A 2MW Flywheel for Hybrid Locomotive Power

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***Abstract*— The University of Texas at Austin Center for Electromechanics (UT-CEM) is currently developing an Advanced Locomotive Propulsion System (ALPS) as part of the Next Generation High-Speed Rail program sponsored by the Federal Railroad Administration (FRA). The ALPS consists of a gas turbine and synchronous alternator, combined with an induction motor coupled flywheel energy storage system (FESS). The prime power and FESS are coupled through a DC power link, as is the conventional AC traction drive system. The energy system includes auxiliary support systems to provide thermal management, bearing systems, controls, and power conversions. The energy exchange capacity of the flywheel is 360 MJ (100 kW-hr). This paper presents the requirements, considerations, and design of the integrated turbine and flywheel power system. Significant development efforts have gone into the high-speed synchronous alternator, the flywheel power converter, the high-speed induction machine for the flywheel, the flywheel itself and its magnetic bearings. The fabrication status of these components and testing progress is also reported.**

Keywords- flywheel; energy storage; hybrid vehicle; locomotive; high-speed.

I. INTRODUCTION

The goal of the ALPS project is to develop a non-electric (diesel-fueled) locomotive propulsion system capable of 150 mph operation on existing infrastructure with good fuel economy and low noise and pollutant emissions [1]. This requires a lighter, more powerful locomotive than existing diesel-electric locomotive designs can achieve. Towards this goal, the ALPS propulsion system incorporates two major elements: (1) a high speed generator directly coupled to a 5,000 hp gas turbine (this package is referred to as the turboalternator), which provides prime power, and (2) a flywheel energy storage system to provide additional power for acceleration and speed maintenance on grades. From a power system design standpoint, the flywheel offers the capability to supply the intermittent power demand, thereby permitting a minimization of the turboalternator output rating. By enabling the prime power to be sized to meet only steady-state load demands, this topology allows the turboalternator to be operated in its optimum efficiency band. The flywheel also improves system efficiency by capturing energy from locomotive braking and making it available during subsequent acceleration cycles. Employed in this manner, the flywheel provides load-leveling for the turbine, thus reducing its thermal cycling and significantly extending turbine maintenance intervals.

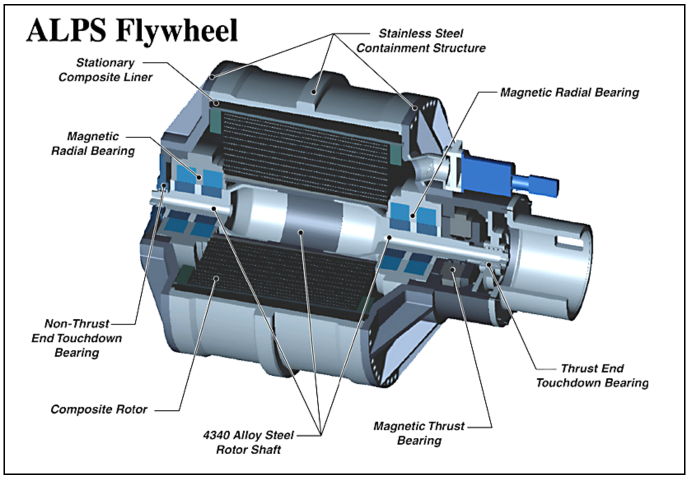

Figure 1. Section view of the ALPS composite flywheel.

Demonstration of the ALPS system is planned in conjunction with an existing turbine/electric locomotive developed as a joint effort by the Federal Railroad Administration and Bombardier Transportation. This approach enables the ALPS project to leverage an existing turbine and traction drive system, allowing UT-CEM to concentrate on the development of a compact, energy-dense flywheel and the required high-speed rotating electrical machines for both the turboalternator and flywheel. In addition, UT-CEM is developing the overall system controls and power management algorithms for the propulsion system. The following sections will describe the major system components and the status of fabrication, integration, and testing completed to date.

