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SUPPLY FOR A 9 MJ RAILGUN DEMONSTRATOR**

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Abstract: Fabrication efforts have begun on a field-based compulsator for firing 9 MJ projectiles from a railgun launcher. The machine is designed to store 200 MJ kinetic energy and fire a salvo of nine rounds in three minutes at velocities between 2.5 and 4.0 km/s. Prime power required to meet this firing schedule is 1,865 kW and will be supplied by a gas turbine engine. It is also possible to fire a burst of two shots in rapid succession, if desired. Operating speed of the machine is 8,250 rpm and it has design ratings of 3.2 MA peak current and 20 GW peak power into a 9 MJ railgun load. A two-pole configuration is used for pulse length considerations and selectively passive compensation is employed to produce a relatively flat pulse and limit peak projectile acceleration to about 980,000 m/s² (100 g's). Other distinguishing features include an air core magnetic circuit, separate rotor armature windings for self-excitation and railgun firing, ambient temperature field coils, and excitation field magnetic energy recovery capability.

The rotor is made of fiber reinforced epoxy composite rings and is supported by high strength metal stub shafts which are shielded from the excitation field by water cooled copper sleeves. Both rotor armature windings are formed from aluminum litz wire to minimize conductor mass and eddy current losses. The stationary compensating winding is supported by a laminated stainless steel stator structure to which the aluminum field coils are attached. Hydrostatic oil film bearings support the rotor and are sealed against the evacuated rotor cavity with segmented carbon ring seals. Separate brush mechanisms are employed to collect excitation and railgun currents. A unique transposition of brush ring conductors in the main discharge circuit is used to ensure uniform current division between brushes. The compulsator mounts are designed to allow the machine to rotate against linear dampers during discharge to minimize peak torque transmission to the skid base.

A detailed description of the machine as designed, and its auxiliary and control systems, is provided in this paper. Fabrication and assembly methods are reviewed and the current status of the project is discussed. In conjunction with this project, a lightweight railgun is being developed and is discussed in a companion paper presented at the 5th EML conference. [1]

Electrical Design and Performance

Compulsators are well suited as power supplies for railguns because a single element stores the required energy, generates the electrical pulse, and preconditions it before delivery to the gun. High system efficiency is achieved because the compulsator recovers the inductive energy in the gun before projectile exit. Burst firing is achievable because sufficient energy can be stored in the rotor for several shots. This allows prime power to be

averaged over several shots, which can reduce system peak power requirements substantially. Other important advantages of compulsators include a naturally occurring current zero at projectile exit, pulse shaping capability, and high energy and power densities relative to other power supply options. For this particular mission, to satisfy weight and size constraints, a two pole, self-excited, air-core machine was selected. To accommodate relatively low projectile acceleration limits (by railgun standards), a selectively passive compensation scheme is incorporated in the design and results in a flat current wave form from the compulsator into a railgun load (fig. 1). A cross section of the machine is shown in figure 2 and a list of important machine parameters are given in table 1.

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Figure 1. Compulsator output pulse shape during a 2.5 km/s, 9 MJ railgun shot

An overall circuit schematic for the compulsator/railgun circuit is shown in figure 3. A small capacitor, used to initiate self-excitation, is charged and the compulsator rotor is brought to full speed. Self-excitation proceeds by lowering the field brushes and discharging the capacitor into the field coil/excitation armature circuit. The resulting ac signal from the excitation armature is rectified and used to build additional field current. About 0.25 s before full field current (42 kA) is reached, the main discharge brushes are lowered in preparation for railgun firing. Switching of the gun circuit is accomplished with ten parallel solid-state devices and the projectile launch occurs in the ensuing 6 ms. Field energy recovery is then begun by properly controlling the rectifier bridge.

System performance projections for various projectile masses and generator speeds are provided in table 2.

