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FABRICATION OF A COMPENSATED PULSED ALTERNATOR FOR A RAPID FIRE RAILGUN SYSTEM

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Abstract - This paper presents a detailed description of fabrication of the compensated pulsed alternator (compulsator) for a rapid-fire railgun system. Presented are fabrication techniques and assembly processes developed specifically for a large pulsed power generator, including stator lamination assembly and armature and field winding fabrication techniques. The horizontal shaft, six pole compulsator design incorporates a rotating field and passive compensation. When completed, the compulsator will generate a 2-kV open-circuit voltage and supply 944-kA, 2.45-ms pulses to the 3-m railgun. Since high energy per unit volume ratios are desirable in pulsed power generators, emphasis is put on reducing weight and volume. Consideration for these areas are evident throughout the machine.

INTRODUCTION

The compensated pulsed alternator is a pulsed power supply designed to drive a rapid-fire railgun system. Eighty-g projectiles will be accelerated from 2 to 3 km/s at 60 Hz. This type of energy storage and conversion system represents an attractive alternative to conventional capacitor banks and the homopolar-inductor-switch configuration. The compulsator originally conceived at CEM-UT in 1977, has evolved through several generations of design, fabrication, and testing [1].

This paper focuses on the fabrication of the passively compensated pulsed power supply with emphasis on critical elements of the machine: the laminated stator, air gap armature winding, rotating field supply and the compensating shield. A sectional view of the compulsator is shown in Fig. 1 with the machine parameters listed in Table 1.

Table 1. Machine parameters

Mechanical	
Rotor radius	0.40 m
Outer radius of machine	0.60 m
Length of machine	1.52 m
Total mass	11,000 kg
Polar moment of inertia	318 J-s^2
Rotor speed	4700 rpm
Inertial energy	38 MJ
Bearings	Hydrostatic

Electrical	
Peak open circuit voltage	2 kV
Peak current in railgun	944 kA
Number of poles	6
Pulse width	2.54 ms
Field current	1000 A
Field voltage	500 V

The 1-MA peak current pulse suggests the substantial stresses induced throughout the structure. The armature winding transfers a 4.07•10^6 N•m (3,000,000 ft/lb) discharge torque to the stator laminations through a fiberglass reinforced epoxy bond. Epoxy bonds are similarly relied on in the laminated stator laminations and in the field winding encapsulation. An epoxy testing program was developed, first to further improve the mechanical properties of the currently used vacuum impregnation, epoxy-resin system, and secondly to develop surface preparations to optimize adhesion.

STATOR FABRICATION

Lamination/Stator Tube Assembly

Traditionally, large generator lamination assemblies are bolted stacks, thus requiring additional lamination area for clamping. Due to weight and volume considerations, the compulsator lamination assembly was done by epoxying the laminations together and bonding the entire stack into the stator tube. The laminations are M-19 steel with a C-5 chromate conversion coating. The laminations were degreased and then stacked into 2 in. thick packs with a thin epoxy layer applied to each lamination. The 5.08 cm (2 in.) stack was then clamped between clamping plates to obtain a 689 kPa (100 psi) interface pressure and then cured.

The next step was to bond the entire 101.6 cm (40 in.) stack together as well as bond the stack inside the stator tube. A temporary steel inner tube and endplates were fabricated to obtain a vacuum in the volume between the two concentric cylinders (Fig. 2). The 5.08 cm (2 in.) stacks were lowered one-by-one into the tube assembly with epoxy and fiberglass reinforcement added with each stack.

Finally, a top plate was mounted and the entire lamination stack clamped. A vacuum was then applied to remove trapped air. The vacuum was maintained throughout the low temperature phase of the cure cycle while the epoxy was at its lowest viscosity. The inner tube and endplates were then machined out.

Armature Winding

The compulsator air gap armature winding is wound in the bore of the stator laminations. After etching the laminations, an elaborate surface preparation process (developed during the epoxy testing program) was done on the lamination bore and a cleanroom atmosphere was maintained throughout the winding operation.