II. ADVANCED LOCOMOTIVE PROPULSION SYSTEM (ALPS)

A. Turbo-Alternator Prime Power & Auxiliaries

The selection of the gas turbine prime mover for the propulsion system is driven by the power required to overcome aerodynamic drag and rolling resistance, negotiate grades, and supply the auxiliary and hotel power needs of the locomotive and coach cars. These requirements indicate a gas turbine capable of providing between 2.5 and 4 MW. The actual power would depend on the train consist, or number and type of cars in the train assembly. Turbines in this power range typically have rated speeds between 14,000 and 16,500 rpm, requiring the use of a speed-reducing gearbox to drive conventional

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electric generators. In contrast, the ALPS program is developing a high-speed generator designed to be directly driven by the gas turbine, eliminating the gearbox and significantly reducing the size and weight of the generator itself. The ALPS generator is approximately 0.7m (28 in) in diameter by 1.37m (54 in) long, weighing 980 kg (2160 lb). The high speed generator is an eight-pole, three-phase synchronous machine designed for 15,000-rpm generation of power at 1 kHz. A full-bridge diode rectifier is used to interface the generator with the Bombardier locomotive power bus at 1,960 V-dc. Thermal management for the generator is provided by air and oil cooling systems, with the latter also providing lubrication and cooling for the high speed bearings.

Initial fabrication and assembly of the generator was completed in June 2001. No-load testing, conducted at the UT-CEM laboratory, revealed some design deficiencies in the oil cooling and insulation systems on the rotor related to the stress of high-speed operation. Rework of the generator rotor addressing these design issues is currently in progress. The next testing phase of the high speed generator is scheduled to resume in the Fall of 2003 with the revised rotor.

B. Flywheel Energy Storage System

The deliverable energy of the flywheel design is 360 MJ (100 kW-hr), providing a capability of 2MW rated power for a duration of 3 minutes. The overall dimensions of the flywheel case are 1.6 m diameter and 1.9 m length, resulting in a volumetric energy density of about 90 MJ/m^3. Its mass of 8600 kg yields a specific energy density of 42 kJ/kg. This compares favorably with other storage devices, such as energy storage capacitors, which have less than 1 MJ/m^3 and 2 kJ/kg. Including the direct-coupled motor generator, variable frequency drive, and auxiliaries, the system energy densities remain high at about 18 MJ/m^3 and 20 kJ/kg.

The high energy density of the flywheel is accomplished through its design speed range of 7,500 to 15,000 rpm. The flywheel rotor is constructed (see Fig. 1) using high strength graphite composite materials, to achieve nearly 1000 m/s rotor tip speed. In comparison, steel structures are strength limited to tip speeds of 250 m/s, or less. To create a flywheel with very low rotational losses (high storage efficiency), the rotor is spun in an evacuated enclosure operating at 1e-3 torr. The bearing system is an advanced, non-contact, five-axis active magnetic design. The flywheel support systems include vacuum pumps, DSP-based magnetic bearing controller, and a water cooling system for the bearing stators and shaft seal.

The gyroscopic forces of the spinning flywheel are isolated from the locomotive chassis by supporting the vertical flywheel in a two axis, pivoting gimbal mount, as shown in the solid model of Fig. 2. Rotor integrity and reliability is ensured through a multiple ring design which maintains radial preload between all rings at all speeds. For further protection in the unlikely event of a rotor ring burst, an energy absorbing composite containment structure lines the high-strain stainless steel housing [2]. A system of rolling-element touch down bearings and squeeze film dampers capture and support the spinning rotor if a loss of the magnetic bearing system occurs.

