HIGH SPEED INDUCTION MOTOR AND INVERTER DRIVE FOR FLYWHEEL ENERGY STORAGE

H.E. Jordan, J.D. Herbst, M.T. Caprio, R.F. Thelen, A.L. Gattozzi, and A. Ouroua
The University of Texas at Austin
Center for Electromechanics
1 University Station R7000
Austin, TX 78712

Abstract

The use of flywheels to store energy is a technology which is centuries old. The confluence of several modern technologies has resulted in flywheels becoming a viable solution for the needs of the transportation, electric utility, and aerospace industries. This paper discusses a high-speed induction motor and its associated inverter drive which were developed for the Federal Railroad Administration's "Advanced Locomotive Propulsion System."

The design of the induction motor provided several significant challenges. A megawatt rated, 12,000 rpm motor operating at a rotor surface velocity speed of 230 m/s required a unique mechanical configuration to withstand the centrifugal forces as well as an electromagnetic design, which produced a high efficiency at 200 Hz. Extending the design practices used in smaller motors would not achieve the goals required for a megawatt size machine. Similarly, the inverter was developed using a soft switching technique in order to meet the demands of high power output in a compact package.

Application requirements, electrical and mechanical features of the motor, design strategy for the inverter, and test results are all presented in this paper.

HIGH SPEED INDUCTION MOTOR AND INVERTER DRIVE FOR FLYWHEEL ENERGY STORAGE

Introduction

Scientific advances in several technologies have combined to contribute to the resurgence of flywheels as an energy storage source for a wide range of applications. Advancements in power electronics and high performance composite materials plus the development of reliable magnetic bearings have enhanced the energy storage density and power delivery capability of flywheel systems. This paper describes a high speed and high power-density induction motor and inverter drive system which were developed to drive a flywheel energy storage unit used in as part of a gas turbine powered locomotive propulsion system. The Advanced Locomotive Propulsion System (ALPS) program is part of the Next Generation High Speed Rail Program sponsored by the U.S. Federal Railroad Administration (FRA). The goal of the program is to provide a fossil-fueled locomotive capable of sustaining speeds of 150 mph on existing tracks and infrastructure. The focus of this paper is on the induction motor/generator and its associated inverter used to alternately drive the flywheel and deliver the flywheel's stored energy back into the locomotive's electrical bus.

Application

The application for the ALPS induction motor and inverter is to provide power to and from the flywheel which was also developed under the ALPS program. The ALPS system has been described by Herbst, et al. [1]. The ALPS system diagram from reference [1] is displayed in figure 1.

The benefits of using a flywheel for the ALPS locomotive were quantified by simulation studies made for the New York to Boston route. Although this particular route is an electrified rail and not a candidate for the locomotive discussed here, it represents a typical city to city route and much data is available from this route for study. Figure 2 [1] displays the traction system duty cycle developed from the simulation.

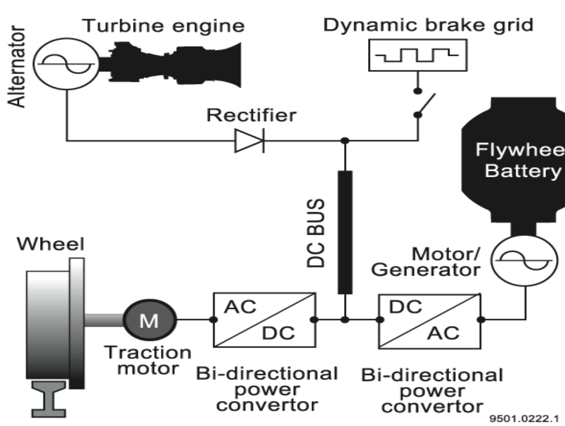

Figure 1. ALPS system schematic diagram

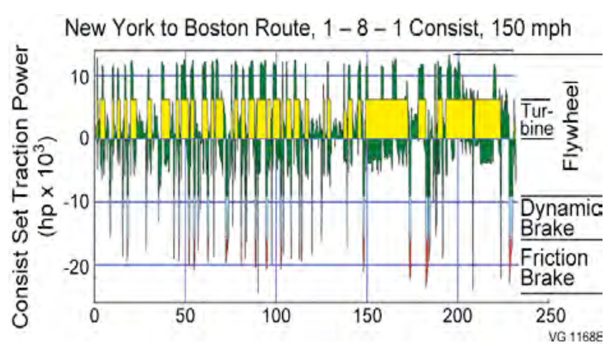

Figure 2. New York to Boston route duty cycle

The simulation study described above was used to establish the base rating for the induction motor and inverter as 2.0 MW. The motor's rated voltage and frequency were set at 1,100 V and 200 Hz. Prior to the present build and testing phase, descriptions of the flywheel, motor-generator, and inverter have been presented in reference [4] [5].

