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Testing of a 3 MW High Speed Generator and Turbine Drive for a Hybrid Vehicle Propulsion System

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ABSTRACT:

The need for increased design flexibility and reduced weight and volume for electric power generation infrastructure has driven an increased interest in the use of high speed generators directly driven by gas turbine prime movers for both military and commercial power generation applications. This transition has been facilitated by the use of DC distribution and recent advances in the performance of solid state power conversion equipment, enabling designers to decouple the power generation frequency from typical 60 Hz ac loads. Operation of the generator at the turbine output speed eliminates the need for a speed reduction gearbox and can significantly increase the volumetric and gravimetric power density of the power generation system. This is particularly true for turbines in the 3-10 MW power range which typically operate with power turbine speeds of 7,000 to 16,000 rpm

The University of Texas at Austin Center for Electromechanics (UT-CEM) is currently developing a 3 MW high speed generator and turbine drive system for a hybrid vehicle propulsion system as a part of the Federal Railroad Administration's Advanced Locomotive Propulsion System (ALPS) Program. The ALPS system consists of a 3 MW turbine/alternator prime mover coupled with a 480 MJ, 2 MW flywheel energy storage system. Although designed as the prime mover for a high speed passenger locomotive, the compact turbine/alternator package is well suited for use in marine applications as an auxiliary turbine generator set or as the primary propulsion system for smaller vessels.

The ALPS 3 MW high speed generator and turbine drive system were originally presented at the ASME Turbo Expo 2005 [1]. This follow-on paper presents the results of mechanical spin testing and No-Load electrical testing of the high speed generator and the Static Load testing of the generator and turbine drive system at NAVSEA Philadelphia with a fixed resistive load. The generator has been tested to a 1.5 MW power level in the Static Load procedures and is being prepared for the final test phased to include dynamic power exchange with the flywheel.

PRIOR TESTING AND ROTOR REDESIGN:

The ALPS high speed generator is designed to deliver 2.5 to 3.0 MW while directly coupled to a gas turbine with a power turbine shaft speed of 12,000 to 15,400 RPM. The generator is a salient-pole, synchronous alternator with a 20 kW brushless exciter alternator and diode assembly on the same shaft. The rotor is oil cooled through a spinning seal connection. The stator and air gap are air cooled by a 75-HP blower providing turbulent air flow through the end turns and passages around the armature windings. The bearings are high speed ball and roller bearings and mount in a squeeze-film damper to control rotor dynamic responses. Figure 1 shows an internal schematic of the generator configuration and cooling scheme. The assembled generator with a Navy-provided Honeywell TF40b engine is seen in Figure 2. In that view the air manifolds, electrical terminals, and axial end oil connections can be clearly seen. The generator is nearly the same size as the turbine, being 1.45 m (57 in.) long and just under twice the mass of the turbine, at 1160 kg (2560 lbs). The electrical output of the generator is nominally 1660 V-AC, 865 A-AC, at 800 to 1024 Hz. The application intent is to rectify the output and use the DC to power an inverter drive and flywheel system, forming a hybrid electric propulsion system with other inverter traction drives on the same DC bus.

Figure 1: ALPS HS-Generator lubrication and cooling schematic.

Figure 2: ALPS HS-Generator mounted with a Navy TF40b engine.

The ALPS high speed generator was first completed for testing in January 2001. It progressed through the No-Load test plan until Run #31 in June 2001 when the rotor winding insulation failed. The rotor assembly failed at three points, all of which were precipitated by the effects of high spin forces on the rotor components. A more detailed description of these failures and the corrective action taken is given by Herbst, et al [2], however, a summary is given in the following section.

One point of failure was caused by the scrubbing of wire insulation by movement of the rotor laminations. The stresses associated with the high rotational speed made conventional techniques of keying the lamination core to the shaft for torque infeasible. In order to maintain contact and adequate friction to transmit full load torque at maximum speed, it was necessary to assemble the core to the shaft with a very aggressive radial interference fit. Therefore, the lamination core was installed with an interference fit of 0.635 mm (0.025 in.), on a 135 mm (5.3 in.) shaft diameter. The laminations went to a slightly conical shape as they cooled to the full interference, which softened the lamination stiffness and resistance to radial growth and, consequently, allowed motion in the spin up and down to abrade the insulation on the rotor winding. The redesign of the

rotor included axially-stiffer end plates on the lamination core to prevent the conical deformation.

The rotor was designed with oil-cooled aluminum wedges in between the salient pole windings to provide support and cooling for the windings. The earlier rotor wedges failed at high stress regions, forming cracks and oil leaks. The wedges were redesigned to be made from single piece and using compression plugs to eliminating all welds. Some regions were reshaped to further lower stress concentrations.