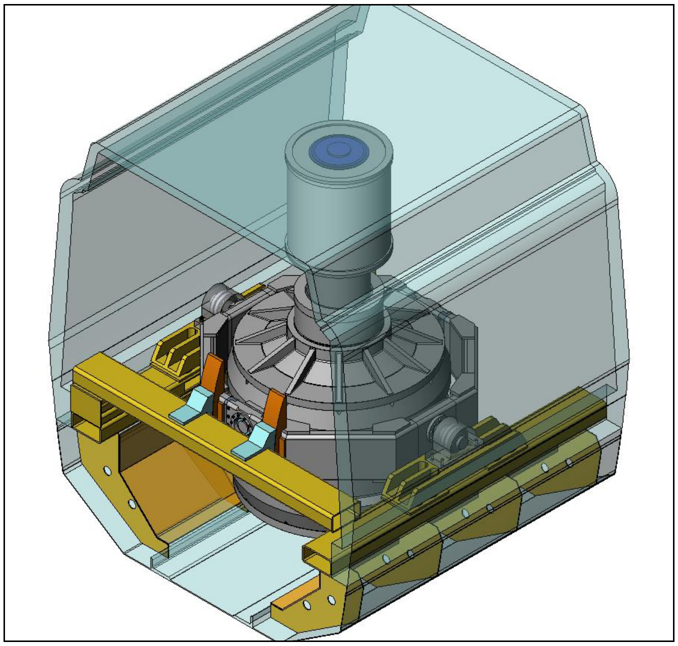

Figure 2. ALPS flywheel and motor-generator in locomotive gimbal frame.

The test plan of the flywheel called for initial commissioning and tuning of the magnetic bearing system with a partially constructed rotor. This incremental approach allows the systems to be demonstrated and evaluated first at relatively low energy, while processing of the remaining rotor rings continues in parallel. Assembly of the flywheel with the partial rotor was completed in October 2002. Testing of the flywheel with the partial rotor entails commissioning of the magnetic bearing system and tuning to incrementally higher speeds, with phases of endurance testing at each stage. Through the endurance testing, performance of the rotor dynamics and magnetic bearing system is thoroughly characterized at each step. At the time of this writing, the partial rotor has achieved stable operation at 5000 rpm and completed endurance testing. Testing with the partial rotor at this speed has successfully demonstrated energy storage of 10 MJ (2.8 kW-hr). Laboratory testing of the flywheel at CEM's spin test bunker facility can be seen in Fig. 3.

C. Flywheel Motor and Power Converter

The motor/generator for the flywheel is a squirrel-cage induction machine designed for a maximum speed of 15,000 rpm. A continuous-duty design power rating of 2 MW (2680 hp) is achieved at the nominal design speed of 12,000 rpm. Thermal management allows for continuous 2 MW charge / discharge cycling between 7,500 and 15,000 rpm. A dual mode cooling system of forced air and oil is employed on this machine as it resides outside of the flywheel vacuum enclosure (see Fig. 4).

Although a larger pole count would be desirable in this machine to minimize the end turn length for compactness, the formed-coil stator is wound in 2 poles to keep the upper range frequency to only 250 Hz. Minimum power frequency is essential in this application due to the necessity of employing a variable frequency drive at this power level.

Figure 3. 100 kW-hr, 2MW flywheel in testing

The core of the motor/generator rotor is constructed of heat-treated alloy steel laminations. The squirrel cage bars and end rings are fabricated from high strength and conductivity Zirconium-Copper and Beryllium-Copper alloys respectively. The motor is supported by oil and air cooling systems, a bearing lubrication oil circuit, seal buffer air, and several levels of uninterruptible power supplies (UPS) to maintain safe operation. The machine is currently under fabrication and assembly; testing is planned in early 2004.

The motor drive for the flywheel system converts power between the 1960 V-dc bus and the three-phase form required by the induction machine. The drive component was designed to provide full flexibility to the flywheel demonstration. It will be operated in a torque-control mode for either motoring or generating, to (from) the flywheel. The ratings are inclusive of the flywheel motor capabilities: producing 150% continuous torque over the 125 to 250 Hz operating range and 150% power over the 200 to 250 Hz range. The control circuitry of the drive is independent of the dc-bus voltage so that even a dead dc-bus may be restarted with a 680 V-dc charging circuit.

An Auxiliary Resonant Commutated Pole Inverter (ARCP) topology [3] is employed to enable high frequency switching with acceptable losses (see Fig. 5). This approach provides zero-voltage and zero-current switching (ZVS and ZCS) in the main and auxiliary power legs, respectively, and has been shown to effectively lower switching losses in higher power motor drive and power bus converters [4]. The switching frequency selected for the ALPS flywheel converter is about 4 kHz using 1700-V high-current insulated gate bi-polar transistors (IGBTs). The exact frequency can be dictated during operation of the flywheel by the FESS controller to maintain a favorable ratio between the switching frequency and the power frequency to the motor.

