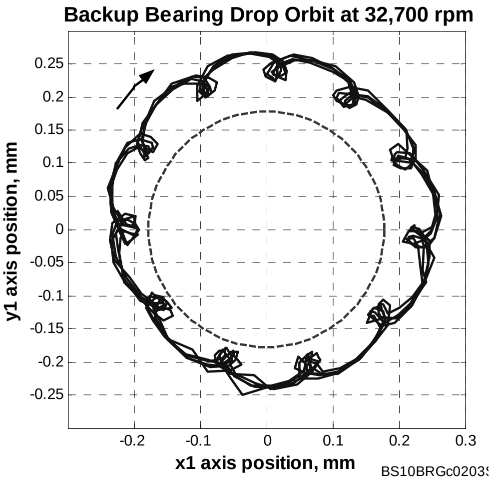

Fig. 3. Backup Bearing Operational Test Data

A progressive approach was implemented to gradually increase the runtime on the backup bearings. A series of tests were performed prior to conducting an unassisted full speed coast-down from 36,000 rpm to zero rpm. Four main types of braking were used to decelerate the flywheel during testing:

1) Load the flywheel generator electrically with a 1-ohm resistor load bank.
2) Generate power through an Uninterruptible Power Supply (UPS) with constant power, i.e. discharge the flywheel.
3) Generate power through the UPS with constant current, which also has the characteristic of applying constant torque on the flywheel.
4) Allow the flywheel to coast-down without assistance, termed unassisted coast-down. This was the worst case and thus has been tested heavily.

Also, a fifth braking method, venting the flywheel vacuum to produce windage loss braking, was tested once to determine if it would cause any concerning impact on backup bearing system characteristics. This did not effect the backup bearings, but did cause a reaction with some of the thrust washer materials that were optimized for vacuum operation.

The first test was conducted using a 1-ohm resistor load bank to decelerate the flywheel. With this braking assistance, it followed an exponential decay curve as depicted in Fig 4. This braking scenario takes 4 minutes to come to a stop and the majority of the energy is lost within the first minute.

A second braking scenario is to generate 25 kW of constant power. This has a parabolic curve as seen on Fig. 4. Varying levels of power can be used with this type of braking. The flywheel had 178.7 seconds of runtime on the backup bearings with this particular test. From time zero to 130 seconds, the FESS generated 25 kW of constant power and after 130 seconds, switched over to a default motoring algorithm.

The third braking scenario includes a number of different constant current values. An initial 125 amps constant current was used to minimize the time the flywheel accessed the backup bearings. By decreasing the constant current value, longer duration of runtime was achieved. Some other values chosen were 100 amps, 75 amps, 50 amps, 35 amps, 25 amps, 15 amps, 10 amps, and 5 amps. All of the curves with this constant current load follow a linear characteristic. Depicted in Fig 4 is an example using 100 amps, which has a runtime of 5 minutes on the backup bearings from 36,000 rpm to zero rpm. Also note the linearity of the spin speed versus time.

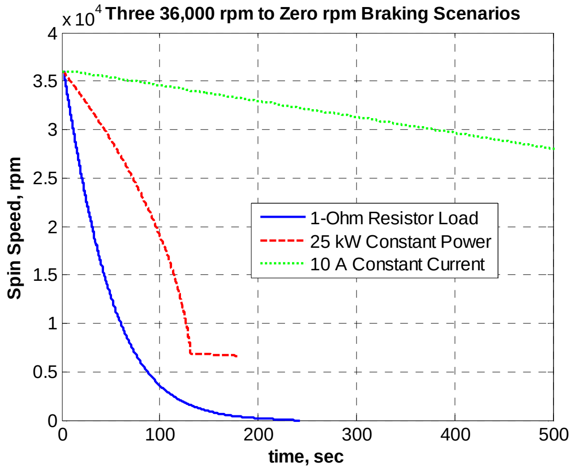

Fig 4. Braking Scenarios One, Two and Three

Fig 5 shows a 10 amp braking scenario and an unassisted spin-down test. The unassisted spin-down is the final and ultimate test from 36,000 rpm to zero rpm. The graph is close to being linear. The total runtime on the backup bearing was 2 hours and 40 minutes or 9,580 seconds.

