MANUFACTURING AND TESTING OF AN AIR-CORE COMPULSATOR DRIVEN 0.60 CALIBER RAILGUN SYSTEM

Prepared by

J. R. Kitzmiller, R. W. Faidley, R. L. Fuller, R. N. Headifen, and R. F. Thelen

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Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
Bldg. 133, EME 1.100
Austin, TX 78758-4497
(512) 471-4496

Manufacturing and Testing of an Air-Core Compulsator Driven 0.60 Caliber Railgun System

J.R. Kitzmiller, R.W. Faidley, R.L. Fuller, R.N. Headifen, R.F. Thelen

Center for Electromechanics
The University of Texas at Austin
Balcones Research Center, Mail Code 77000
Austin, TX 78712

Abstract—The Center for Electromechanics at the The University of Texas at Austin (CEM-UT) has completed final assembly and is currently testing a laboratory based, small caliber, electromagnetic launcher and compensated pulsed alternator power supply. The objective of the program is to develop a compact, lightweight test bed capable of accelerating a salvo of three, 32-g masses to 2 km/s at a rate of 10 Hz. The 0.60 caliber, augmented railgun is powered by an 850 kg self-excited, air-core compulsator which develops 674 MW peak power delivered through a solid state, silicon controlled rectifier closing switch. The incremental test plan is scheduled to bring the system to full power levels during the summer of 1992. This paper presents critical component fabrication and assembly details of the compulsator and supporting subsystems. Early system commissioning and test data is presented including low speed (8,000 rpm) tests of the compulsator involving external excitation of the field coil.

INTRODUCTION

Following a feasibility study conducted by the Close Combat Armaments Center (CCAC) at the U.S. Army Armament Research, Development, and Engineering Center (ARDEC), an air-core compulsator was chosen as the best power supply for a field portable, small caliber, electromagnetic (EM) launcher. This was in large part due to the superior features of compulsators, including higher useable energy densities than either capacitors, homopolar generators, or batteries [1]. In addition, compulsators offer high voltage and current performance in a single element energy storage device, a smooth pulse profile, and naturally cycled current zeroes which can allow for extremely low muzzle currents and simplified switching requirements. All of these factors combine to make the compulsator extremely attractive for driving EM launchers.

During the first phase of the contract, a computer optimization code was developed to aid in determining the optimal configuration for the compulsator rotor [2]. Using this code, an optimum machine configuration was obtained composed of a self-excited, two pole, air-core compulsator which satisfied all of the design constraints placed on the system.

Fig. 1 shows the small caliber compulsator (SCC) system installed at its test site at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). Final assembly of the small caliber compulsator was completed in October 1991 and testing is currently underway. An incremental test plan should bring the system to full energy during the summer of 1992. Related papers during the project have dealt with system analysis and design [2][3]. Additionally, other papers concentrated on the design and testing of the 1.6 m long, laminated and augmented launcher, as well as the 400 lbf preload pneumatic autoloader [3][4][5]. This paper focuses on some of the more critical and challenging aspects of compulsator system fabrication and assembly. Additionally, test data is presented from preliminary low speed (8,000 rpm) commissioning runs, including armature voltage generation created by exciting the field coil using an external power supply.

- Ⓐ compulsator Ⓓ skid
- Ⓑ SCR switch Ⓔ launcher
- Ⓒ autoloader Ⓕ power train

SYSTEM DESIGN OVERVIEW

The SCC has been developed as a laboratory based EM gun system. Table 1 presents the compulsator's general specifications and a layout of the compulsator is shown in Fig. 2. Comprising the SCC system are five major components including (highlighted items below are elaborated on in this paper):

- (1) Two pole 9 MJ air-core compulsator
 - (a) **Composite flywheel**
 - (b) Ceramic shaft
 - (c) Stator/field coil
 - (d) Ceramic bearings, dampers, and seals
 - (e) Self Excitation System
 - (f) Main silicon controlled rectifier (SCR) switch
- (2) Auxiliaries
- (3) Augmented EM launcher
- (4) Autoloader
- (5) **Firing and fault controller, instrumentation and controls**

As previously stated, system optimization settled on a two pole air-core rotor configuration. In this configuration, the rotor would contain dual rotating armatures and the field coil (FC) would be self-excited. Ultimately, this design lead to the incorporation of several state of the art features including: multilayer composite rotor, silicon nitride ceramic shaft, and hybrid silicon nitride bearing designs. In the following sections, critical component fabrication is described.