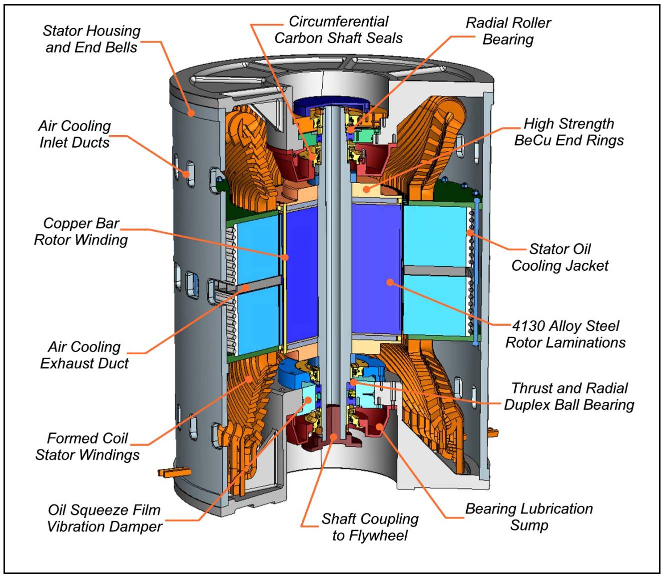

Figure 4. Section view of flywheel high-speed motor/generator.

The drive is further equipped with a dc chopper switch to drive a 1.3 MW resistor grid. This provides a local means to discharge the flywheel energy at the end of operations, or can be used as an at-will, continuously-variable load to be applied to the flywheel or locomotive output power. This circuit uses a 500 Hz PWM switching frequency. An automatic overvoltage protection circuit uses the resistor to quickly load the dc-bus if the voltage rises above set thresholds.

The drive is fabricated by Silicon Power Corporation, Inc. (Exton, PA); using a vector-drive controller by Baldor Motor Company and their own gate drive and protection circuits. Fabrication is expected to be completed in August 2003, followed by pre-shipment acceptance testing and delivery in September 2003.

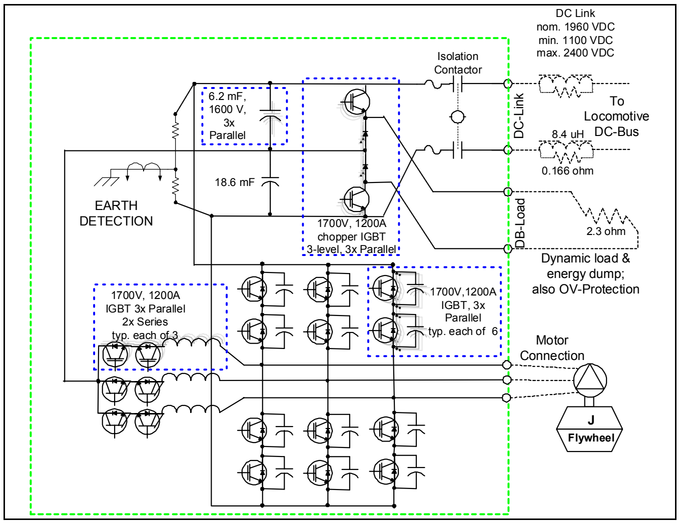

Figure 5. ALPS flywheel power converter with ARCP motor drive topology.

