High Voltage Stator for a Flywheel Energy Storage System

CLEARED
FOR OPEN PUBLICATION

T.A. Aanstoos, J.P. Kajs, W.G. Brinkman, H.P. Liu, A. Ouroua, and C. Hearn
The Center for Electromechanics at The University of Texas at Austin

MAR 24 2000 9

DIRECTORATE FOR FREEDOM OF INFORMATION
AND SECURITY REVIEW
DEPARTMENT OF DEFENSE

J. Sargent and H. Gill
The State University of New York, Buffalo

REVIEW OF THIS MATERIAL DOES NOT IMPLY
DEPARTMENT OF DEFENSE INDORSEMENT OF

FACTUAL ACCURACY OR OPINION. Continuous, high power (3 bursts 1 s apart at 1 MJ at 5 MW)

Abstract-- The University of Texas at Austin Center for Electromechanics (UT-CEM) has designed and conducted component test/development for a flywheel energy storage system for pulsed loads and mobility load leveling in a tactical vehicle. Performance goals of this machine dictate that the stator windings will see continuous voltages of 6.7 kV and spikes to 10 kV. To manage the thermal loads produced by the intermittent 5 MW output pulses, and continuous 350 kW duty, the generator is cooled by oil at a maximum temperature of 90°C. UT-CEM designed and developed a novel insulation system and dual coolant passage arrays for the stator. Design performance was verified in laboratory prototype testing. This paper summarizes design goals, analysis, and mockup testing of the motor-generator stator.

- have minimal idling losses (< 1,000 W)

This paper deals with the analysis, design, prototype construction, and testing of the FESS motor/generator stator designed for the Combat Hybrid Power System (CHPS) program. Companion papers [1,2] discuss the composite rotor assembly and the magnetic bearings. The FESS designed for the CHPS program is a composite flywheel integrated with a rotating permanent magnet polyphase motor/generator, and supported by inside-out magnetic bearings in a vacuum enclosure (fig. 1). The basic parameters of the FESS are summarized in Table 1. Numerous simulations were performed to predict the electrical performance of the FESS. Fig. 2 shows the predicted performance of the machine discharging into a fixed resistive load via a rectifier circuit, starting from full speed (20,000 rpm) and discharging down to 15,000 rpm.

The machine is predicted to be highly efficient, and indeed is capable of delivering more than the specified 5 MW over the speed range. Thermally and electromagnetically, the flywheel should be capable of much higher powers for slightly limited energy. Thus, simulations indicate that there is significant headroom in the design of the stator with respect to design electrical performance. The following analytical and test results support these findings.

I. INTRODUCTION

FLYWHEEL energy storage systems (FESS) have strong roles in hybrid electric combat systems, both as very high power density pulsed power supplies (e.g., 5 MW for 0.2 to 2.0 s, and multigigawatt for ~1-ms) and as mobility load levelers (~350 kW, continuous). Preliminary analysis indicates that a well designed FESS that can meet the pulse power requirements of a 14-ton class tactical (scout) vehicle can also perform mobility load leveling efficiently, avoiding the life-limiting cycling issues associated with using batteries for load leveling. This paper covers the design and validation testing for a high voltage, high power motor/generator intended to be one component of a FESS for a scout vehicle.

The design goals for the FESS were structured to allow evaluation of benefits, liabilities, and design limits for multi-megawatt class flywheel system powering both pulse and mobility loads. The FESS should:

- minimize mass and volume
- cool with 90°C cooling oil worst case (70°C nominal)
- perform mobility load leveling into a dc bus at 350 kW continuous
- supply pulsed loads represented by recharge of a 240-500 kJ, 10 kV capacitor bank

II. ANALYSIS

Electromagnetic analysis of the stator core included a 3D finite element code (opera-3D) from Vector Fields Inc. [3] to calculate the flux density distribution, torque capability, demagnetization effects, and fringe effects on stator heating. Calculations were carried out for various configurations of number of poles, magnet geometry and material, back iron material, as well as stator size and material. The model with the stator, shaft, magnets, and one of the three phase windings is shown in Fig. 3. Two magnets were left out for clear view of the geometry. The estimated losses for the selected stator material are calculated to be 250 W at 20,000 rpm.