ROTOR FABRICATION

Composite Sublayer Assembly

The rotor is a built-up composite structure composed of 15 individual layers with wall thicknesses varying from 0.25 to 0.5 in. Of these 15 layers, two are armature layers, two are

TABLE I
COMPULSATOR GENERAL SPECIFICATIONS

Description	Value
Rotational speed	25,115 rpm
Tip speed	502 m/s (98,820 fpm)
Rotor energy	9.01 MJ
Compulsator energy density	10.5 kJ/kg
Compulsator peak power	664 MW
Pulse width	1.87 m/s
Primary peak voltage	2,600 V
Primary peak current	386 kA
Secondary peak voltage	4,510 V
Secondary peak current	5.0 kA

made from hand wound fiberglass cloth, and two have a high percentage of axial (0°) fibers. The remaining nine hoop wound rings are assembled with appreciable interference to maintain the rotor in radial compression throughout operation. Except for the outer UHMS graphite banding, the rotor was preloaded together using tapered interference fits.

For assembly, each ring was instrumented with strain gauges to verify targeted assembly stresses. Assembly of each ring on to the rotor required the design and manufacture of three steel tooling rings. These rings located the position of the ring being installed and prevented bending stresses from developing as the composite ring was being expanded out over the rotor body

The outer banding was assembled using a procedure recently patented at CEM-UT, named the 'pressurized cure' method. The ring to be assembled onto the rotor is manufactured with an inner diameter a few mils larger than the rotor body, so that when the ring is installed there is a small annulus between the ring and rotor. Specially tooled end plates with end face O-ring seals are then clamped on the ends. One O-ring seal against the ends of the ring and the

Fig. 2. SCC layout

other against the end of the rotor near the outer rim. Epoxy is then pumped into the annulus until the desired assembly pressure is reached. The assembly is held at this pressure until the epoxy is fully cured. The advantage of using this method is that the pressure is hydrostatic, hence it will be constant throughout the annulus. There are no bending or axial stresses developed as the ring is stressed, as occurs with a tapered press fit. A side effect of this method is the resulting thin (approximately equal to the desired amount of interference) layer of cured neat resin in the rotor.

During installation, the banding layer had three strain gages attached to it at equal intervals along its length. The target strain for the end gages were 1987 and 2036 microstrains. Due to the stack up of the previous layers, the rotor has a slight difference in radial stiffness between the thrust end and the nonthrust end. The resulting strains were 1756, 1853 and 2032 microstrains. A critical aspect of the pressurized cure procedure is that there is no centering forces to keep the outer ring concentric to the inner rotor. With the banding, this was achieved with a centering lip in the end plates used for pressurizing. After the epoxy had cured, the banding runout was checked at approximately 0.007 in. It is not desirable to grind the banding outer surface because of resulting cut fiber ends which could possibly unravel during operation. The outer surface of the ring had a thin film of epoxy over it as a result of its manufacture which was lightly sanded to produce a smooth finish.

Rotor Armature Layer Fabrication

A novel approach in applying the rotor armature layers was developed specifically for use in the composite rotor design. The problem was in forming and holding the armature windings onto the rotor for epoxy vacuum pressure impregnation (VPI). The method developed to hold the wire in position was to sew the armature windings down to the rotor. Figs. 3 and 4 show the excitation and main armatures following this procedure.

Fig. 3. Excitation armature on rotor

Fig. 4. Main armature on rotor

To install the wire in position, dry fiberglass cloth was first wound over the surface of the flywheel. The desired winding pattern was then marked on top of the cloth. The wire was then formed into shape turn by turn and hand sewn with fiberglass thread down to the dry cloth. Additional fiberglass cloth was serpentine over and under the nonactive end turns as they were laid down to provide further axial strength to the layer. After both armature poles had been sewn in position, all the remaining void regions were packed with dry cloth and sewn down. Following this, the layer was wrapped tightly with several layers of dry fiberglass sheet. A custom made fiberglass cloth ring was then assembled over the layer to act as a mandrel for the VPI.