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Figure 2. Task C compulsator cross section view

Table 1. Self-excited, air core compulsator characteristics

Rotor Speed	8,250 rpm
Rotor Energy Storage	200 MJ
Peak Excitation Flux Density	2.4 T
Peak Armature Voltage	5.8 kV
Peak Current Rating	3.2 MA
Maximum Discharge Torque	21.3 MN·m
Avg. Armature Shear Stress	7.5 MPa
Excitation Armature Voltage	17 kV
Excitation Current	42 kA
Machine Mass	18,500 kg

Table 2. Compulsator driven gun performance for several 9-MJ projectiles

Projectile Mass (kg)	Muzzle Velocity (km/s)	Peak Gun Current (MA)	Peak Acceleration (kgees)
1.13	4.0	2.8	182
1.47	3.5	2.7	124
2.00	3.0	2.6	89
2.88	2.5	2.8	69

Key Design Issues

Key design issues for the compulsator include the following interrelated areas:

- armature end-turn geometry,
- field coil shielding and end-turn design,
- rotor shaft material selection, and
- rotor dynamics.

The chosen two-pole design subjects the full rotor volume to the excitation flux. This causes extreme eddy-current heating in any solid metal components in the rotor. This heating can be minimized by material selection, reducing the time the excitation field is present, and by internally shielding conductive rotor components. All of these techniques are used to allow the use of a high strength metal shaft for the compulsator rotor. A 17 kV excitation armature winding (separate from the main armature winding) is included in the rotor to decrease field self-excitation time and the field is rapidly quenched by regenerating the field inductive energy back into the rotor. Shaft eddy current heating is minimized by water cooled copper sleeves which shield the stub shafts from the excitation flux. Quick field charging is also enhanced by breaking up conductive paths in the stator structure which would otherwise experience circulating currents opposing field rise. Unfortunately, these stator conductive paths could be useful in shielding rotor armature discharge flux

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Figure 3. Detailed compulsator and railgun electrical schematic

from interacting with the field coil. Without them, the field-coil conductors will experience additional induced currents and electromagnetic (EM) loading from their coupling with the discharge fields.

Another key design issue results from a trade-off between main armature voltage generation, EM discharge loading, and rotor length. From a rotor dynamics viewpoint, a shorter rotor is more rigid and therefore, more likely to operate subcritically. Due to the high armature current and the nine shot burst requirement, the stranded armature conductors are necessarily large (2.5-cm thick x 22.8-cm wide). Accomplishing the end turns for these conductors takes a large fraction of the rotor active length. By placing the field coil end turns outside the armature end turns, generating the required 6-kV voltage can be achieved with a minimum rotor active length. Unfortunately, the required minimum rotor length results in a rotor too flexible to allow operation below the first rotor flexural critical speed. Bearing stiffness and damping are therefore optimized to allow operation approximately 30% above the critical speed so that 9-MJ shots from full speed will not drop the rotor speed into the range of the critical frequency.

Interaction of the radial excitation fields with the armature end turns is another major consequence of locating the field coil end turns outside the rotor end turns. Large axial loads on both the rotor and field coil result from this interaction and must be balanced on each end of the machine to avoid overloading the thrust bearing. A symmetric armature design is required to ensure an axial force balance during discharge.

Rotor Mechanical Design

The compulsator rotor is primarily a fiber reinforced composite structure built from concentric annular rings. Use of composites is required since rotor materials must be both nonmagnetic and nonconductive, but these lightweight materials also allow energy storage at a high specific value. Size of the rotor is dictated by shear stresses at the armature/flywheel interface at discharge, voltage generation, and energy storage requirements. The rotor consists of six primary components including thrust end and connection end stub shafts, a composite intermediate shaft structure, the excitation armature winding, a composite flywheel structure, and the main armature with its banding. All armature conductors are stranded and transposed aluminum litz wires which are vacuum impregnated with a glass cloth reinforced epoxy for structural integrity. Assembly of the rotor is accomplished by starting with the stub shaft and installing additional layers, many of which are interference fit onto the substructure. A section view of the rotor is shown in figure 4.

Shafts

Electrical connections and output conductors for both armature windings are included in the connection end shaft. Transition litz wire conductors are routed between the shaft and the flywheel and make crimp joints to solid copper coaxial output conductors. Excitation and main armature output conductors are concentrically arranged and carry the respective currents to brush slip rings at the outboard end of the connection end shaft. Copper coated aluminum brush rings are used to minimize mass and inertia of the brush rings, which directly affect torsional stresses in the shaft during discharge deceleration. An iron-nickel alloy, Invar™, is used as the structural portion of the shaft for its low coefficient of thermal expansion. As the copper conductors are resistively heated by a multiple-shot burst, the Invar™ prevents excessive shaft thermal growth and minimizes bearing clearance changes over the nine-shot sequence. The thrust-end shaft, attachment to the turbine drive, supports the thrust-bearing runner and is fabricated from a high strength stainless steel alloy.