The third failure point involved an insulation failure that appeared to be caused by spin forces on trapped debris to push through the double Kapton™ insulation layer in the spinning diode region. The rotor redesign included several changes to improve the robustness of insulation and the removal of any foreign matter.

NO-LOAD TESTING

The No-Load test plan for the high-speed generator called for a hydraulic motor and speed-increasing gearbox as a spin source. The rotor was first tested in a dummy stator, which held the bearings and oil cooling passages while providing ready access to the rotor for instrumentation and inspections. Figure 3 is a view of the rotor and dummy rotor being installed for testing. The hydraulic motor, gearbox, and torque meter are seen already in place.

Figure 3: High-speed generator rotor and dummy stator tube during installation.

The graph of Figure 4 is a summary view of the No-Load test progress through a speed range to 105% of 12,000 RPM. During the speed run-up the modes of vibration and the radial growth of the machine were closely monitored. At first, the rotor oil cooling was not employed so that a dry rotor baseline of the rotor dynamics might be established. Then the oil cooling circuit was tuned on to observe any changes in balance or natural frequencies. Finally, the dummy stator was replaced with the wound stator so that test of the open-circuit and short-circuit electrical characteristics might be conducted.

The rotor assembly improvements resulted in a 5% to 8% decrease in radial growth and an improvement in the matched growth ratio of end turn banding to the rotor lamination/wedges from 173% down to 114%.

The rotor oil cooling wedges maintained their integrity and the rotor was successfully tested with oil circuits flooded. The rotor cooling flow, however, was observed to decrease with speed and the spinning induced a back pressure not previously accounted for. Some hydraulic supply changes were able to increase delivery pressure and changed the supply from essentially a pressure-source supply to more of a flow-source supply to compensate for the back-pressure changes with speed.

During the spin tests, the torque meter registered a total of 55 kW shaft power at 12,000 RPM. A complete analysis of losses is beyond the scope of this paper and may be covered in a future presentation.

Figure 4: Summary view of No-Load Testing phases.

Electrical testing started with open-circuit voltage characterizations. Figure 5 shows a typical three-phase voltage recording. The evident space harmonics were not unexpected. During the winding of the stator armatures it was found that the skewed slot design intended was too difficult to execute in such a compact generator structure. Consequently, the stator lamination slots were allowed to be built straight, at the cost of additional 11th and 13th harmonics in the voltage waveform. The generator stator is built with four parallel windings per phase and these leave the machine by way of four 3-phase terminals. The voltage measurements were able to establish a variation of less than 0.2% in voltage magnitude among the parallel windings and among the three phases.

During the open-circuit voltage tests, the torque meter registered a total of 80 kW shaft power at 1170 V_[L-N] (120%). This represents the windage and bearing losses plus the lamination core losses and field excitation losses.

Figure 5: Three phase open circuit voltage waveform.

The short-circuit current tests were plagued with sensor cross-talk at first but eventually the leads and Hall-based, wide band current transducers could be placed in such a way to minimize those measurement errors. Figure 6 shows the three-phase currents: the harmonics are greatly reduced but the phase to phase magnitude differences are a bit higher. The variation from norm for these currents were measured at 2.2%.

During the short-circuit current tests, the torque meter registered a total of 130 kW shaft power at 1320 A (150%). This represents the windage and bearing losses plus the winding I^2R losses and field excitation losses. Post-test inspections showed that temperature indicating labels on the rotor end turns registered a maximum 170°C, compared to a design limit of 220°C. The highest recorded stator winding temperature was briefly 192°C during the 1320 A test.

Figure 6: Three-phase short-circuit current waveforms.

STATIC LOAD TESTING

The Static Load testing was conducted at the US Navy Small & Medium Turbine Test Facility at the Navy Surface Warfare Center – Carderock Division in Philadelphia, PA. Eighteen runs were conducted over three months with six runs exceeding 1 MW to the resistor load. A Navy ETF40 engine was direct coupled to the generator and the electrical output was rectified for a DC resistor load bank. Power to the load was controlled both by

adjustments in resistor value between runs and by adjusting the excitation current during the run. Figure 7 shows the installation of the generator in the Navy's test cell.

Figure 7: View of high-speed generator installed in turbine test cell with ETF40 engine.

The other major components employed in this phase of testing were the rectifier and the load resistor. The rectifier is an air-cooled, 3-phase, full diode bridge, using two fast recovery diodes in parallel at each position. The rectifier has been fully described previously in [1]. The Static Load tests were begun using a 1.3 MW locomotive braking rheostat as the load resistor (see Figure 8). Later, as higher power levels were desired, a load bank was leased from the Transportation Technology Center, Inc (TTCI). This load bank is capable of switched configurations ranging from 1 to 3.5 MW at 2 kV-DC. Figure 9 shows the larger load bank being moved into position for hook-up to the rectifier output.

