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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 to 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, PA) 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 phase to include dynamic power exchange with the flywheel.

INTRODUCTION

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 three engines mentioned in this article are summarized in Table 1. 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 lb). The electrical output of the generator is nominally 1660 V-ac and 865 to 1040 A-ac at 800 to 1024 Hz, corresponding to 12000 to 15400 rpm for the 8-pole armature. 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 operated on the same dc distribution bus.

Table 1
Vericor TF-Series Marine Gas Turbine Engines [2]

Model	shp @ rpm	Mass [kg]
TF40B	4000 @ 15400	602
ETF40B	4960 @ 15400	682
TF50A	5100 @ 16000	710

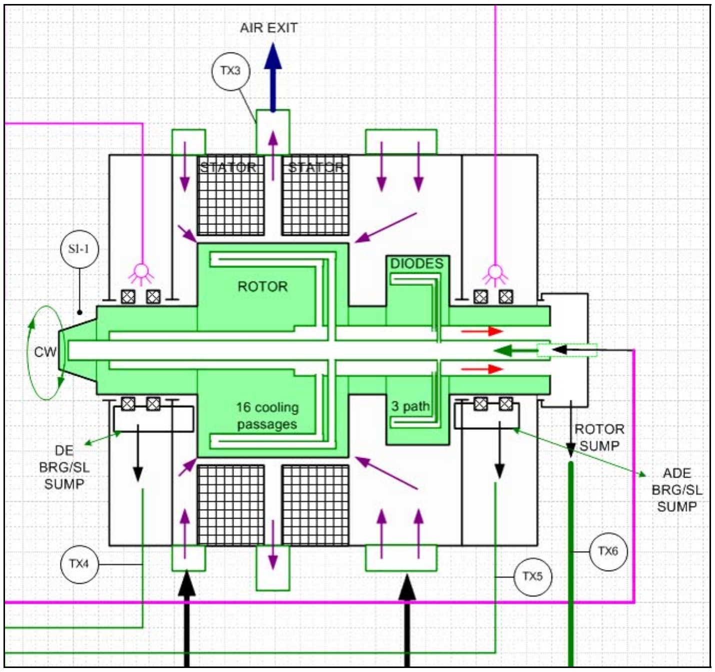

Figure 1. ALPS HS-Generator lubrication and cooling schematic

Figure 2. ALPS HS-Generator mounted with a Navy TF40B engine (1700 kg, as shown)

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 in reference [3], however, a summary is given here.

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. This in turn provided a softened lamination stiffness and resistance to radial growth. Consequently, the laminations were able to move during the spin up and down, in such a way that the insulation on the rotor field winding was abraded. 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 a single piece of stock and used compression plugs in holes to eliminate all welds in the fabrication. 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 which pushed 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.

NOMENCLATURE

ALPS — Advanced Locomotive Propulsion System, an R&D technology demonstration program of the Department of Transportation, Federal Railroad Administration.

UT-CEM — The University of Texas – Center for Electromechanics, Austin, TX

NAVSEA — Naval Sea Systems Command

NSWCCD-SSES — Naval Surface Warfare Command, Carderock Division – Ships Systems Engineering Station.

TTCI — Transportation Technology Center, Inc., a wholly owned subsidiary of the American Association of Railroads, located east of Pueblo, CO.

MGTE — Marine Gas Turbine Engine

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 stator 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 turned on to observe any changes in balance or natural frequencies. Finally, the dummy stator was replaced with the wound stator so that testing of the open-circuit and short-circuit electrical characteristics might be conducted.

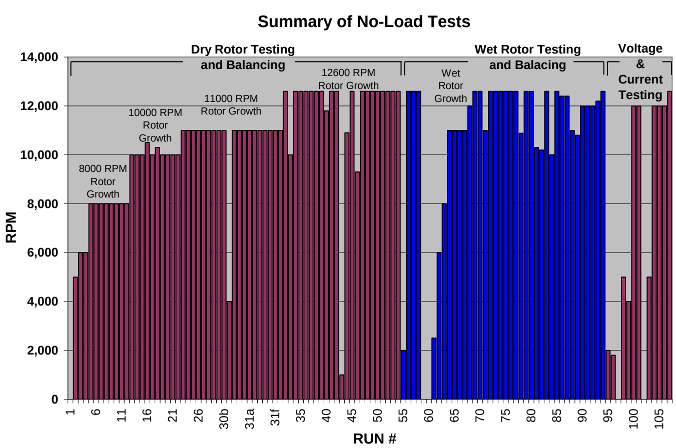

Figure 4. Summary view of No-Load testing phases

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 executed to increase delivery pressure and changed the supply from essentially a pressure-source supply to more of a flow-source supply which would 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.