Both stub shafts are fitted with water cooled magnesium-zirconium-chromium (MZC) copper alloy eddy current shields. Eddy currents generated in the shields oppose the excitation field and exclude it from the shaft components. The shields, however, do experience substantial losses and require active cooling for a multishot firing sequence. A 0.76 l/s flow rate of an ambient temperature water-glycol solution is introduced through a pressurized gallery sealed with carbon ring seals on each end of the rotor. To prevent the heated shields from damaging composite structures in the rotor, a ceramic sleeve is located around each shield to serve as a thermal barrier. The ceramic is placed in a state of compression prior to installation by a graphite-epoxy banding which is thermally interference fit.

Excitation Winding

The armature winding used to provide field coil self-excitation current is located between the rotor shaft and flywheel. It is a two-pole winding that is 90° phase shifted from the main armature winding to avoid EM coupling. Each pole has 12 turns and the two poles are connected in series so that peak voltage generation is increased and field coil charging times are reduced. The aluminum litz wire conductor is composed of two square conductors to allow forming of the end turns in the same plane as the winding. Winding conductors are sized to allow nine consecutive charging cycles without active cooling. Temperature rise per cycle is 15°C in the conductors and 10°C when averaged with the surrounding epoxy used to encapsulate the winding.

Figure 4. Rotor cross section

Flywheel

The rotor flywheel is made up of seven composite rings using both graphite and S-glass reinforcement. These rings provide the bulk of the energy storage and serve to support the main armature winding. Each flywheel ring is installed with interference using a hydraulic assisted press fit method wherein hydraulic pressure is used to expand the ring so that it can be slid onto the assembly. Epoxy is used as the working fluid so that an interfacial bond is established between rings.

Armature and Banding

The primary armature winding is a two pole, six turn per pole configuration with the two poles arranged in parallel so that each conductor carries half of the peak current generated by the machine. End-to-end symmetry in the winding is required to balance axial loads created by the interaction of the end turn currents with the excitation field, and is accomplished by fabricating the winding in two layers wound from opposite ends of the flywheel. The aluminum litz wire experiences a 12°C per shot temperature rise, therefore, no cooling is required for a nine-shot burst. Pole start and finish leads are located on the faces of the flywheel and supported by hoop wound graphite plates through shear stresses in a bonded interface. These leads are joined to the copper litz wire transition conductors at the J2 position located above the flywheel extension region (fig. 4).

Constraining the armature centrifugal loading and keeping it in contact with the flywheel during motoring are functions of the armature banding. A high strength, high modulus graphite fiber composite tube is used for the banding, which is installed with a heavy interference fit after the armature winding has been epoxy impregnated. About 5.17 MPa radial interface pressure between the armature and flywheel is maintained at full speed to enhance the bond shear strength and overcome radially outward EM loading in localized areas within the armature conductors. The graphite banding is axially segmented every 7.6 cm to reduce eddy current losses.

Stator Mechanical Design

Selectively passive compensation of the rotor armature is provided by a stationary compensating winding located on the bore of a laminated stator structure. This structure also serves to support the two pole, solenoidal type field coil and transfer the stator discharge torque to the casing of the machine. Compensating end plates are attached to either end of the laminated structure with 48 stainless steel tie bolts. Main stator end plates house the shaft radial bearings and are attached to the stator casing as well. The thrust bearing housing is mounted off the main end plate on one end of the machine and the brush mechanisms are attached to the end plate on the opposite end. Due to the length of the brush end rotor shaft, an additional radial bearing is located between the main discharge and the field-excitation brushes. The machine is mounted with bearings on two fixed pedestals to allow the stator to rotate approximately 10° against linear dampers during discharge to minimize peak torque transmitted to the skid base.

Design of the compulsator stator is driven by management of EM loading arising from field coil self-loading, compensating winding currents, transient

fields generated by rotor armature conductors, and the interactions between all of these effects. As the rotor rotates during the generation of a pulse, the loading is distributed differently among stator components. When the armature and compensating windings are aligned (minimum inductance position), the armature currents are well compensated by image currents in the compensating winding. Practically all stator discharge loading is absorbed by the compensating winding at this position. At maximum inductance, when the two windings are 90° out of phase, the armature flux produces eddy currents in all other stator conductive structures. To minimize field charging time and losses, shielding of the field coil from the armature discharge flux is not complete. This allows the field coil to couple flux from the discharge current and produces additional field current. The interaction of the armature flux with the current in the field coil also generates additional load on the field coil conductors.