Although there is no external braking assistance, the majority of the energy is dissipated through the drag of the open circuit PM motor with some additional drag from mechanical contact of the radial sleeve, combo sleeve, and thrust washer with the backup bearing inner races.

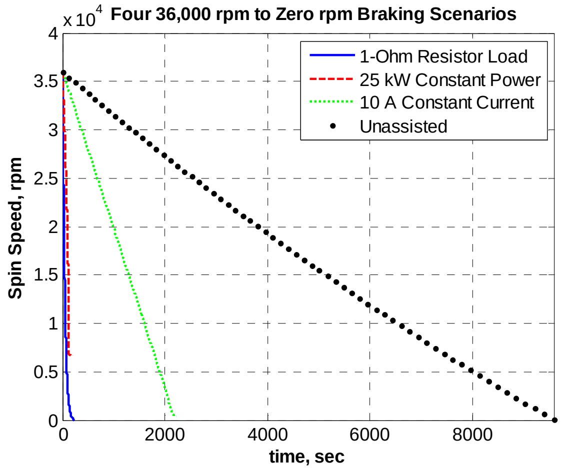

Fig 5. Braking Scenarios and Unassisted Coast-Down

There were two types of de-levitation used in testing, soft and hard. The soft drop uses an algorithm to slowly de-levitate the flywheel onto the backup bearing, minimizing the impact load. This is the normal commanded de-levitate for the magnetic bearing control. The hard drop immediately zeros the current commands on all channels, simulating the scenario of a sudden loss of power to the MBC. Initial testing in these backup bearing tests was done by de-levitation soft drops. After successful soft drop testing, hard drops were implemented during the tests.

As mention earlier in this paper, a low forward whirl frequency is desired, minimizing the load on the backup bearings. On Fig 6, the forward whirl frequency is 50 Hz. This data was recorded from the same 36,000 rpm to zero rpm unassisted hard drop as in Fig 3.

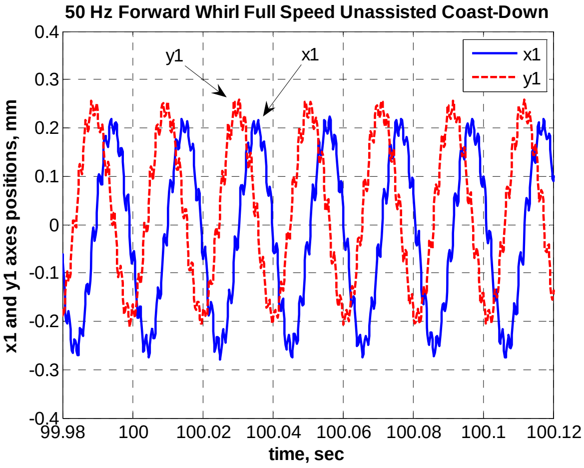

Fig 6. 50 Hz Forward Whirl Frequency

During testing a number of performance issues were discovered and corrected to meet the backup bearing life requirements of the FESS – 3 successful full speed unassisted drops on the backup bearings. Three different failure modes arose during testing as described below.

Infant Mortality

New bearings sometimes seized when used for the first time on a high speed drop test. These early bearing failures on the radial end were found to be the result of improper grease run-in on the bearings. This was corrected with a grease run-in procedure on every flywheel module when using new bearings. This procedure includes initial unassisted spin downs from 5,000 rpm, 12,000 rpm, and 18,000 rpm in sequence to properly warm and channel the bearing grease.

Excessive Thrust Washer Wear

During early testing with fast braking (short spin down times), very minimal wear was observed on the rotor thrust washer. However, during the initial unassisted spin down testing, the original metal thrust washer consistently wore approximately 0.05 mm during thirty minutes of the test. 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. Several different materials and coatings were tested, and of those, the one with the lowest coefficient of friction gave the best performance, lasting through three 2.75 hour spin downs with less than 0.025 mm total wear.