Induction Motor Electromagnetic Design

The induction motor/generator is a copper-bar induction machine designed to operate over a speed range of 7,500 to 15,000 rpm. It is rated at 2.0 MW at 12,000 rpm, constant torque down to

7,500 rpm and constant power above 12,000 rpm. It is connected through an inverter to the dc bus of the locomotive and can operate in either the motoring or generating regions, depending upon whether it is commanded to accelerate the flywheel or deliver power to the dc bus.

Two unique features of the induction machine design are the rotor construction and the stator winding design.

Centrifugal forces are a major factor in the design of the rotor considering that the rotor surface velocity is 286 m/s at 15,000 rpm. A round copper bar is used in place of the more usual rectangular bar to provide a better mechanical stress pattern in the rotor teeth. Also, a proprietary design for locking the end ring to the rotor structure has been developed and is described elsewhere in this paper.

At 12,000 rpm the two pole armature winding operates at 200 Hz. This frequency is high enough to cause significant "skin effect" losses in the stator conductors. The final design utilizes 20 rectangular copper conductors (0.045 in. thick) in parallel for each turn to control the ac resistance loss. This design achieved a 1.1 ratio of ac to dc resistance. Earlier designs had ratios of 1.5 and higher.

The electromagnetic design was conducted using both an algorithmic design program and a finite element analysis (FEA). Figures 3 and 4 display results from the FEA analysis.

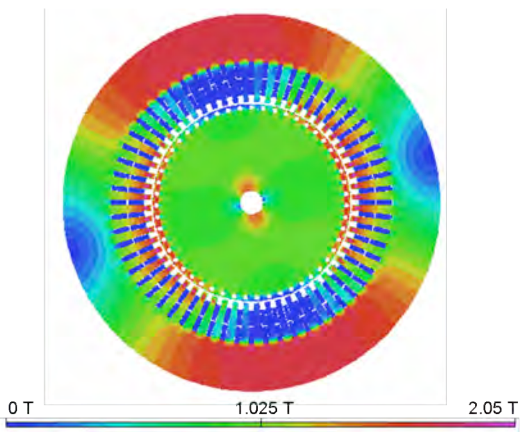

Figure 3. Flux density plot of the ALPS induction motor at no-load

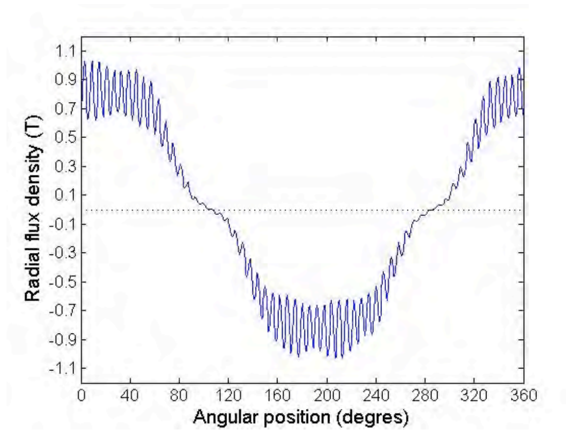

Figure 4. Radial flux density in the center of the air-gap of the ALPS induction motor at no-load

The peak air-gap radial flux density calculated by the algorithmic program and the FEA analysis agreed within approximately 15%. Correlation between the calculated results and available test data is presented in a later section of this paper.

Mechanical Design of ALPS Induction Motor

A novel end ring design was developed to meet the challenging mechanical requirements of this high speed, high temperature, power dense application without compromising electrical performance. A combination of advanced end ring design features were developed to act in concert to alleviate the usual strength limitations of the end ring-to-bar area of a squirrel-cage rotor for high-speed application (fig. 5)

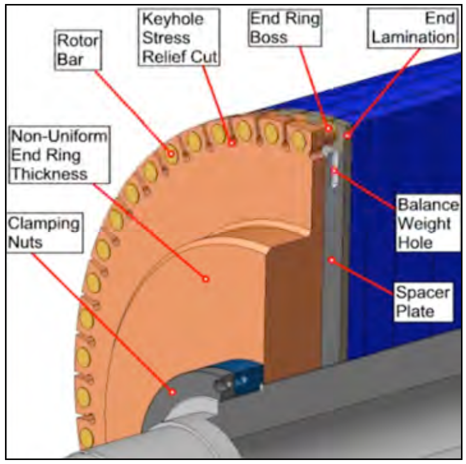

Figure 5. Section view of advanced end ring features

In this design, the end ring is piloted directly to the shaft through an interference fit for rigid support of the end ring to ensure that forces associated with imbalance are not transmitted to the rotor bars. However, at these tip speeds, a uniform cross section end ring is not feasible due to separation of the ring from the shaft resulting from the high centrifugal loads. The end ring was therefore designed with a heavier inner diameter section and a thin web extending to the bar radius. This design maintains compressive interface pressure between the shaft and the end ring throughout the speed and temperature ranges of the machine (0 to 15,000 rpm, -18 to 180°C), with a minimal interference fit that results in manageable stresses.