When current is applied during normal operation, the newly generated fields tend to oppose the magnets and permanent demagnetization may occur, resulting in a loss of

Manuscript received December 21, 1999. The work presented here was funded by SAIC under the DARPA/US Army TARDEC Combat Hybrid Power System program from June 1997 through April 1999 (Subcontract No. 4500002919).

00-5-1542

functionality of the machine. The geometry of the magnets, initial magnetization direction, residual magnetization, and coercive force are chosen carefully so that permanent demagnetization does not occur under fault conditions. In effect, the generated current is equivalent to a short circuit current. An over-current three times as large as the nominal current is necessary to cause permanent demagnetization when operating at 150°C, a scenario that is unlikely in this machine.

In this topology fringe fields at machine ends can be very large, causing significant heating in the stator end surfaces. By changing the magnetization direction of the end magnets from radial to axial, the flux density on the stator end surfaces is reduced to acceptable values. The generated voltage drops by 4%, but the reduction in stator heating is very significant (~70% reduction in heating).

Extensive thermal analysis of the stator was performed. The conductor winding configuration and oil flow pattern in the end-turn area are very complicated, and the end-turns are immersed in the flowing oil. Depending on the end-turn locations, heat loss is removed by conduction, free convection, and forced convection to the oil coolant. Also, heat exchange between the end-turn and active section will occur through axial thermal conduction with the relatively high equivalent thermal conductivity along the litz wire. End-turn cooling cannot be predicted with high fidelity. For simplicity, it was assumed that:

- the end-turn heat loss is entirely removed by the end-turn oil bath
- the heat losses of the winding and the core laminations in the straight section are entirely removed by the oil in the coolant passages embedded in the windings and in the core laminations, by transverse thermal conduction

There are 20 coolant passages (0.1875 in. diameter) in the core laminations and 150 coolant passages (0.085 in. inside diameter) in the straight-section stator winding. A two-dimensional (2D) planar finite element thermal model mesh was used to analyze the steady state and transient thermal behaviors of a stator straight section. The model included cooling passage in the laminated core, FEP Teflon® roll cover, insulated conductor wire bundles in FEP tubes, cooling passages, epoxy potting resin, and the G-11 stator sleeve.

The continuous heat losses at 350 KW machine output in stator winding and laminations are 955 W and 600 W, respectively. The heat generation in the stator winding includes ohmic heat loss and eddy current loss. Most (74%) of the winding is in the 12.5 in. long straight section while 26% is in the end turns; however, 84% of the 955 W winding loss is generated in the straight-section winding area. As a result, the straight-section winding has a higher heat loss density than that of the end-turns.

The coolant chosen for the stator cooling is MIL-L-7808 oil. Thermal analyses were performed under normal (70°C) and worst (90°C) oil inlet temperature conditions. Effective turbulent flow cooling was not feasible because the stator's internal thermal resistance is comparable to the external thermal resistance of the coolant film in the passages. An oil temperature rise of 0.8°C was calculated for a total of 18 gpm

laminar oil flow (12 gpm in the core and 6 gpm in the winding). Coolant pressure drop in the 12.5 in. passages of the straight section was calculated as 1.2 psi. Analysis predicts that the maximum stator temperature, (~17°C higher than the oil temperature) occurs within the winding bundle layer, directly above the FEP roll cover.

For high power operation, the energy loss of a pulse (0.2 s duration) was estimated as 42 kJ. Stator transient thermal analyses with continuous heat loss at 350 kW output and pulse-duty heat load under various oil cooling scenarios based on 90°C and 70°C inlet oil temperatures have been performed. The stator reaches steady state in approximately 1 hr under the constant 350 kW output. The pulse-duty transient analysis was initiated after the thermal steady state was reached. In the analysis, a nine-pulse burst was assumed, followed by multiple three-pulse bursts. Analysis of the case in which oil is allowed to cool for 10 s between bursts is shown in Fig. 4. After the initial nine-pulse burst (which is a 1.8 s event), the winding temperature increases by 36°C (4°C per pulse).

The model predicts that 60 cycles produce a maximum temperature of 218°C with 90°C oil inlet temperature and 10 s cooling between bursts. The maximum temperature drops to 170°C for the case with 70°C oil inlet temperature and 15 s cooling between burst. Since the oil inlet temperature is 70°C most of the time, it appears that 15 s between bursts is consistent with the insulation temperature limit of 150°C to 180°C. Extended testing of all insulation materials in heated oil (15 months at 100°C) indicated no deterioration in insulation properties.

