Design, Fabrication, and Test of a 5 kWh Flywheel Energy Storage System Utilizing a High Temperature Superconducting Magnetic Bearing[1]

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Abstract
The Boeing team has designed, fabricated, and is currently testing a 5 kWh / 100 kW Flywheel Energy Storage System (FESS) utilizing the Boeing patented high temperature superconducting (HTS) bearing suspension system. The Boeing FESS is designed to provide 100 kW of continuous power for one minute, as well as provide lower power for longer periods, dependant on demand. The passive HTS magnetic bearing allows the rotor to spin freely without energy absorbing mechanical connections to the stationary structure. This combination creates a mechanical energy storage device featuring very low standby losses within the passive bearing suspension system and it eliminates the complex control systems of active magnetic bearing systems.

Introduction

A flywheel energy storage system typically works by combining a high-strength, high-momentum rotor with a shaft-mounted motor/generator. This assembly is contained inside a vacuum / containment vessel and operates normally in a non-contact fashion with magnetic bearings acting as a suspension system. Once up to a high speed (typically 10,000 rpm or higher) the rotor's momentum can drive the generator on demand for a sustained period. The power draw starts whenever the generator's stator windings are switched into a load, and the discharge time available depends on the ratio of power drawn out to total kinetic energy of rotation. At some point the load is removed from the system, after which the flywheel will coast until it is convenient to recharge it. Recharging can be done with essentially the same power switching electronics that are used for the discharge, except that the timing of currents in the motor/generator stator windings is adjusted to push the flywheel back up to high speeds. Once at high speed, the flywheel system can idle thus storing energy and acting as a battery. The basic concept of a flywheel electrical system is noted in figure 1. Other common power electronic circuits invert power from the motor/generator to line voltages and frequencies.

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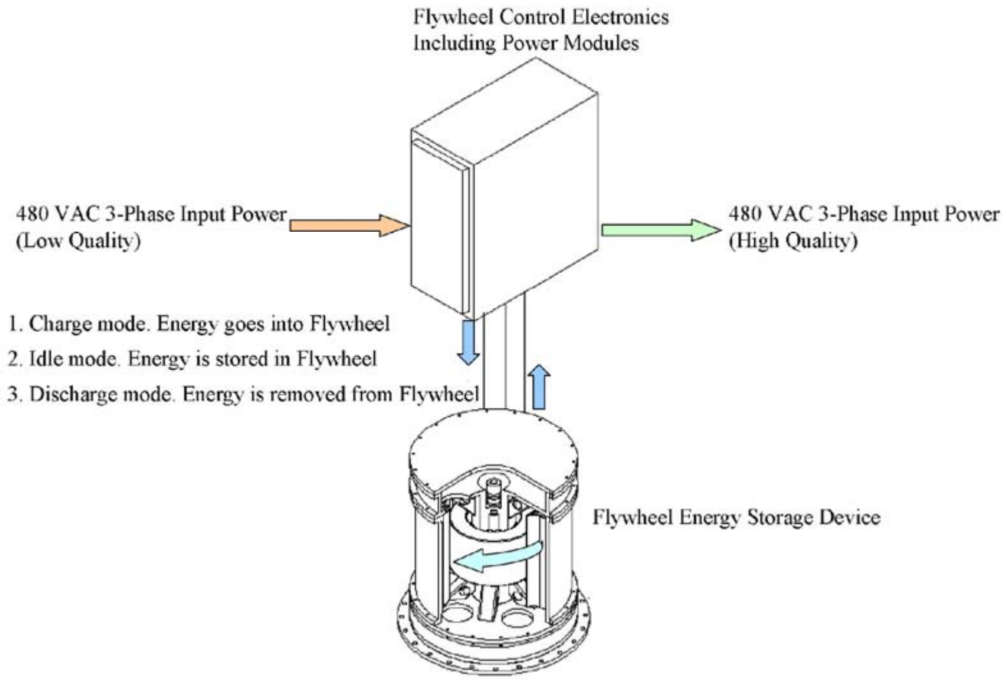

Figure 1. Basic concept of a flywheel energy storage system.

Beginning in 1997, Boeing began working with the Department of Energy's Office of Power Technologies to develop systems for other terrestrial uses such as uninterruptible power systems (UPS) and off-grid hybrid applications. Since then, Boeing has designed and built laboratory prototype systems of 1 kWh to 10 kWh storage capacities, with power outputs of 3 kW up to 100 kW.

Design

The primary design features of the Boeing FESS include: a robust 5 kWh rotor design utilizing composite rims combined with a metallic hub; a passive HTS bearing suspension system cooled by a closed loop liquid nitrogen system regulated at less than 77K; and a brushless 100 kW motor/generator and power electronics. Full system integration of the 5 kWh / 100 kW FESS is currently underway at the Boeing Company's test facility in Seattle, Washington. A cutaway view of The Boeing Company's 5kWh / 100kW FESS is shown in figure 2.