Figure 8: Locomotive braking resistor being install for loading up to 1.3 MW.

Figure 9: Positioning 3.5 MW resistor load bank for higher power Static Load tests.

The bar graph in Figure 10 is a summary view of the Static Load testing sequence. Any runs showing less than 12,000 RPM did not get switched from the Idle mode to Run. On Run # 5 the speed was increased to 105% (12,600 RPM) to record the machine vibration data up through that point. The darker bars represent the power level which the load was brought to: Run #17 has the maximum attained at 1500 kW.

Three inadvertent “Emergency Stop” trips occurred in the course of testing. The trip control event was found to be benign, specifically turbine or generator overspeed upon dropped load did not occur. The highest speed recorded after a trip was 12,300 RPM. The first trip in Run #3 was simply a bad parameter setting in the turbine controls, resulting in a false over-speed detection.

In Run #16, the air cooling duct worked itself free enough to blow out a rubber coupling piece. The loss of air cooling pressure resulted in a successful “E-Stop” control sequence. Run #17 tripped the Generator Protection Circuit (GPC) shortly after coming to the 1.5 MW load level. The GPC includes a function to sum the currents from each of the four 3-phase terminals to see that the “neutral” current does not exceed its threshold. This function precipitated the trip but unfortunately insufficient high-speed recording channels did not allow a capture of the twelve currents to corroborate the fault. The parameter magnitudes were being recorded at 1 sample per second and that record showed the summed currents to be running about 5 amps, whereas the trip threshold was set at 80 amps. Assuming that the GPC had falsely tripped, the neutral current function was defeated for the next run and the parameters were wired for real-time monitoring on the data acquisition computer screen. Later internal machine inspections failed to show any damage that might be due to or cause such a failure.

Figure 10: Summary view of Static Load Testing showing speed and power levels for each test.

Run #18 was the final run and was conducted the same day after the Run 17 E-Stop event. In this Run, the generator was brought up to the 1.25 MW level to repeat previous run data. Slight differences in excitation level and machine temperatures made the test engineers wary. When the at-power stator winding temperature was seen to climb to the self-imposed test limit, the engineer aborted the run. After this, the machine was brought back to the CEM-UT lab in Austin, TX for disassembly and diagnostic inspections.

Four runs were sustained until thermal steady-state was reached for the generator. Based on these results and earlier analysis that predicted a hot spot temperature that could be 150% higher than the measured winding slot temperature, the graph of Figure 11 was produced. As a conservative test limit, 155°C was selected for this phase of generator testing to assure that no part of the generator exceeds the 220°C design limit. As can be seen in the plot, if the hottest spot temperature rise is 150% of the rise at the points measured, one might use even 175°C as a limit. However, additional derating was employed to cover the uncertainties of points unmeasured. In the perfect world of the design phase, all cooling slots are equally effective and one would not have to derate the machine operation at all from the sampled winding temperature. In that case the plot below shows the delivered power rising to 2.7 MW before the 220°C limit is reached. The generator design originally targeted 2.5 MW for a continuous power rating (in a somewhat higher ambient temperature of 50°C).

Figure 11: Map of generator temperature rise with power.

THE TURBINE AS PRIME MOVER

(Section by Ben Canilang)

- ❖ *Description of engine used*
- ❖ *Performance observations*
- ❖ *Issues or benefits seen in testing; for future applications with HS generators.*

CONCLUSIONS:

The generator has demonstrated continuous power production at a level of 1.3 MW to the load and peak power at 1.5 MW. Because of the compact size of the generator it achieves thermal equilibrium in the relatively short period of about 30 minutes. Electro-magnetically, the machine appears to be capable of exceeding the 2.5 MW level, however thermal-dynamic inequalities arising from manufacturing variability may limit the machine to less than this figure. These limits will be further explored in upcoming tests planned for early 2007.

Some technical challenges remain for the high speed generator developed for the ALPS propulsion system, but the core generator technology is suitable for use in a number of user applications. Lessons learned during the fabrication, assembly, and testing of the ALPS generator provide a path to address the remaining technical challenges and achieve the required power performance while improving manufacturability. The high pressure stator air cooling system developed for the ALPS generator proved to be a significant challenge to implement with “real world” coil forming and installation techniques. The auxiliary power for the high pressure blower needed to supply the stator cooling air is also significant, impacting the overall efficiency of the power generation subsystem. Improvements to the field winding insulation and field coil installation techniques could also be used to simplify fabrication and improve the robustness of the field windings. Design variations developed as a direct result of the ALPS high speed generator work are

being utilized in the design of other high speed rotating electrical machines at CEM-UT in different power generation applications [3].

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