Occasional Failures during Extended Duration Testing

Seemingly random failures of the thrust end backup bearing pair began occurring during unassisted spin-downs. These failures manifested in the system as bearing seizing.

Bearing failures during full speed unassisted rundowns typically occurred within 60 seconds after the start of the run. The ball bearing seized during the spin-down and immediately started wearing on the thrust washer. Within 0.3 seconds the thrust washer would wear to the point that the rotor would contact other stationary components, such as axial sensor and magnetic thrust bearing axial pole faces. Auto re-levitation of the rotor prevented the bearing failure from damaging the rest of the module. Fig's 7 and 8 show a bearing failure during an unassisted spin down test. Initially the bearings are levitated and the rotor drops to the backup bearings when it is de-levitated. The rotor then operates on the backup bearings, which for a successful full speed spin down lasts 2.75 hours. Shortly after start of operation on the backup bearings a sudden change in axial displacement is seen, where Fig 8 is an expanded timescale of the change in axial position. The MBC reacts to re-levitate the rotor once axial displacement passes the 0.36 mm displacement limit, thus preventing system damage and allowing the ball bearings to be inspected for their failure mode. This recovery of the bearing at the instant of failure was critical for determining a corrective action to achieve successful bearing operation.

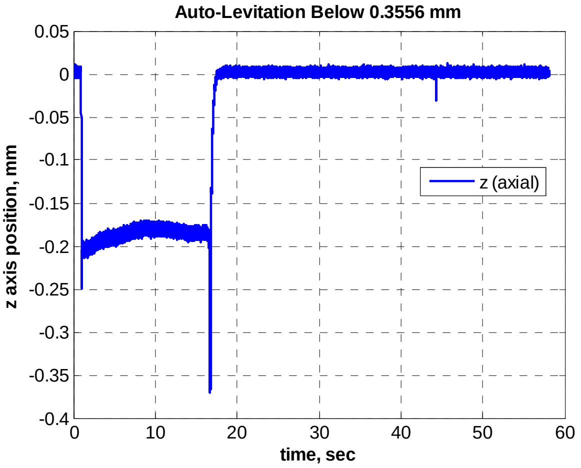

Fig 7. Flywheel axial axis showing auto-levitation

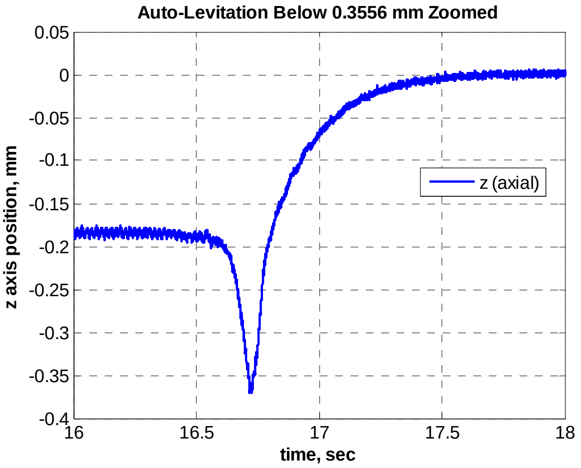

Fig 8. Bearing Failure and Rotor Re-Levitation

Also during these failures, changes in the radial bearing positions provided clues as to the ball bearing impending failure. These plots are shown in Fig's 9 and 10, showing changes in whirl frequency during bearing failure.