The armature winding is composed of six separate lap windings of 7 x 7 x 16 #24 AWG copper Litz wire. Each winding makes up one-half of two adjacent poles (Fig. 3). A lap winding requires the least amount of space for the endturns. Only 31% of the total length of armature wire, and 23% of the stator length is occupied by the endturns. A summary of the armature winding insulation system is shown in Table 2.

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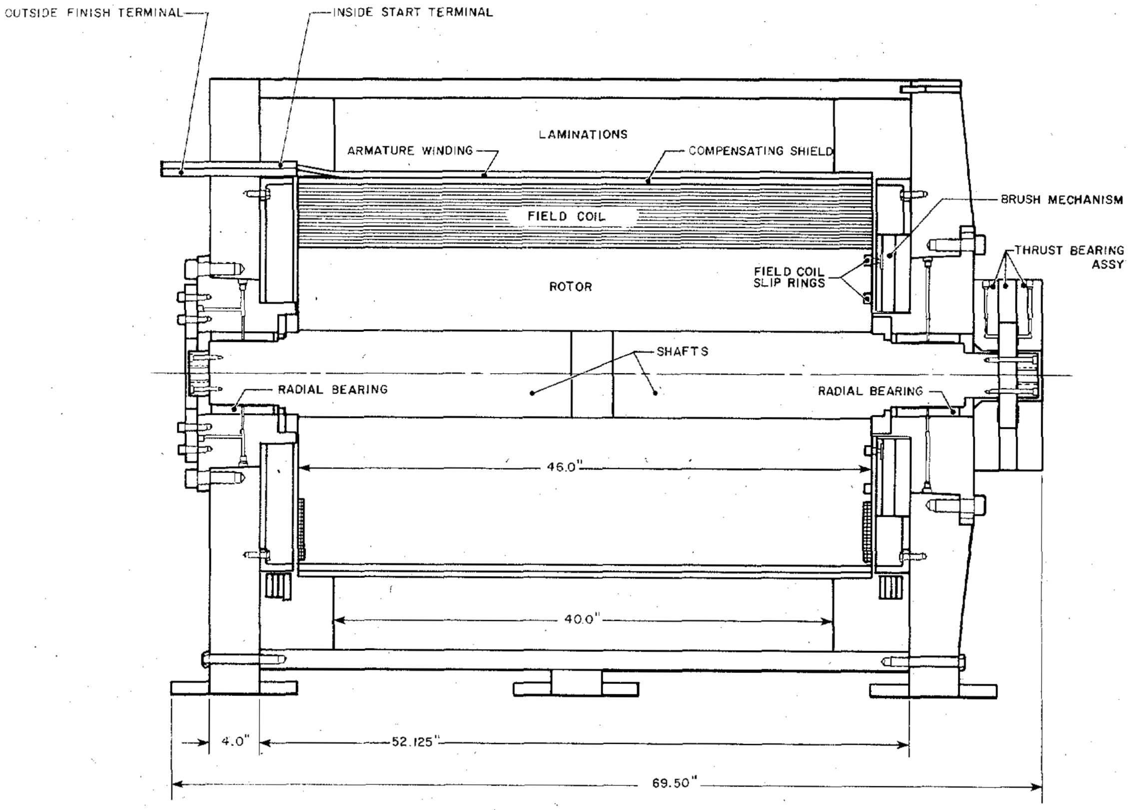

Fig. 1. Sectional view of compulsator.