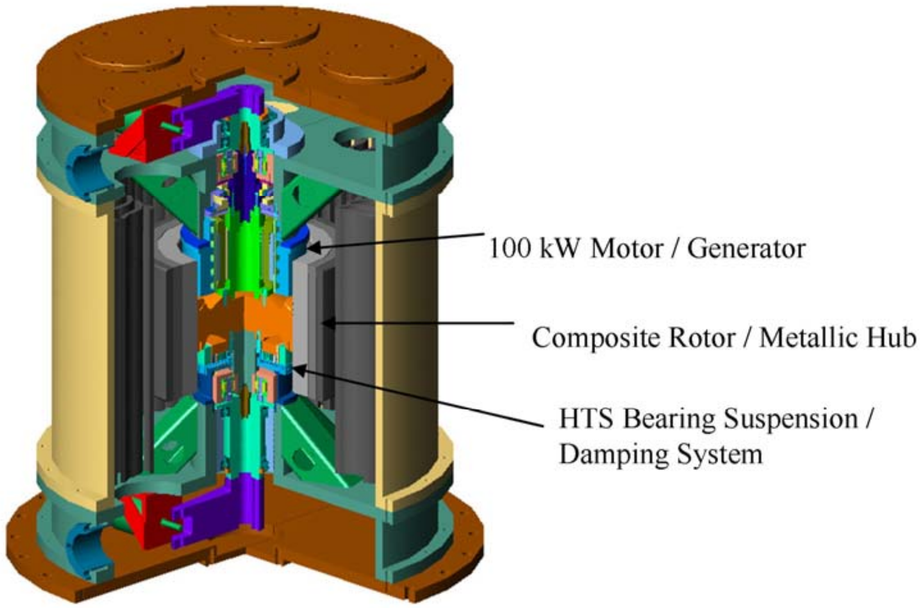

Figure 2. Cutaway view of the Boeing 5kWh / 100kW FESS.

The approximately 360 pound rotor stores the bulk of its energy in the carbon-fiber composite rim. The center hub of the Boeing 5 kWh rotor is a solid metallic structure, utilized in conjunction with the composite materials to create a rotor without critical resonances within the normal operating range. All of the carbon-fiber composite parts of the rotor have been designed with a factor of safety of 2.0 relative to ultimate tensile strength, while the metallic sections have been designed with a factor of safety of at least 1.5 relative to yield strength. The composite sections of the rotor were sealed to maintain a low out-gassing rate in order to reduce the pumping requirements on the vacuum system. The Boeing team has evaluated multiple composite rim materials resulting in the successful fabrication of two 5kWh rotor assemblies with the total indicated run-out of the latest entire rotor assembly held to 0.002”. Both rotors have successfully completed spin-test qualification testing to 105% of the design operating speed at the Boeing spin test facility in Seattle, Washington.

Qualifying the rotor and rotor components for high-speed operation was accomplished by the use of an air turbine system. This method of rotor component testing is commonly referred to as “quill testing.” The rotor is suspended via a single thin shaft, known as a quill shaft, (in this case a 9/16” diameter shaft) from the air turbine system mounted on the top of the vacuum chamber. The rotor is placed inside a vacuum chamber to reduce the effects of aerodynamics during a high-speed test as shown in figure 3.

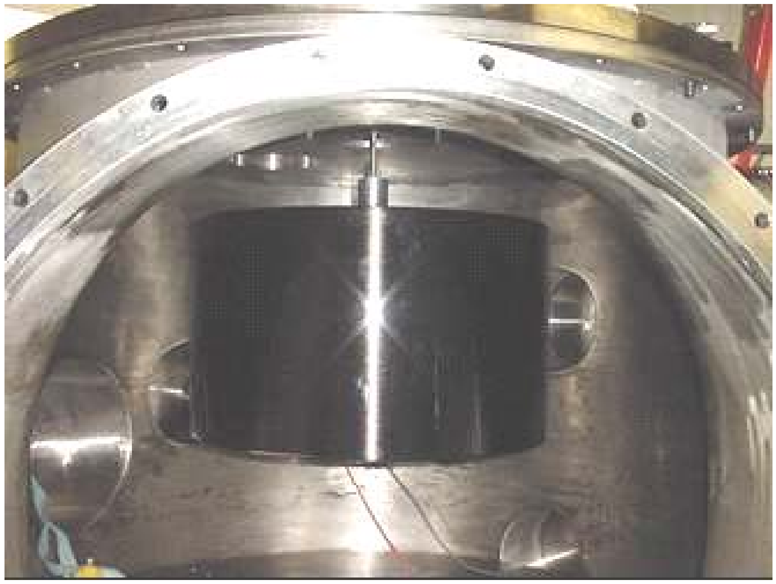

Figure 3. 5kWh rotor suspended from 9/16" quill shaft inside a vacuum chamber.