The thick section end ring with direct connection to the shaft serves a secondary purpose of providing bolster support to the lamination stack to prevent conical buckling of the highly interference fitted core necessary for high speed use.

Selecting a material for the end ring that balanced the electrical and mechanical material requirements was a challenge in this application. The selected BeCu C17510 TH04 material provided the best balance between electrical and mechanical requirements.

The rotor construction has been tested up to 13,000 rpm and performed well at that speed.
Note: the features described in this paper are covered under a US Provisional Patent Application #60,647,898 and a final patent application is being processed.

Inverter

Since the maximum rotational speed of the flywheel was set at 15,000 rpm and a two-pole induction motor design was selected (limiting the drive power frequency to 250 Hz), the inverter switching frequency was chosen as 4 kHz to exceed 15 times the power frequency over the full operating range. To further reduce the switching losses and the size of the power electronic package, the inverter was designed according to the auxiliary resonant commutated pole (ARCP) topology as first described in [3]. The ARCP inverter belongs to the class of soft-switched machines. At these power levels and switching frequencies, this inverter is believed to be the largest built to date for a specific application.

The inverter is shown in figure 6, and is organized in four sections, being from left to right, the control and braking section, the A-phase, B-Phase, and the C-phase sections. All power switches are water cooled. Within the motor drive proper it was decided to leverage the software developed and contained in a commercial off-the-shelf PWM drive control board to provide the basic six-gate switching sequence. These signals are captured, however, by field programmable gate arrays (FPGA) which have been programmed to transform the switching sequence to the nine-switch requirements in the ARCP configuration. The output of the FPGAs are conveyed via optical fibers to the gate drive boards, which gate each IGBT in a switch-group after a verified voltage zero is detected across the switch (in the case of the main switches) or zero current is detected through the switch (as in the case of the auxiliary pole switches). The FPGAs also handle the drive initiation logic to establish a resonant switching rhythm in the start-up of each phase. Figure 7 shows a typical set of waveforms during the operation of the soft-switching inverter. The inverter also includes a hard-switched "braking"section that serves multiple purposes. The dc bus is protected against over voltage and the balance of bus voltage (with respect to the bus mid-point) is maintained via discharge through an external load resistor using hysteresis control. The same section also provides a 500-Hz PWM switching control to generate a variable, on-demand load with same resistor.

Figure 6. Photo of ARCP drive inverter for 2-MW flywheel motor-generator

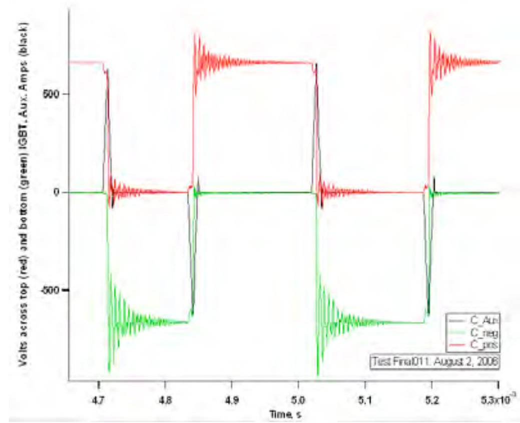

Figure 7. Captured soft-switching voltage and current waveforms from the 2-MW ARCP inverter

Test Results

At this writing, the electrical testing of the induction motor has only been under no-load conditions and at 60 Hz because the system integration of the inverter, motor and flywheel has not yet been completed. The motor has, however, been powered by a commercial inverter up to a frequency of 217 Hz and 13,000 rpm. This was a very important test since it confirmed the integrity of the mechanical construction of the rotor. No-load saturation curves of current and power vs. voltage were plotted from this data and are displayed as figures 8 and 9. Electrically the motor was operated no-load at 60 Hz over a voltage range of 78 to 240 V.