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 current is conducted out 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.

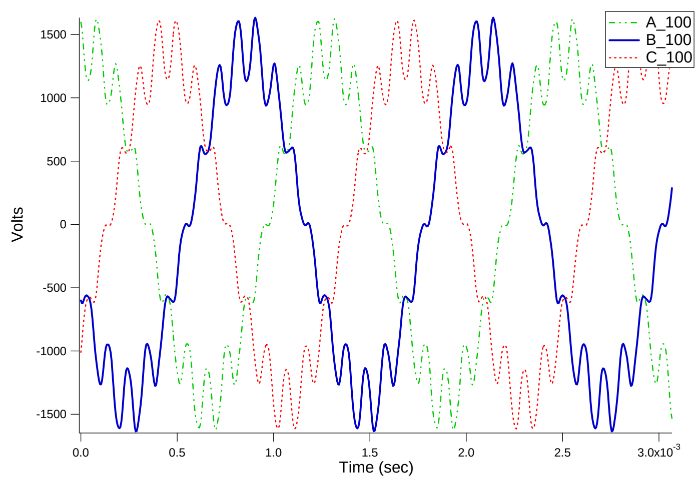

Figure 5. Three phase open circuit voltage waveform

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.

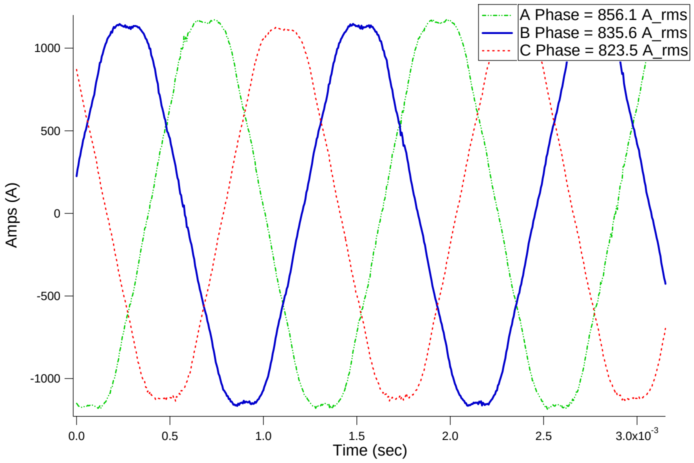

Figure 6. Three-phase short-circuit current waveforms

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 ETF40B engine with Full-Authority Digital Engine Control (FADEC) was directly coupled to the generator. The electrical output was rectified and fed to 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.

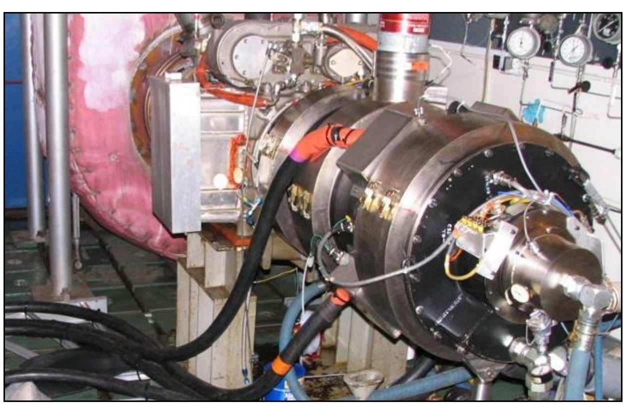

Figure 7. View of high-speed generator installed in turbine test cell with ETF40B engine

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 (Figure 8). Later, as higher power levels were desired, a load bank was leased from the Transportation Techology Center, Inc (TTCI). This load bank is capable of switched configurations ranging from 1 to 3.5 MW in the 2 kV-dc set up (Maximum capability is 8 MW dissipation at lower voltage). Figure 9 shows the larger load bank being moved into position for hook-up to the rectifier output.