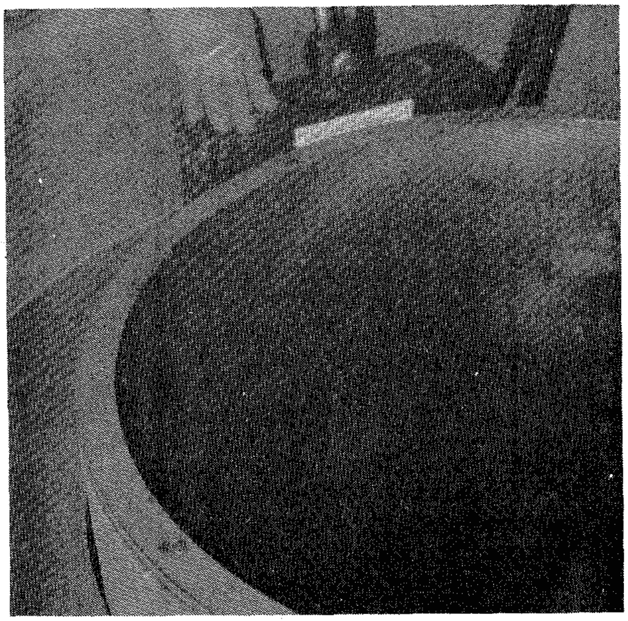

Fig. 2. Assembly of lamination stacks into stator tube.

Table 2. Armature Winding Insulation Summary.

Winding Location	Insulation Thickness	Dielectric* Strength	Insulation** Stress
Ground Plane	50 mils	400 VPM	40 VPM
Turn-to-turn	28 mils	400 VPM	18 VPM
Endturns	56 mils	400 VPM	9 VPM

* Based on dielectric tests - Epoxy testing program
** Determined by dividing maximum voltage potential at location by insulation thickness.

In addition to the above insulation, each 24 AWG wire is coated with heavy armored polythermaleze 2000.

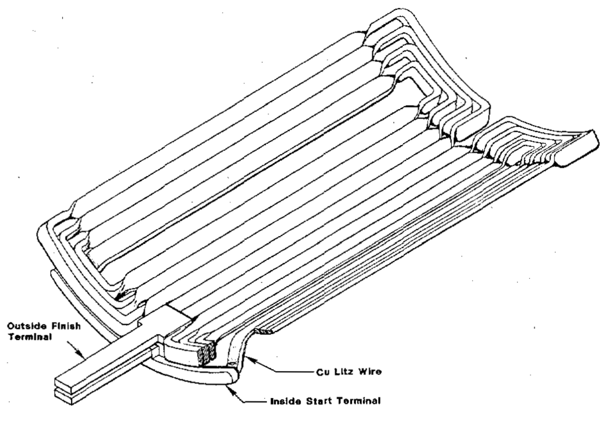

Fig. 3. 3-D view of two adjacent armature windings.

The armature endturns are anchored in G-10 rings at each end of the lamination stack. The G-10 rings consist of several 2.54 cm and 3.18 cm (1.0 and 1.25 in.) rings laminated together to form two sub-stacks. Two sub-stacks were required to simplify the task of milling the slots on the ID of the rings and upon completion, they are epoxied and doweled together. The goal of the endturn slot design was to mill out as little G-10 as possible to maintain the structural rigidity of the surrounding G-10 and eliminate voltage tracking paths. Extensive CNC mill work was required to achieve the design and yet much of the finer detail was done by hand because of the inaccessible locations.

The laminated 14.0 cm (5.5 in.) thick G-10 rings are inserted into each end of the stator. The rings are centered and aligned end-to-end. Each of the six axial G-10 winding spacers are bolted at each end of the stator to a G-10 ring. These laminated G-10 spacers are preformed on a mandrel so the radius matches the armature windings. Figure 4 shows the stator during the armature winding process.