Modeling of the dynamics of the rotor prior to high-speed spin testing was accomplished by the use of the software tool XLRotor [1]. The analysis provided by XLRotor, shown in the left-hand graph of figure 4, predicted the absence of any critical frequencies within the operating mode of the rotor with the top speed displayed at 25,000 RPM. The model was in agreement with the data collected via the use of non-contact displacement sensors placed near the rim and quill during the high-speed spin testing of the rotor as it was spun up to 23,675 RPM (as shown in the right-hand graph of figure 4). Note: The response at the lower rotor speed (shown on the left-hand side of each graph in figure 4) is the pendulum mode of the quill shaft.

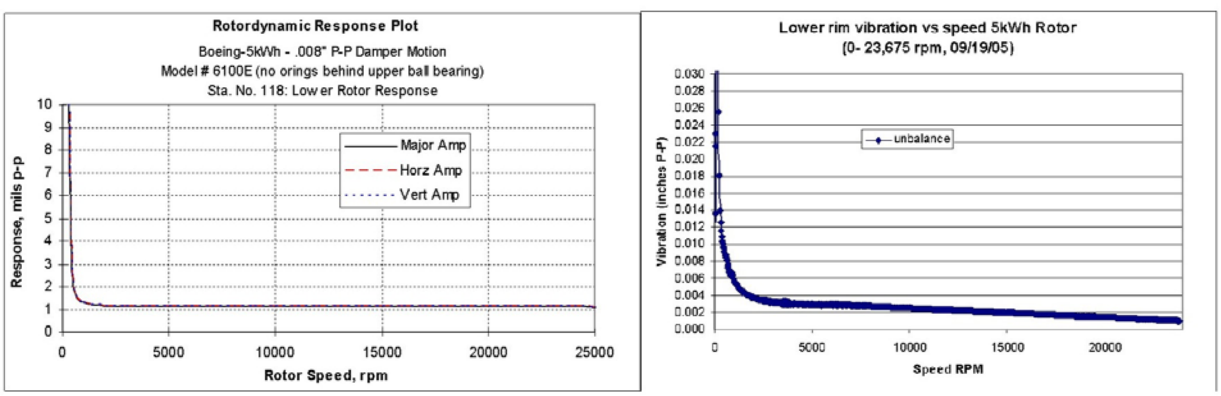

Figure 4. Rotor dynamics model of the 5 kWh rotor quill test vs. vibration data from 5kWh rotor quill test.

The energy losses associated with mechanical and electromechanical bearings can be prohibitively high for nearly all potential flywheel applications. These losses can be typically at least 3% to 5% of the stored energy per hour. With the high energy requirement for the flywheel system, the bearing loss can be great enough to significantly reducing the overall system efficiency. The 5 kWh / 100 kW FESS utilizes the hybrid HTS magnetic bearings [2]. The passive HTS bearing design employs horizontally-polarized circular magnets contained by a carbon composite ring to achieve a high magnetic stiffness per unit area of superconductor. Unlike the magnetic bearings used in other flywheel systems, the HTS magnetic bearing design is completely non-contact in normal operation, and requires no active positioning control algorithm. The HTS bearing is effectively a "solid-state" equivalent of a complex electromagnetic bearing, made possible by the interaction of the rotating stability magnet with the stationary high-temperature superconducting wafers located in the adjacent cryostat. The current system level tests should verify bearing losses that are as low as 0.1% per hour - after imposing a cryogenic overhead factor FCOH of 20 – 30 at 77K. Recent Boeing data on bearing losses on the Boeing 10 kWh / 3kWh flywheel energy storage system utilizing the same design have demonstrated bearing losses equivalent to about 0.1% per hour with FCOH = 20 [3]. The HTS bearing will enable autonomous operation of the 5 kWh / 100 kW FESS as a peak power device, efficiently storing energy when not being called upon for a 100 kW discharge. HTS bearings possess other significant advantages such as dynamic stability, simplicity, and reliability. Operation of the HTS bearing is maintained by a closed loop, liter-sized liquid nitrogen reservoir utilizing a passive thermal-siphon delivery system and regulated by an "off the shelf" Gifford-McMahon cycle type cryocooler driven by an air-cooled compressor. Temperature regulation of the FESS HTS bearing for a typical test run starting from ambient to less than 77K is shown in figure 5.