Figure 8. Locomotive braking resistor being installed 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. The runs showing less than 12,000 rpm (wider bars, left axis) were conducted in the Idle control mode, which holds a constant gas producer speed, and the power turbine or generator speed is determined by the level of electrical load. The 12,000 rpm and above runs are in a Run control mode which regulates fuel to maintain a constant power turbine (output) speed. On Run # 5 the speed was increased to 105% (12,600 rpm) to record the machine vibration data up through that point. The darker, narrow bars represent the power level (right axis) to which the electrical load was adjusted: Run #17 has the maximum power attained at 1500 kW.

Four 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.

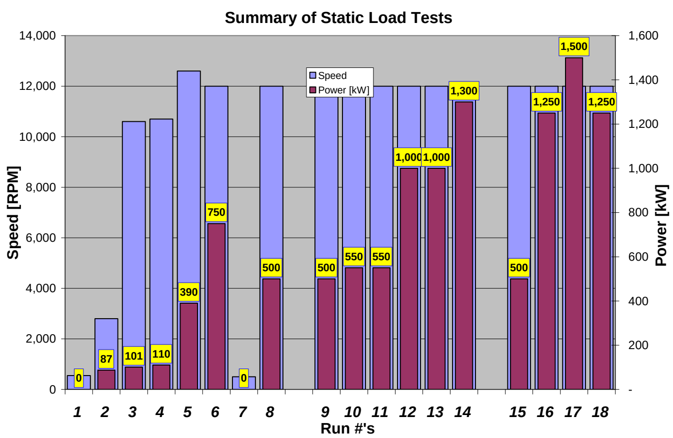

Figure 10. Summary view of Static Load Testing showing speed and power levels for each test

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 UT-CEM lab in Austin, TX for disassembly and diagnostic inspections.

The power rating of an electric machine is determined by the limits imposed by such factors as magnetic field saturation, shaft torque capability, and insulation temperature. The former are representative of fairly predictable material property selections. The temperature limit, however, is determined by not only insulation material properties, but also the thermal dynamics of the machine losses and the effectiveness of its cooling solutions. With the as-built oil and air cooling systems and machine efficiencies of this prototype, tests were conducted to project the limit of steady-state power capability for the generator. Four different power levels were sustained long enough for the generator to reach a thermal steady-state condition (about 30 minutes at power). Based on the recorded results from these runs, the graph of Figure 11 was produced.

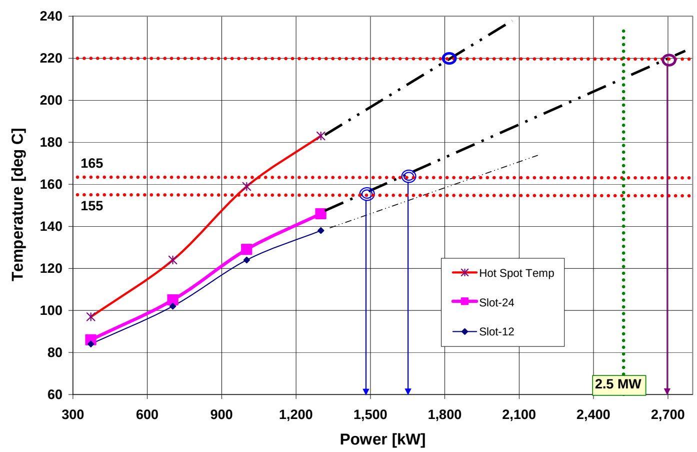

Figure 11. Map of generator temperature with power including a “hot spot” temperature estimate.

Two embedded temperature sensors monitor the center of the armature windings in slot #12 and #24 (two other slot sensors had failed during manufacturing). A preliminary test was conducted after the stator was first wound to gauge the resistance of the stator cooling passages to air flow. That test revealed a distribution among the numerous paths having a 6.1% SD around the mean air flow rate. The worst case slots showed air flows of only 66% of the mean, however. Slot #24 was very nearly an average flow slot and slot #12 exhibited a 20% higher flow rate.