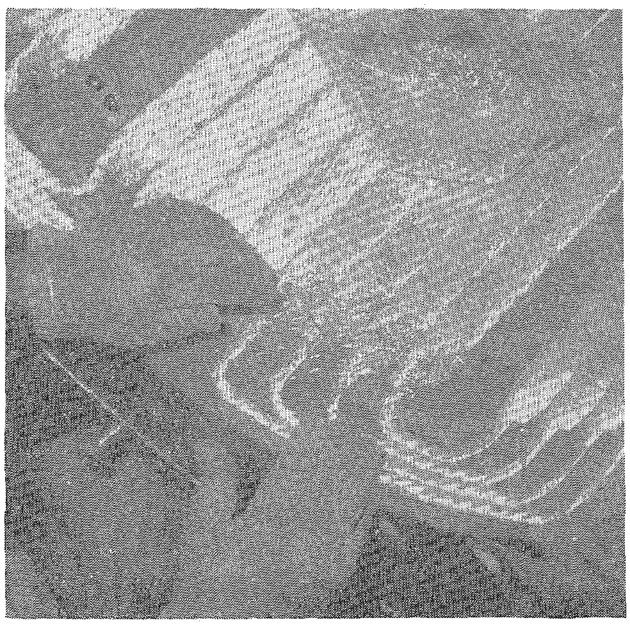

Fig. 4. Armature winding in progress.

Winding proceeds by bolting the crimped lugs of two lengths of Litz wire to their respective "inside start" terminal slots. The "inside start" terminal is wrapped with fiberglass tape and inserted into its slot in the endturn rings. Sixty degree segments of 1.27 cm (0.5 in.) G-10 plate is used to clamp the endturns axially. Adjacent windings are wound together since the "outside finish" connections are crimped and bolted simultaneously. After each pair of windings are completed, a cylindrical 60° mandrel is placed over each winding and clamped to the stator. At this point, the stator is rotated 120° to the next pair of windings.

The purpose of the armature mandrel is to compress the winding to ensure that the bore finishes at the proper radial dimension and is centered in the lamination bore. The mandrel must also provide a vacuum seal for the epoxy vacuum impregnation of the windings and be removable. Ends of the stator assembly are sealed by aluminum endplates which have provisions to seal the three pair of extending terminals.

ROTOR FABRICATION

The compulsator entails a rotating 500-kW D.C. field coil, wound onto a solid salient pole rotor. Six 12.7 cm (5 in.) deep, 2.5 cm (1 in.) wide slots were milled into the rotor to contain the coil. The rotor is shown in Fig. 5 and weighs approximately 44.5 kN (10,000 lb). Rotor material is 4340 steel, hardened to HRC 35. This coil is unique in that it is wound on a solid salient pole rotor rather than a segmented rotor, making the winding process more difficult because the entire rotor must be handled. High stresses in the rotor during operation eliminated the possibility of segmentation.

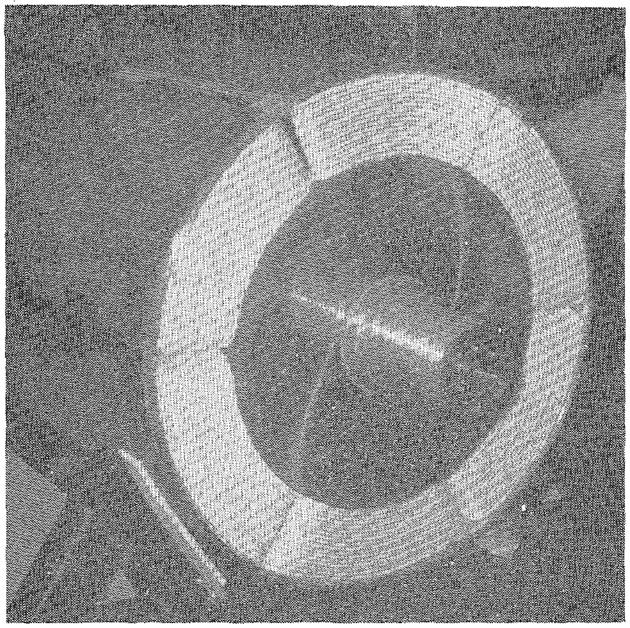

Fig. 5. Field winding in progress.