A difficult procedure in the fabrication of the armature layers was in making the joint transitions from the aluminum litz wire bundles to the AL60 copper shaft output conductors. The problem was compounded by projected eddy current heating of the joints which had to be made on the end face of the flywheel due to volume required for the joints. The armature wires transition into 28 individual insulated shaft conductors. To reduce the size of the joint for eddy current heating, each conductor was spilt into two connections at the litz wire junctions located on the rotor face. Connections were then individually insulated with glass cloth and the entire region woven with additional insulation as shown in Fig. 5. Copper shaft conductors were insulated using heat shrinkable Teflon™ tubing. Since epoxy will not bond to the Teflon™, a thin sleeve of fiberglass braided tubing was slipped over the length of the conductors. This braiding wicks epoxy and binds the Teflon™ coated conductors together.

Rotor Connection End Plate Design/Fabrication

A critical element of the rotor is the end plate which is located on the connection end of the rotor. This multilayered composite plate is tasked with containment and support of the rotor end face connections. To accomplish this, it must also match spin induced growth with the rotor. A schematic

Fig. 5. Rotor connection end face

of the resulting design is shown in Fig. 6. The end cap is a multilayered composite disk which, like the flywheel, is preloaded together using interference fits. The cap is bonded to the face of the rotor and preloaded under the flywheel banding.

Rotor Balancing

Prior to assembling the rotor, critical individual components were prebalanced. These titanium components included the commutation extension shaft (CES), journal for the outer CES bearing, thrust end seal runner, and drive coupling.

The rotor was installed in a set of ABEC class 7 steel bearings to simulate actual bearing conditions during operation and then balanced in two stages. The first stage determined the level of unbalance. Results were a 15-gm unbalance at the connection end (CE) and 10 gm at the nonconnection end (NCE) of the rotor. Due to the low

density of the composite material, it was not possible to correct the unbalance by removing mass. Mass addition was investigated by first using a nonmetallic ceramic. Zirconia ceramic was the most dense ceramic that was readily available having a density of $5,500 \text{ kg/m}^3$. Analysis showed that using this material would have required removing too much of the balance ring and compromised its strength. A higher density material was therefore needed, such as tungsten. Limitations on eddy current heating of these balance weights determined their geometry, leading to a pin diameter as 0.093 in.

On the NCE, pins were made 0.45 in. long. These pins had an effective mass (mass of pin less mass of material removed from hole), of 0.86 gm. Thirteen of these pins were set into the balance ring at 4° (approximately 0.5 in.) spacings. On the NTE, due to the risk of hitting a wire, 0.281 long pins were made. With the exception of two locations, these pins could be placed anywhere in the end plate without interfering with the connectors. These pins had an effective mass of 0.589 gm. This required 29 pins. The pins are located at two radii and spaced 3° apart. Following this procedure, the rotor was returned to the balance machine and trimmed to ISO 1940 G2.5 tolerances on the machine using additional tungsten pins. Fig. 7 shows the completed rotor following balance procedures.

STATOR

The most challenging aspect of stator manufacturing was the distributed field coil. The field coil is a three-dimensional structure made in two halves, with each half made up of seven layers. Within each half there are 350 turns in series. Each electrical grade 1100 H14 aluminum layer was constructed from three solid pieces including two end plates and a rolled and welded cylinder. The spiral pattern in each layer was manufactured by using a waterjet cutter at CEM-UT. After cutting all the end plates and cylinders, the end plates were welded onto respective cylinders and x-ray inspected for flaws.

Fig. 6. SCC connection end plate design

Fig. 7. Completed SCC rotor

Electrical insulation of the turns and layers was accomplished in stages. First, the 350 turns on the two coil halves were deburred to remove all sharp corners. The halves were then acid etched and electrostatically coated with an epoxy-base insulating coating called Limitrac™. Finally, a single piece epoxy compatible fiberglass braid was installed over the coil conductors.

After insulating, the coil halves were stacked and layer to layer joints made by overlapping welds performed in a clean room environment. A skin mold was designed and manufactured for use in separating the coil halves during stacking. The skin mold also served to insulate the coil from the compensating shield. Once stacked, the coil halves were installed over a dummy mandrel which was machined to the same dimensions as the compensating shield casing, then placed inside the external potting mold and sealed.

After assembling the vacuum mold, the VPI was performed. Fig. 8 shows the field coil after removal from the mold. Some minor postmachining was required on the outer diameter. The field coil was then split in half at the joint of the inner mold and the inner potting mandrel removed.