Electromagnetic analysis for the compulsator was performed using the CEM-UT developed, three-dimensional, finite element based transient codes. These codes predict flux distributions due to known currents, eddy currents in surrounding structures, and calculate the forces produced on both conductors and structures.

Laminated Stator Structure

The stator structure must be axially laminated to minimize the formation of eddy currents during operation. Eddy current losses in the stator structure are acceptable with 1.21 mm thick laminates of 301 stainless steel. The sheets are bonded together with a 0.2 mm thick film adhesive and then axially preloaded through the compensating end plates with 48 tie bars. To prevent the tie bars from forming conductive loops, they are insulated from the laminations and the compensating end plates.

Compensating Winding

The compensating winding is located as close to the rotor armature as possible to provide maximum coupling and therefore reduce the minimum inductance of the machine. Bonded onto the bore of the laminated stator structure, this two-pole winding is composed of 26 shorted turns per pole. Each conductor is roughly 2.5 cm square and made of aluminum litz wire. Image currents flow in the compensating winding only when it couples armature discharge flux. No coupling exists when the two windings are 90° out of phase. This can be seen in figure 5 which shows representative current vs. time traces for several of the shorted loops in the winding.

Field Coil

A solenoidal arrangement of the field coil was chosen to provide a more uniform distribution of radial flux over the voltage generating region of the armature. A total of 5.8-MA-turns provide a 2.4 T radial field at the armature conductors. Due to the two-pole geometry, this field appears through the entire machine and represents 40 MJ of inductive energy storage. This energy is recovered back into the rotor after each shot. Resistive energy losses of 6 MJ result in a temperature rise of the room-temperature coil of only 3°C per charging cycle, therefore no cooling is required.

Figure 5. Compensating winding current profiles during a 9 MJ shot

The lightweight aluminum conductors are fabricated by waterjet cutting 1.9 cm thick plates in spiral fashion to form four turns. After bending operations, the plates are stacked and joined to provide 70 turns per coil half. Each coil half is then epoxy impregnated for structural and electrical insulation purposes. Upon installation around the laminated stator structure, the two coil halves are connected electrically in series. Support for the field coil is derived from the laminated stator structure, the stator casing, and the main stator end plate.

Bearings and Seals

Support of the rotor is derived from pressurized hydrostatic oil film radial and thrust bearings. Hydrostatic bearings were selected for their high stiffness and damping characteristics, and because these parameters can be easily adjusted as required during initial testing. Supply pressure to all bearings is 20.6 MPa and total flow rate is 9.15 l/s. Each of the two radial bearings provide a radial stiffness of 7×10^9 N/m and a damping rate of 5.65 N-m/s at the design speed of 8,250 rpm.

Due to the high peripheral speed of the rotor, the pressure in the stator cavity must be reduced to about 5 torr to avoid excessive windage loss. Sealing of the stator cavity against the bearing sump region is accomplished with three segmented carbon ring seals. The galleries created by the three seals are either pressurized with nitrogen gas or actively scavenged. Similar seals are used to seal inlet and exhaust cooling water for the shaft eddy current shields.

Brush Mechanisms

The main brush mechanisms transfer the 6-ms long, 3.2 MA peak current discharge pulse from the shaft brush slip rings to the railgun busbars. Each terminal utilizes 330 brushes which are each pneumatically actuated onto the slip ring with 65 N. Mechanism design is similar to that developed for pulsed homopolar generators, but the short pulse duration creates problems with current distribution along the length of the slip rings. To ensure a uniform current distributor between individual brushes, they are connected to a set of transposed conductors before

making attachment to the brush housings. Although the integral of current squared and time is well below demonstrated levels for this type of brush, the peak current per brush creates higher EM loading on the straps. A robust strap design is used to prevent excessive stresses and deflections from occurring when they are carrying the discharge current.

Field excitation current is carried by 21 brushes per terminal or 1.97 kA per brush, since the current carrying time is much longer than in the main discharge circuit. Normal field charging and regeneration takes about 1.6 s; but in certain shut down modes where the field circuit is used to electrically brake the rotor, these brushes must carry reduced current for 45 s.