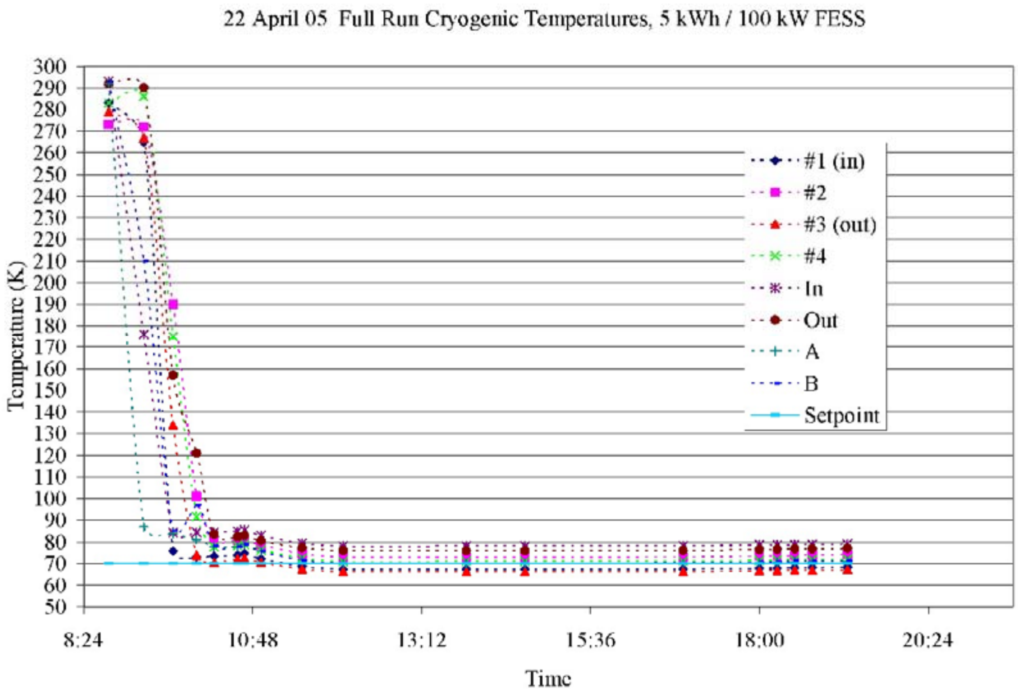

Figure 5. HTS bearing assembly temperature profile.

The Boeing 5kWh / 100kW rotor system design uses permanent magnet ring assemblies to carry most of the rotor's weight, significantly reducing the thrust requirement on the HTS bearing. A small but inevitable amount of instability in the lift system is counteracted with the stabilizing HTS bearing. This approach has been validated in flywheel systems built at Boeing such as the 1 kWh / 3kWh FESS system presented at the 2003 EESAT conference [4].

The energy is removed from the high-strength, high-momentum 5 kWh rotor with the shaft-mounted brushless 100 kW motor/generator. This system design of the Boeing 5kWh / 100kW FESS provides true isolation for critical loads by converting the 3-phase 480 volts alternating current (VAC) input power into 600 volts direct current (VDC) and re-inverting to clean, 3-phase 480 VAC output power by use of commercially available inverter power electronics. The system is capable of responding to line or load transients within four milliseconds for the uninterruptible protection of critical loads such as digital processors or medical facilities. Earlier efforts on the integration of a 3 kW shaft-mounted brushless motor on the 1 kWh machine [4] laid the foundation for the expansion to the 100 kW motor design. The overall power layout of the Boeing FESS with the 100 kW power electronics is shown in figure 6.

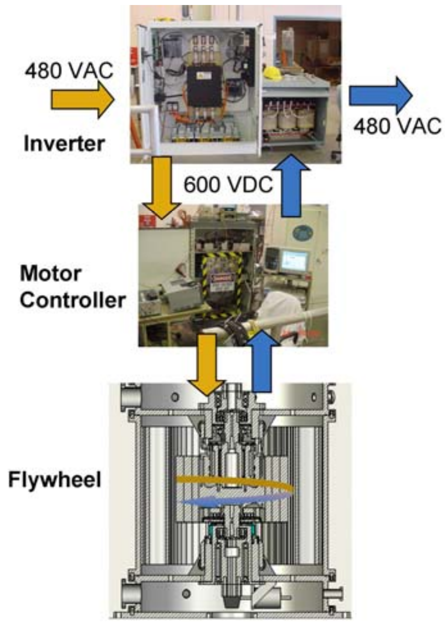

Figure 6. Overall power flow of the Boeing 5 kWh / 100 kW FESS.

Conclusion

The combination of a robust rotor design without critical resonances within the operating range, a high temperature superconducting magnetic bearing, and a brushless motor / generator / power electronics has created a mechanical energy storage device featuring very low standby losses and capable of responding to transient line voltage problems all the while eliminating the complex control systems of active magnetic bearing systems. This system design approach will be scaleable to larger systems capable of spinning at much higher speeds without paying the penalty of increasing the complexity of the rotor stabilization / damping system.

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