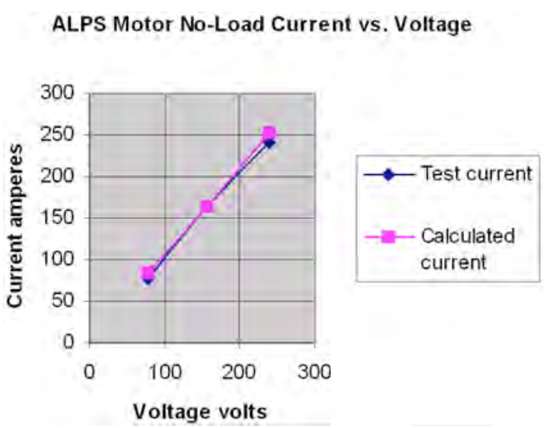

Figure 8. Induction motor no-load current vs. voltage at 60 Hz

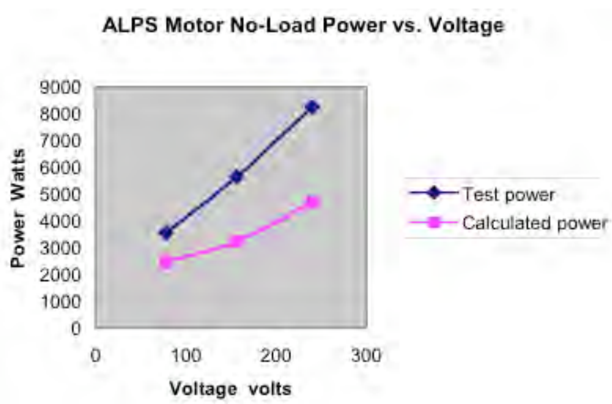

Figure 9 Induction motor no-load power vs. voltage at 60 Hz

A loss separation technique described in reference [6] enables one to obtain the test values for friction and windage and core loss from the no load data. Table 1 presents a comparison of tested and calculated losses and current.

Table 1. Test and calculated results for no-load performance of induction motor

Item	Test	Calculated
F&W at 3,600 rpm	2,192 W	2,000 W
Core loss at 60 Hz., 240 V	5,707 W	1,998 W
Total loss at 60 Hz, 240 V	8,255 W	4,670 W
Current at 60 Hz., 240 V	240 A	252 A

The results show good agreement between test and calculated for the friction and windage and the motor current. The tested and calculated values of power did not correlate well. This discrepancy is attributable almost entirely to the core loss. The tested core loss is 2.85 times the calculated value. This is consistent with results reported by others [7] which state that core losses can increase by approximately a factor of 3:1 when motors are powered by PWM inverters. The calculated core loss was based on an assumed sine wave of flux density, which is customarily done.

Further testing will be performed on the induction motor when it is actually driving the flywheel but data from this testing is not available at this writing.

Conclusions

1. The design of a high speed, high power density induction motor has been presented.
2. Unique designs both electromagnetically and mechanically to realize a 200 Hz, 12,000 rpm induction motor in the 2.0 MW size range are discussed.
3. A new design of a soft switching inverter to power the 2.0 MW machine is described.
4. The application described herein was developed to drive a flywheel for a high speed electric locomotive but the design features are applicable to other high speed, megagwatt size electrical machinery.

References

[1] J. D. Herbst, R. F. Thelen and W. A. Walls, “Status of the Advanced Locomotive Propulsion System (ALPS) Project,” presented at 17th Annual High Speed Ground Transportation Association Conference, Philadelphia, PA, May 10-13, 2000.

[2] H. E. Jordan, J. D. Herbst and R. J. Hayes, “Flywheel Energy Storage System and Their Applications,” SMMA 2002 Fall Technical Conference, St. Louis, Missouri, November 6-8, 2002

[3] R. W. De Doncker, J. P. Lyons: “The Auxiliary Resonant Commutated Pole Converter,” IEEE IAS Annual Meeting, 7-12 Oct. 1990, Vol. 2, p. 1228-1235.

[4] R.F. Thelen, J.D. Herbst, and M.T. Caprio, “A 2 MW Flywheel for Hybrid Locomotive Power,” IEEE Semiannual Vehicular Technology Conference, Orlando, FL, October 6-9, 2003, VTC 2003-Fall. 2003 IEEE 58th, vol. 5, pp 3231-3235.

[5] John Herbst, Matthew Caprio, Robert Thelen, “2 MW 130 kWh Flywheel Energy Storage System,” 2003 Electrical Energy Storage – Applications & Technology (EESAT-2003) Conference, Sir Francis Drake Hotel, San Francisco, CA., October 27 - 29, 2003.

[6] IEEE Standard 112 “Test Procedure for Polyphase Induction Motors and Generators,” Institute of Electrical and Electronics Engineers, New York.

[7] M. Sokola, V. Vuckovic, E. Levi, “Measurement of Iron Losses in PWM Inverter Fed Induction Machines Proceedings of UPEC 95,” London, UK, Sept. 1995.