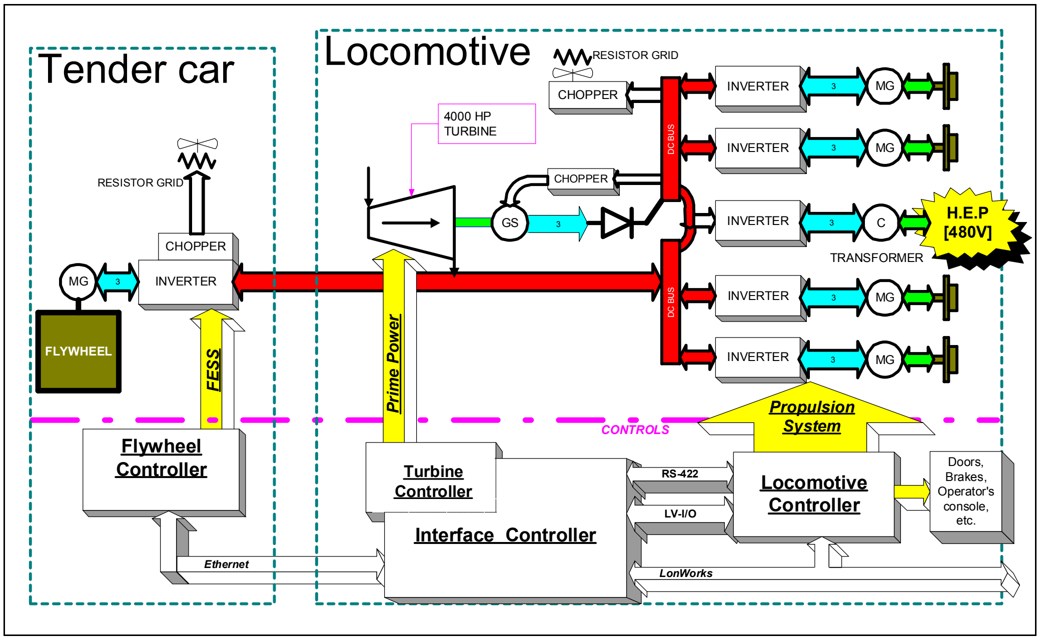

Figure 6. ALPS control architecture with energy management in "Interface Controller."

D. *Interconnections, Controls & Tests*

The ALPS hybrid power system is coupled through the locomotive's electric dc-bus. For the demonstration, the flywheel energy storage system will be installed in a tender car, which is towed behind the prime-power locomotive. The tender car is to be constructed in a LRC model locomotive body, and the two cars will be coupled at the rear, or B-ends. The dc-bus is extended by means of locomotive cable with isolation switches and impedance elements to control the bus transient response.

Each of the two chassis will have a severable controller and a high-speed data link between them. Control system development involves a structured test cycle of target controllers with different levels of simulators to be employed while the fabrication of the hardware systems is being completed. The control architecture is shown schematically in Fig. 6. While the locomotive and propulsion system controller derives the energy demand at any given moment, the so-called interface controller arbitrates the energy allocation between the turbine prime mover and the flywheel energy storage system (FESS). The energy management algorithm is also being tasked with arbitration of braking energy between the dynamic braking resistors and the FESS.

Testing and demonstrations in the ALPS project are progressing from component level towards an assembled ground test at the Austin Texas laboratories of the Center for Electromechanics. This major demonstration, anticipated in mid-2004, will involve the operation of the key ALPS components in concert: the turbo-alternator package, the flywheel with its motor and drive system, and a 3.5 MW resistor grid (representing the traction load) leased from the Transportation Technology Center, Inc. (TTCI, Pueblo, CO). The FESS controller, Interface/Turbine controller, and a simulator for the balance of the locomotive propulsion system will complete the control system for this test.

After successful ground testing, integration of the turbo-alternator and FESS into their respective vehicles will lead to rolling demonstrations of the ALPS configuration at the TTCI test track in Pueblo, CO. This is currently scheduled for mid-2005.

III. CONCLUSIONS

The ALPS program represents a significant extension to the state of the art in flywheel energy storage and hybrid vehicle power. The successful demonstration of this novel locomotive power system will be a major landmark in the path of providing high-speed passenger rail transportation to vast regions of the country where electrified track are not already in place. Furthermore, the power system as a whole, and individual components, provide key enabling technology elements for other applications such as mobile multi-megawatt power generation stations, marine propulsion, industrial stand-by power, oil exploration, and load-leveling for variable generation facilities such as windmill or solar energy farms.

ACKNOWLEDGMENTS

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Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the Federal Railroad Administration and/or U.S. DOT.

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