III. STATOR DESIGN

The core is comprised of Carpenter HyMu 80® Alloy (80% nickel) high permeability, low loss laminations, 0.006 in. thick. The stator core supports the winding and provides a mechanical path to ground and a thermal path to the coolant system. The laminations are punched for cooling channels near the OD for axial coolant flow. The stator shaft is magnetic steel; a non-magnetic copper sleeve has been added between the core and the shaft to minimize eddy currents. Sample lamination stacks were procured both with and without a nickel oxide surface treatment to determine the B-H characterization and mechanical capabilities (shear stress, peel stress) of each option prior to purchasing a full stack.

One function of the stator core is to transmit discharge torque to the vacuum housing of the machine. Shear stresses between the winding and the core, and between the core and the stationary shaft, react the discharge torque. Peak discharge torque is 2,348 ft-lb, and the resulting peak shear stress at shaft is 19.1 psi. Because these interfaces are essentially round and smooth, radial pressure must be maintained in this assembly to ensure sufficient frictional force. A nested ring analysis using an in-house linear code (TEMPEST) was performed, assuming conservative coefficients of friction. This analysis showed that ample radial pressure can be developed with a light interference fit (radial pressure <1,000 psi) with factor of safety = 4 against slippage, achieved by warming the core to ~200°F (much lower than the anneal temperature of 1,600°F). Also, this fit

maintains assembly stresses well below the HyMu-80[®] yield stress (33 ksi). Therefore, the stator fabrication is insensitive to measurement and temperature precision.

The stator winding parameters are shown in Table 2. Fig. 5 shows the end view. The filler epoxy (1) inside the 0.25 in. FEP insulation is rated for 140°C heat deflection temperature (HDT) and the outside filler epoxy (2) is rated for 155°C HDT. FEP was chosen for three reasons:

- it is the best insulation for 14 kV, 204°C, high frequency applications
- during construction, it is possible to inject the filler epoxy (1) inside the un-shrunk FEP tubes and fill the voids in the 1,050 strands of #38 wire
- after shrinking a FEP tube, a second unshrunk tube can be placed over the first tube and also shrunk in place. This doubles the voltage standoff capability and is used for the end turns

The stator winding is unique in that it is constructed in three layers per slot instead of the usual two layers. Also, it does not have metallic teeth to physically define the "slot" locations. The fifth and seventh harmonics of the base frequency of 1,667 Hz should be minimized. Winding belt calculations were used to find the best winding layout to reduce these harmonics, as shown in Fig. 11. Note that phase 2 occupies slots 1 through 5 in layer 1, slots 4.5 through 8.5 in layer 2, and slots 2.5 through 6.5 in layer 3. Table 3 shows the differences in belt distribution fractions for the winding as compared to the winding of a regular ac machine.

IV. STATOR MOCKUP

Fig. 6 shows the tooling for placing a phase on the stator surface. A 4 ft length of FEP tube is placed to completely overlap a previously shrunk FEP tube at the connection end (CE) region. By simultaneous application of vacuum and pressure injection, filler epoxy (type 1) is inserted in 4 ft. of cable. A heat gun is then used to shrink the FEP tube starting at the overlap and proceeding to the free end. This process removes any remaining air. Then a non connection end (NCE) double piece of FEP is slid down into position and shrunk around the first tube. Special tooling was constructed to position the windings accurately as they are placed in position and to preserve the needed space for the cables not yet laid down. Temperature control of the process proved to be crucial. A medium temperature (above room temperature) makes the filler epoxy (type 1) flow easily into the cable and displace the air. The heat from the gun should shrink the FEP tube while not heating to the point of initiating the exothermic reaction.

A manufacturing process and temperature control procedure reduced production time to only two days per phase for each layer. Clamps and jigs were installed to put the cables in proper final position. The temperature was set high in order to begin cure of the epoxy inside the cables overnight. The clamps and jigs were removed and used to initiate the next two-day production cycle. Fig. 7 shows the three layers after winding.

V. TESTING THE STATOR MOCKUP

Thermocouples (19 units) were placed in various locations in the armature winding. In addition, the #12 FEP tubes (150 units) were plugged in order to ascertain the relative cooling of the stator end turns, the straight region, and the 20 lamination holes. Data showed that the end turns (which represented a third of the total cable length) were removing two thirds of the total heat.