FIRING AND FAULT CONTROL MONITOR

Operation of the SCC requires a high speed time-controlled sequence of events, accomplished through the firing and fault control monitor (FFCM). Field initiator capacitors are discharged into the field winding while the field gate control begins gating the rectifier thyristors synchronously with voltage generated. When the desired current level is reached and the rotor phase matches the desired firing angle, the first salvo discharge is fired. Desired time between shots is counted off while the autoloader reloads the launcher. After the elapsed time and check with the autoloader controller, the correct rotor position is awaited and the second salvo shot is fired at its own desired firing angle. An optional third shot proceeds like the second. Meanwhile, the field level is maintained by an on-off control about the desired field level reference. After the last shot is fired, the field gating is disabled and excitation current is allowed to decay to zero. This sequence is executed within 1 s of receiving the "enabled" interlock from the programmable logic controller (PLC) when preconditions of motoring auxiliaries are satisfied.

While the firing sequence is being executed, a fault control monitor detects and handles any electrical faults involving the launcher or field charging circuits. At full speed, the compulsator stores more energy than can be safely converted to heat in an armature short-circuit. The main armature current is monitored three ways to detect a possible fault: 1) excessive positive polarity current, greater than 440 kA, 2) excessive negative polarity current, greater than 70 kA, and 3) greater number of current pulses detected than the planned number of shots. Should any of these occur, the fault controller actuates logic to fire the gun circuit protective opening switch and shut down the field excitation. In the

Fig. 8. Field coil following VPI

field excitation circuit, excessive ac or dc current indicates a fault and the field excitation protective switch is activated.

The finished FFCM is pictured in Fig. 9. It is constructed of three subassemblies: 1) an operator interface controller, 2) a cycle-portion controller, and 3) a fault capture and output control board. The operator interface controller is a single board microcontroller with canned program to secure the run set up information by way of the front panel. The cycle-portion controller uses a self-adjusting clock to measure the period of each compulsator voltage cycle and a look-up table written with the firing angle of each shot represented. Finally, a digital comparison of the current cycle position with the firing angle reference number is made to set the control output. Fault capture and output control board has the signal conditioning, comparators, and combinational logic to detect and latch up any fault conditions. Combinational logic allows the firing command to reach an output port when all preconditions are correct and no faults are detected. This board also controls the output for the bridge thyristor drive circuit.

Fig. 9. Firing and fault control monitor

COMPULSATOR LOW SPEED TEST RESULTS

Prior to commissioning test runs, the armature windings and field coil impedances were measured. In all windings, electrical resistance was measured using a micro-ohm meter. Armature inductance was measured by analyzing capacitive discharges through the windings while the field coil inductance was measured directly by using an LCR video bridge. The measured and predicted values are presented in Table II.

TABLE II
FIELD COIL AND ROTOR ARMATURE IMPEDANCE VALUES

Armature/Field Coil	Inductance (Measured/Predicted)	Resistance (Measured/Predicted)
Excitation	22.15/26.5 mH	10.32/11.0 mΩ
Main Discharge	02.7/2.42 μH	966.00/875 μΩ
Field Coil	34.03/30.7 mH	232.00/190 mΩ

Due to current limits on the field initiator circuit, the SCC cannot self-excite until reaching 15,000 rpm. Because of this and the generator's convenient location at the iron core compulsator test site, it was decided to use the ICC resident field supply to excite the SCC for early testing purposes. The 1,500 dc supply provides for approximately 33% of full excitation of the SCC field coil and allowed for evaluation of the operation of several SCC system components, including rectifier operation, firing and fault control monitor operation, and general instrumentation and control. At the writing of this paper, the launcher was being prepared for railgun tests starting at 10,000 rpm.

Fig. 10 is a plot of rotor speed, ICC field current, and SCC armature voltages during an 8,000-rpm test. Scaling the results provided by these initial tests indicate that the compulsator will achieve the voltage levels required to drive

Fig. 10. Field current and armature voltages @ 8,000 rpm/33% excitation

the augmented launcher to contractual goals.

CONCLUSIONS

The SCC is currently operational and on schedule to full-energy performance by the end of March 1992. With its composite rotor, self-excited air-core design, it represents a significant leap forward in the current state of the art in generator technology. Many new manufacturing and assembly procedures were developed and executed along the way which will aid greatly in producing future generations of these air core machines, as well as high energy density composite flywheel technologies in general.

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