Based on these observations, it was decided to predicted a hot spot temperature that would have a temperature rise 50% higher than the temperature rise in a slot with average air flow resistance (e.g., slot #24). In the four tests represented in Figure 11, the cooling air temperature is supplied at ~70°C due to compressive heating by the blower (50°C over ambient). The estimated hot spot temperature is calculated, then, from the measured slot #24 temperature rise over the supply air temperature or, in formulation:

$$T_{HS} = (T_{24} - T_{AS}) \times 1.5 + T_{AS} \qquad \text{(Eq. 1)}$$

As a conservative operator's limit, 155°C was selected for this phase of generator testing to assure that no part of the generator exceeds the 220°C insulation design limit. It can be seen in the plot of the projected hot-spot temperature that a limit up to 175°C might have been used. However, additional derating was employed to cover the uncertainties of points unmeasured. In the perfect world of the design phase, all the cooling slots would be equally cooled and one would not have to derate the machine operation at all from the sampled winding temperature. In that case, the plot shows the delivered power projects out to 2.7 MW before the 220°C insulation limit is reached. So it appears that the manufacturing variability among coil slots and air passages will limit this machine below the intended level of continous operation. Specifically, a more constant cooling efficiency over the 48 stator winding slots is required, either by improved manufacturing consistancy or by a more forgiving cooling design.

The generator exhibited some interesting vibration behavior. The bearing support system was designed by engineers at the AlliedSignal Engine division in Phoenix, AZ (now, Honeywell). The rotor is supported radially by two 105 mm cylindrical roller bearings, and axially by two 100 mm ball bearings. The ball bearings are located outboard of the roller bearings, and are spring preloaded against each other with over 1000 lb of preload. The roller bearing outer races are surrounded by oil squeeze film dampers, also designed by AlliedSignal. There is no centering spring, so these dampers are "uncentralized", and can therefore exhibit nonlinear behavior [5].

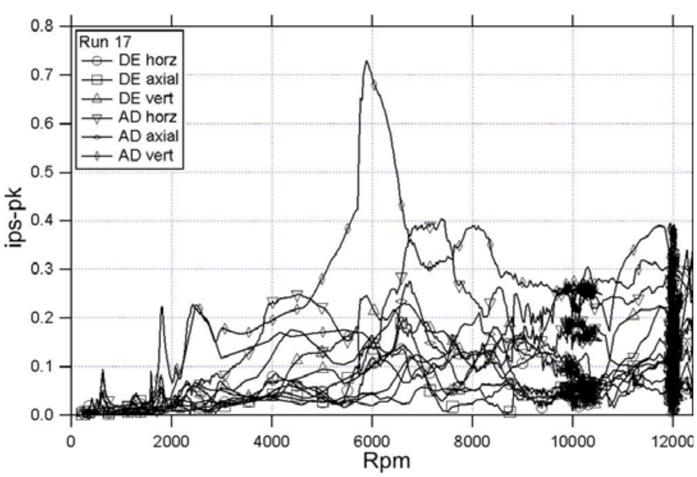

Figure 12. Synchronous component of housing vibration expressed in velocity units.

The structural support of the generator housing would be considered quite flexible compared to common industrial machine mounts. The generator is cantilevered from its mounting flange with the turbine (see Figure 2). There is a single vertical strut under the anti-drive end, the base of which is on rubber isolation pads. Figure 12 shows the synchronous vibration where startup was rapid, but shutdown from 12000 rpm took about 3 minutes. The dominant critical speed seen at 6000 rpm (100 Hz) has the two ends of the machine vibrating in phase mainly in the vertical axis. This may be a rigid body mode of the rotor on the dampers since the first flexible rotor mode is >300 Hz. At 12,000 rpm the synchronous vibration is about 0.3 ips-pk, which would be considered high for stiffly mounted machines, but perhaps not so high for flexibly mounted machines. The vibration is fairly insensitive to changes in balance weights. This could be due to the nonlinear influence of the dampers, or runout excitation from the ball bearings.