Using an oil coolant with a 70°C inlet temperature, stator cooling tests were performed under various winding heat loads and oil flow rates. Since the laboratory tests cannot generate eddy current losses in the winding and in the core laminations as the actual machine operation does, in the cooling tests, all the stator losses were put in the winding by introducing current into the winding. Table 4 summarizes the steady state and pulse test results. Test No. 3 most closely matched design winding heat input-- the measured stator winding temperature is 10°C above the oil temperature, while predicted is 17°C. The discrepancy between the analysis prediction and the test result attributes to several factors. First, the heat loss distribution used in the analysis (or generated in the actual machine) was not truly reproduced in the tests. In the actual machine, there is a 600 W eddy current loss in the core lamination, and more heat is generated in the straight-section winding than in the end-turns due to the eddy current effect. However, during the cooling tests, all the losses were uniformly distributed in the entire winding; as a result, more heat loss was in the end-turns than it should be. Second, the test thermocouples were located outside the litz wire conductor bundles enclosed by FEP insulation tubes. The maximum stator winding temperature, predicted to occur at the middle of the conductor bundles directly above the lamination core, cannot be measured by the thermocouples. Thirdly, the winding end-turn cooling effect was not considered in the 2D planar analysis. The cooling test results do indicate the oil bath in the end-turn areas can effectively remove the end-turn winding loss. Also, the end-turn cooling can reduce the straight-section winding temperature through axial winding heat conduction, which is especially pronounced for a stator having a relatively short straight section.

UT-CEM joined with the State University of New York at Buffalo (SUNY) to perform motorette sample testing of the stator insulation scheme. In addition, the fully wound prototype stator was tested at SUNY in August 1999. Table 5 shows that the seven motorette samples did not show onset of partial discharge until well above peak machine voltage. Unfortunately, the test thermocouples (not part of the machine final design) did have partial discharge at a lower voltage than desired. High dv/dt tests indicate that our insulation system will perform above expected dv/dt values.

The stator mockup was tested for static torque generation. Fig. 8 shows the full scale stator mounted on pedestal bearings and with a center 2 in. axial length "rotor" which is composed of 40 permanent magnets. The torque arm is attached to the stator endplate and a force transducer is attached to the far right side to ground. Since this machine is a 10-pole generator, only the torque over a mechanical angle

of 18° required investigation. As the relative positions of the centerlines of the rotor and stator poles were unknown, a series of tests (shown in Fig. 9) at 180 A peak was performed to find the angle of maximum torque. Then the test rig was further tested up to 800 A (rated current is 26 A) as shown in Fig. 10. A 3D FEA model of the test assembly was constructed. Only the straight parts of the conductors (450 in total) were modeled, as the winding end turns do not contribute to the torque. Agreement between this model and test results is within experimental errors (Fig. 10)

VI. CONCLUSIONS

The analyses and testing reported here indicate that there is significant headroom in the design of the CHPS FESS stator with respect to its electromagnetic and thermal performance. While it might be tempting to conclude from these results that the machine could be redesigned for smaller volume and less

mass, other figures of merit (life, rotordynamics, etc) must also be considered in any redesign. From the perspective of a laboratory demonstrator, ample design margin as seen in the stator of this machine is not inappropriate. Final design for production would be impacted by numerous other factors, however, not the least of which would be manufacturing economy.

VII. REFERENCES

- [1] J.H. Beno, M.D. Werst, R.C. Thompson, S.M. Manifold, and J. Zierer, "End-of-Life Design for Composite Rotors," presented at Tenth EML Conference, April 2000
- [2] M.A. Pichot, J.P. Kajs, A. Ouroua, J.H. Beno, and R.J. Hayes, "Active Magnetic Bearings for Energy Storage Systems for Combat Vehicles," presented at Tenth EML Conference, April 2000
- [3] Vector Fields, Inc., 1700 N. Farnsworth Ave., Aurora, IL 60505

3911.0009.1

Fig. 1. 25 MJ, 5 MW CHPS FESS designed for load leveling and pulsed loads in a 14-ton scout vehicle.