The compulsator field coil consists of a six pole series lap winding with 68 turns per pole. Each pole incorporates a 4 x 17 conductor cross section of solid copper wire 0.582 cm x 0.582 cm square (0.229 in. x 0.229 in. square). As in the armature, the field winding also uses a lap wound configuration to reduce endturn area. The conductor is insulated with a coating of a modified polyester base with an overcoat of polyamide-imide. In addition, the wire is wrapped with a "half-lap wrap" of 0.013 cm (0.005 in.) dry fiberglass tape. After the coil is wound onto the rotor, it is vacuum impregnated with epoxy using the shield and temporary aluminum endplates as a vacuum mold. The development of the field winding technique began with the winding of the ARFC rotor which consisted of a four pole series winding and a 4 x 4 conductor cross section. [2]

An explanation of the winding procedure is as follows: Six separate windings, connected in series make up the six pole field. Series connection of the six poles is desirable to reduce the variation in excitation flux per pole, and therefore the magnitude of circulating currents in the armature winding. Each of the six windings consist of 34 turns of the copper conductor positioned in a 2 x 17 matrix. The inner 17 turns are wound onto the rotor first, beginning at the base of the end slot and wound counterclockwise, radially outward. Likewise, the outer 17 turns begin at the base of the end slot, but are wound clockwise. The ends of the inner and outer winding are joined at the rotor surface, thus the proper current flow along each pole is achieved.

The six windings are connected in series through a circumferential trough at the base of the end slot. Brush rings are mounted flush with the end of the rotor and brazed to their corresponding field coil terminal. Since the series winding propogates in circumferential manner around the rotor, a conductor loop opposing the winding loop was added to compensate the resulting field.

Due to the symmetry of this winding, only 14 brazed joints are required. Six of these joints, joining the inner and outer conductors at the rotor surface, must be done in place with insulation adjacent to the joint. It is for this reason that a resistance brazing technique was modified to fit the needs of the field coil conductors. The original unit uses an AC transformer and plier-like grips with carbon contacts. An arc welder replaced the AC transformer and heavier welding cables enabled the use of higher currents and therefore a quicker braze with no flame. Siltemp Thermal Barrier is placed over the dry fiberglass tape adjacent to the brazed joint to protect the tape from the heat. Using this equipment, excellent silver brazed joints were made within 10 seconds using 430 A.

Shield Assembly

The entire concept of passive compensation for the compulsator relies on the rotating conductive shield. A 7050 aluminum alloy ring forging was chosen as the material. The aluminum shield has to withstand the discharge torque of the generator as well as the rotational stresses. The assembly of the shield was done by a thermal shrink fit. To prevent contamination of the surface preparation in the field coil slots, the rotor remained at room temperature while the shield was heated.

Prior to the shrink, precise measurements were made of the shield's inner diameter to ensure that runout of the bore was within the tolerance necessary for the thermal shrink. The maximum deviation from a round bore was 0.23 mm (0.009 in.). This deviation was in the direction to decrease the bore from the nominal dimension. Therefore, the amount of interface is slightly greater than the nominal amount in these areas. A summary of the shrink fit parameters is as follows:

Nominal Radial Interference	0.69 mm (0.027 in.)
Delta T	149°C (300°F)
Radial Assembly Clearance	0.81 mm (0.032 in.)

The rotor surface was coated with epoxy prior to the shrink fit. The epoxy acts as a lubricant during assembly, and once cured, increases the coefficient of friction between the shield and rotor. Surface preparation of the shield bore involved grit blasting with aluminum oxide and a thorough rinsing with trichloroethylene.

The shrink fit process took approximately 2 min. beginning with the opening of the oven doors. The crane used for raising and lowering the shield had a vertical lift/lower rate of 1 ft/s. Figure 6 shows the shrink fit in progress. Once the shield was in place, the rotor/shield assembly was rolled into the oven to cure the epoxy at the interface. The effect of heating the shield to 191°C (375°F) caused some decrease of the material properties. It is estimated that the original tensile/yield strength ratio of 70/60 k psi (7050-T74 alloy) was reduced by 10 to 15 k psi. These reduced strength values are well within design requirements.