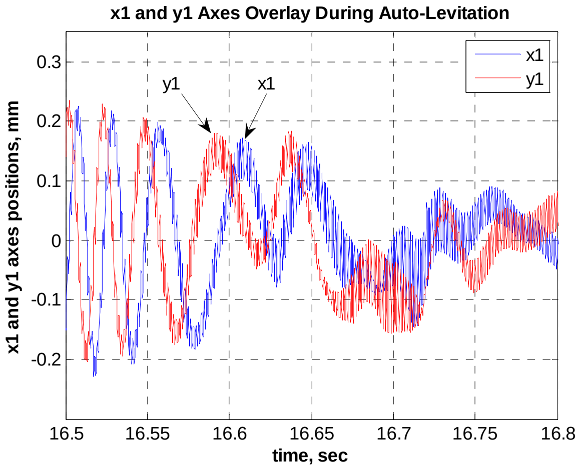

Fig 9. Non-Thrust End Radial Axis Position During Thrust End Backup Bearing Failure

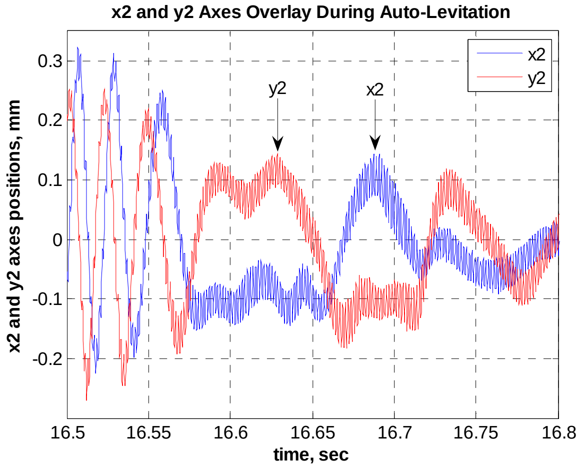

Fig 10. Thrust End Radial Axis Position During Thrust End Backup Bearing Failure

Investigation of the bearings following failures indicated inner race brinelling, as shown in Fig 11. Brinelling appears to have occurred prior to the smearing of metal, thus indicating the bearings were brinelled prior to the testing.

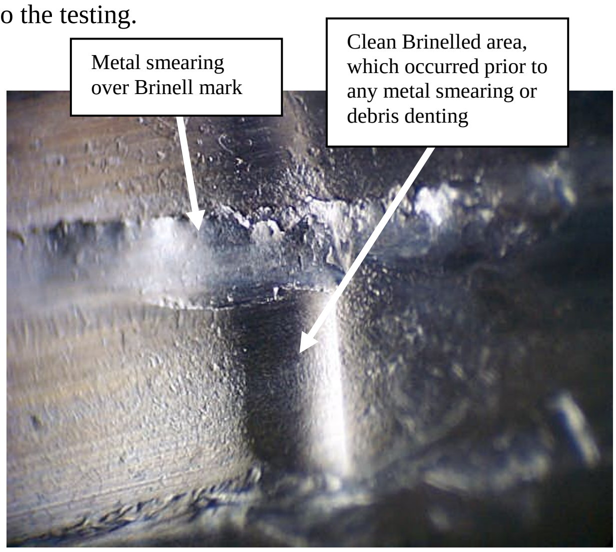

Fig 11. Failed Backup Bearing Inner Race

It was determined that the issue was in fact not the actual operation of the ball bearings, but in the test process. Following each spin-down test, data on final axial wear was collected by pulling the rotor back and forth in the backup bearing clearance space using the magnetic bearing coils with bias current. Following the spin-down the ball bearings were hot, most notably the inner races, which thereby increased the bearing preload. While a number of drop tests were performed, prior to any full speed unassisted spin-down test a full speed assisted spin-down test would be run. This spin-down would last approximately 4 minutes. This would heat the bearing inner races very quickly, yet not bring the rest of the bearing to a uniform temperature, thus significantly increasing the bearing preload. Upon de-levitation, which essentially dropped the rotor onto the backup bearings, this would result in brinelling of the bearing races. While not consistent on every module, once this procedure was changed accordingly, consistent successful rundowns were achieved.

IV. CONCLUSION

Extensive design and testing has been done to verify the ability of the backup bearing system in Vycon's 140 kW FESS. Multiple unassisted coast-downs from full speed of 36,000 rpm to zero rpm have been tested on one single unit successfully. And many more full speed unassisted coast-downs have been performed. Further improvements are still being considered to extend the life of the flywheel and backup bearings.

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