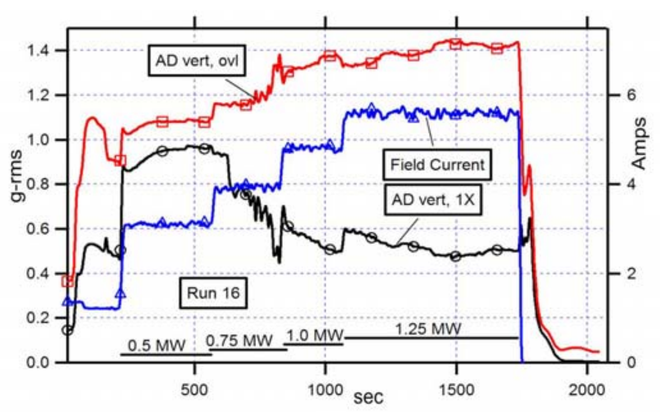

Figure 13. Influence of power level on filtered (1X, synch.) and unfiltered (0-2000 Hz) vibration.

Under load, the vibration also contains significant components which are not 1X. Figure 13 shows that at 12000 rpm the synchronous and overall vibration both change as power level changes. The maximum component of vibration was 1.5 times generator speed (precisely 300 Hz) measured at the anti-drive end vertical position.

Figure 14 shows that the spectrum is affected by power level. The variable speed of the compressor rotor indicates the power level, starting at 268 Hz at 0.5 MW. The 0.5X and 1.5X components exhibit amplitude modulation in the form of sidebands at rates varying from 3 to 8 cycles per second.

Time wave forms of the vertical acceleration suggest the possibility of two "impacts" occurring every 2 rotations, but spaced precisely 2/3 revolutions apart. A plausible explanation for the 0.5x and 1.5x components could be the first flexible mode of the rotor possibly being near 1.5x (300 Hz or 18000 cpm), plus the rigid body mode at 0.5x (100 Hz). These two vibration components do show up most strongly in the vertical axis. So the shaft mode vibrates 3 cycles in 2 revolutions, where two of those cycles produce "impact" like response, and one cycle does not. This would produce two events spaced 2/3 revolutions apart, and then no events for 4/3 revolutions. This matches the pattern observed in time history data.

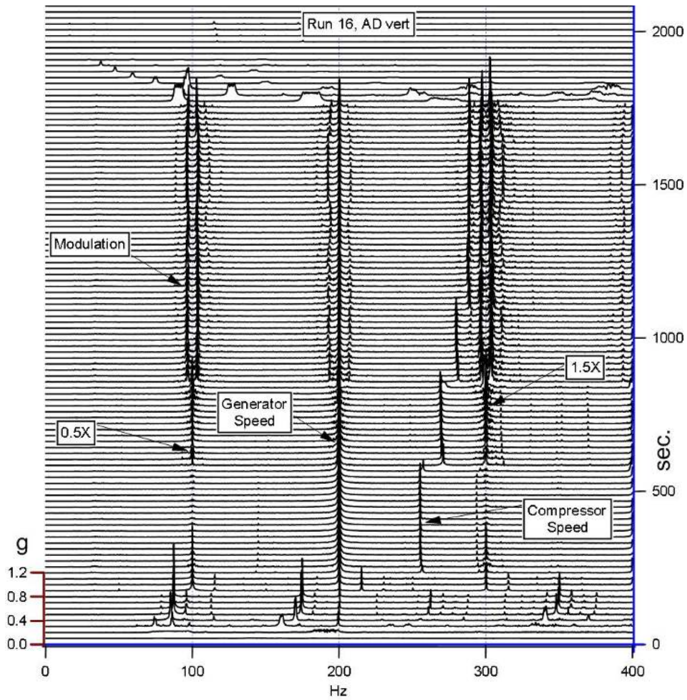

Figure 14. Waterfall plot of housing vibration. Four compressor speeds correspond to 0.5, 0.75, 1.0 and 1.25 MW.

THE TURBINE AS PRIME MOVER

The ETF40B Marine Gas Turbine Engine (MGTE) was designed for main propulsion on board all US Navy Landing Craft Air Cushion (LCAC) vessels which have undergone the Service Life Extension Plan. This Enhanced-TF40B engine is really a combination of two other engines: the TF40B, which powers the original Legacy LCAC and the more powerful TF50 model.