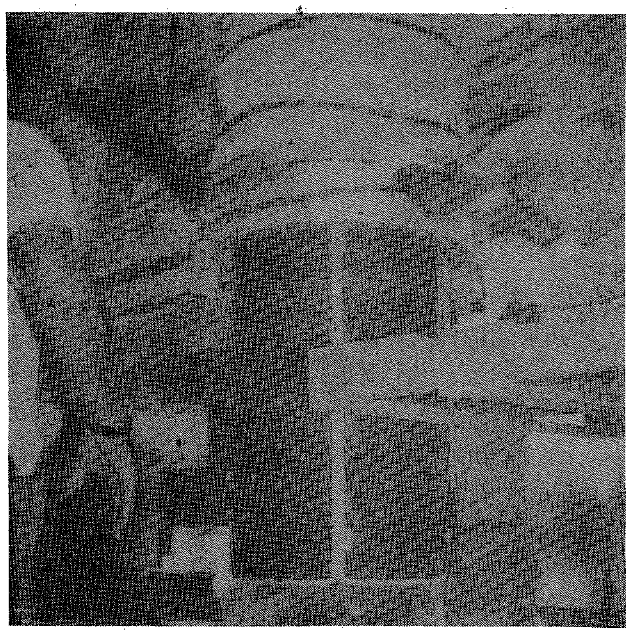

Fig. 6. Shrink fit of aluminum shield in progress.

Vacuum Impregnation of Rotor

With the shield assembly complete, the V.I. of the field coil was the next step. Aluminum endplates had been fabricated to seal the ends of the rotor. O-ring seals against the shield and rotor face enabled the rotor to be pulled down to 20 microns of Hg. Although the vacuum impregnation process is performed at 2 T or greater, a high-vacuum quality chamber is necessary for a void-free encapsulation.

Once the initial vacuum testing was completed, the endplates were removed so that all voids in the field coil could be filled with fiberglass cloth and a mold release could be applied to the endplates. The V.I. process took place with the rotor in a near vertical position inside the CEM oven as shown in Fig. 7.

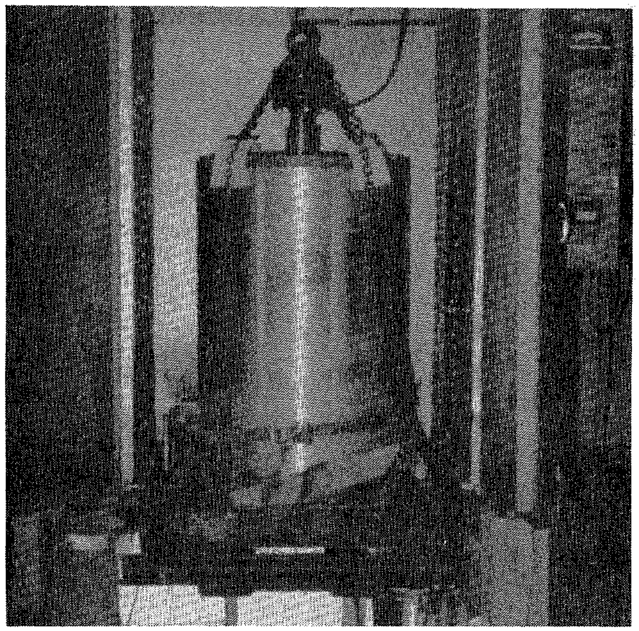

Fig. 7. Rotor in position for V.I.

Approximately 3 gal of epoxy was required to encapsulate the field coil winding. Upon completion of the epoxy cure cycle and removal of the rotor endplates, the rotor was then ready for final machining.

CONCLUSION

Fabrication of the compulsator is 90% complete. Final assembly and initial testing is expected to begin before the publication of this paper. This paper has presented a few of the fabrication tasks required to assemble a rotating machine of this caliber. The development of fabrication techniques for pulsed power generators is an ongoing effort of CEM-UT engineers to provide the EML community with state-of-the-art power supplies.

ACKNOWLEDGMENTS

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