TABLE 1. SUMMARY OF THE DESIGN PARAMETERS OF THE CHPS FLYWHEEL ENERGY STORAGE SYSTEM

Parameter	Unit	Value
Overall FESS		
Power	MW	5
Energy stored	MJ	25
Speed	rpm	20,000
Overall length	in.	38
Outside diameter	in.	24
Overall volume	m ³	0.28
Weight	lb	1,431
Stator		
Winding OD	in.	11.7
Winding ID	in.	10.6
Core length	in.	12.5
End turn length	in.	2.5
Overall winding length	in.	17.5
Efficiency (peak power)	—	99.2
Losses (peak power)	kW	130
Losses (350 kW)	kW	2.4
Weight (winding + core)	lb	91

Fig. 2. Simulation of the FESS into a fixed resistive load.

Fig. 3. 3D FEA model of the stator winding (one phase depicted; two rows of permanent magnets not shown for clarity).

Fig. 4. Predicted peak temperature excursions of the stator (90°C oil inlet, 10 s cooling between bursts)

TABLE 2. ARMATURE WINDING

Armature Winding		Strand	
Poles	10	AWG	38
Phases	3	# strands	1,050
Slots	150	Film ins.	ST
Layers	3	Bare diameter	0.004 in.
S/P/phase	5	Ins. diameter	0.0045 in.
Phases		Winding	
Connected	Y	ID	10.6 in.
Neutral?	Yes	OD	11.8 in.
Volts L-N	4,428	Height	0.6 in.
Volts L-L	7,660	Stack length	12.5 in.
Frequency	1,667	Phase length	236 ft
Cable Parameters			
Cable diameter	0.185 in. (without insulation)		
Ground insulation	0.010 fluorinated ethylene propylene (FEP)		
Final cable diameter	0.205 in.(with insulation)		
Packing Percent			
In 0.185 cable	62 (with magnet wire insulation)		
In 0.185 cable	49 (without magnet wire insulation)		
Overall	28 (0.6 in. tk)

Fig. 5. Stator armature winding (end view)

TABLE 3. WINDING BELT RESULTS

Frequency (Hz)	Stator Belt Factor	Regular ac Machine Belt Factor	% Reduction vs. Regular Machine
1,667	0.9134	0.9556	4.5
8,335	0.0332	0.200	83.4
11,669	0.028	-0.149	81.2

Fig. 6. Winding fixture used for constructing the mockup stator

Fig. 7. Completed three-phase stator winding.

TABLE 4. THERMAL TEST RESULTS

Pulse Duty					
Laser event is 126 kJ, $i^2t = 210,000$ and ΔT winding = 21.5°C					
Test	Current (A)	Time (s)	i^2t	DT winding	DT hottest tc
1	70	10	49,000	5	2.5
2	140	1.25	24,500	2.5	1.25
3	659	0.95	411,280	42.0	21.0

Steady State				
2D FEA model predicted temperature rise of 17°C over inlet oil temperature (70 or 90°C) for 18 GPM, 1,555 W (i^2R)				
Test	Watts	GPM	Oil Inlet (°C)	ΔT , °C
1	2,365	10.4	70	13.5
2	1,016	12.1	70	5.4
3	1,599	12.1	70	10.0
4	2,365	12.1	70	12.5
5	2,365	17.3	70	11.0

TABLE 5. INSULATION TESTS

Component	Peak Machine Voltage	Onset of PD	Remarks
Single FEP tube, epoxy	7.7 kV ac + 6.0 kV dc	10 kV ac + 18 kV dc	3 samples in air
Double FEP tubes, epoxy *	7.7 kV ac + 6.0 kV dc	10 kV ac + 23.8 kV dc	3 samples in air
Two cables with single FEP	800.0 V ac	1,800 V ac	In air
Test rig	7.7 kV ac + 6.0 kV dc	*	Filled with oil; test inconclusive

* Premature partial discharge (PD) due to thermocouples

dv/dt tests at SUNY:

A double FEP tube sample with epoxy tested to 167 kV/ μ s

Rated conditions estimated at:

0.5 kV/ μ s for laser discharge

40 kV/ μ s at 350 kW continuous rating

D3911.0013bw

Fig 8. Static torque test arrangement of the mockup stator.

11441bw

Fig 9. Measured static torque of the mockup stator as a function of mechanical angle.

11440bw

Fig 10. Maximum static torque of the mockup stator - measured vs. calculated