As a marine engine, the compressor and turbine are designed for and coated with appropriate materials to withstand the harsh environment the LCAC encounters from off shore, through the surf/shore interface, and even several miles inland when required.

The engine used during the ALPS testing was the prototype test engine designed and manufactured by Honeywell. Unlike engines used in the fleet, this particular engine is heavily instrumented to monitor a variety of parameters, which in turn allow careful observation and evaluation of engine performance, degradation and changes in operating characteristics.

A typical fleet-use run cycle includes various output shaft speeds and various loads with a maximum craft limit of 3955 shp (gearbox operating limit). Since, on board the craft, engine load varies with sea state and craft loading, a range of power outputs is typical for a standard mission.

The ALPS high speed generator was considered the more sensitive item during testing at NSWCCD-SSES, hence the initial runs were tailored to fine tune how the engine and generator acted together. Initial speed ramps were gradually introduced to protect against possible over-acceleration of the generator. After several runs, the observed performance showed that the system was capable of transitioning from engine idle to 100% rated speed of the generator without the need for interim speed steps. It was also noted that even under the zero load condition, the idle speed of the engine did not exceed 100% rated speed of the generator. This would ensure that, as long as the controls remained set, no damage would result from the engine running with the generator unloaded.

Since the majority of testing involved single-speed set output, engine operation was limited from transitions between start, idle and run (pre-set to 80% of engine rated speed) without any direct operator input for speed control. All power demands were automatically adjusted for by the FADEC engine control by varying N1 and fuel demand. These adjustments were automatic as they were required to maintain the set output speed.

Coupling the ETF40B MGTE to the ALPS high speed generator was a deviation from the original intent of the engine. Capped to a maximum output speed of 12,000 rpm corresponds to roughly 80% of rated engine output speed (15,400 rpm). Craft operations rarely, if ever, run at this speed hence the engine was operating outside of its standard range.

The deviation from standard operation in order to power a generator had several consequences. Since the engine, independent of the craft drive train, is capable of producing up to 5700 shp (4.25 MW, boost), operating far off the power point results in an loss of engine efficiency. Since gas turbine engines are generally purpose built, this drawback would apply to a coupling of any high speed generator to an engine originally designed as a main propulsion unit. Furthermore, as this particular engine was never designed to operate at constant speed at all times but is instead designed to operate over a range, designs associated with operation over the wider range were not taken advantage of and may have even limited the engines potential at the generator speed. While dedicated gas turbine power units exist, they incorporate reduction gear boxes between the output shaft and generator unit and hence the gearbox itself and associated losses draw away from the true customer power output of the engine. However, these engines are typically designed with the specific intent of operating at a set output speed.

The benefit in this installation, even using a purpose built engine, and as witnessed in testing at NSWCCD-SSES is that the engine is allowed to operate at a steady output speed regardless of power output with only the gas generator or core having to adjust for changes in demand. From an engine life-cycle standpoint, this greatly reduces the stresses associated with transient speeds and repeated starting and securing of the engine itself. Additionally, operation of the engine at only 80% speed drastically reduces the risks posed by potential overspeed resulting in a safer operating environment.

Since, on board the LCAC, the engine is geared directly into the main propellers, physical contact with the propeller blades can cause the engine to undergo an extreme deceleration. A shear section is built into the output shaft of the engine to limit the potential for damage in this case. To protect against overspeed the engine is designed to shut down if the output speed exceeds 108% of rated. In the case of the ALPS test a sudden drop of load could allow the engine, if not stopped, to undergo an extreme acceleration in the power turbine. However, observations during the un-commanded shutdown on Run #16 proved that a digital control system is capable of containing this type of failure within the standard operational limits of this engine. The opposite scenario was not considered a high risk as there is no mechanical link between the spinning core of the generator and the stator casing.

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 this and a number of other 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 [4].

The generator and a Navy-supplied TF40B engine (analog controller) are now being assembled at the UT-CEM laboratory in Austin for the next phase of testing: the turbine-alternator in conjunstion with a 2-MW, 100 kWH flywheel energy storage system. During these tests, further diagnostics are planned to help resolve issues raised in the testing and results reported here.

ACKNOWLEDGMENTS

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