Prime Power and Auxiliaries

Prime power for the compulsator will be supplied by a General Electric LM500 turbine through a speed-increasing gearbox and slip clutch arrangement. During discharge of the compulsator, deceleration of the power turbine rotor is softened by the slip clutch, which will be set to slip below the turbine maximum torque specification. Backup auxiliary power will also be available from power take-off points on the drive gearbox. Primary auxiliary power is supplied by a Pratt and Whitney PT6 class gas turbine and reduction gearbox. Compulsator bearing supply and scavenge pumps, LM500 hydraulic start system, water cooling pumps, and other miscellaneous systems will be driven by the PT6 turbine.

A lightweight aluminum skid will serve as a mount for the turbines, auxiliaries, and fuel and lube oil reservoirs. Onboard control of the system will be accomplished by a programmable logic controller located on the auxiliaries skid. This controller will have the capability to fully operate the system, but a remote link for operator override control and data transmission is also provided.

Conclusions

Design of the compulsator for the 9 MJ Range Gun has been delayed significantly by the desire to provide the best demonstration of the technology and several unforeseen technical requirements. Limiting peak projectile acceleration has required use of a new compensation technique. While experiments conducted at CEM-UT and in Culham Labs [2] have shown the concept of selectively passive compensation to be viable, it has had major implications on the EM and mechanical design of the machine. Elimination of all cryogenic requirements was an important step in credibly demonstrating the compulsator for high energy field deployable railguns. While the mass and size of the machine are larger than would be the case with a cryogenically cooled version, the present design is a significant advancement in compact railgun power supply technology. Presently, this machine is under construction and is scheduled for initial testing in late 1990.

References

- [1] J.H. Price, J.L. Bacon, and R.C. Zowarka, Jr., "Lightweight, Large Caliber Railgun Development," to be presented at the 5th EML Conference, April 2-5, 1990, Eglin AFB, Florida.

- [2] C.R. Spikings, "Experimental Verification of Selective Passive compensation," Proceeding of 7th IEEE Pulsed Power Conference, Monterrey, CA, June 1989.

Bibliography

- [1] W.A. Walls, et al., "Design of a Self-Excited, Air-Core Compulsator for a Skid Mounted, Repetitive Fire 9 MJ Railgun System," IEEE Transactions on Magnetics, vol 25, no. 1, January 1989.
- [2] M.L. Spann, S.B. Pratap, W.A. Walls, and J.D. Herbst, "The Conceptual Design of a Lightweight Compulsator-Driven Electromagnetic Accelerator," Digest of Technical Papers, 6th IEEE Pulsed Power Conference, Arlington, VA, 1987, pp 739-742.
- [3] W.F. Weldon, M.D. Driga, and H.H. Woodson, U.S. Patent 4,200,831.
- [4] M.D. Driga, S.B. Pratap, and W.F. Weldon, "Design of Compensated Pulsed Alternators with Current Waveform Flexibility," Digest of Technical Papers, 6th IEEE Pulsed Power Conference, Arlington, VA, 1987, pp 111-114.
- [5] M.L. Spann, S.B. Pratap, W.G. Brinkman, D.E. Perkins, and R.F. Thelen, "A Rapid Fire, Compulsator Driven Railgun System," IEEE Transactions on Magnetics, vol Mag-22, no. 6, November 1986, pp 1753-1756.
- [6] M.D. Werst, D.E. Perkins, S.B. Pratap, M.L. Spann, and R.F. Thelen, "Testing of a Rapid Fire Compensated Pulsed Alternator System," IEEE Transactions on Magnetics, vol 25, no. 1, January 1989, pp 599-604
- [7] W.A. Walls, and S.M. Manifold, "Applications of Lightweight Composite Materials in Pulsed Rotating Electrical Generators," Digest of Technical Papers, 6th IEEE Pulsed Power Conference, Arlington, VA, 1987, pp 103-106.
- [8] M.D. Driga, S.B. Pratap, and W.F. Weldon, "New Trends in Compulsator Design," IEEE Transactions on Magnetics, vol 25, no. 1, January 1989, pp 142-146.
- [9] M.L. Spann, W.L. Bird, W.F. Weldon, and H.H. Woodson, "Detailed Design, Assembly, and Testing of an Active Rotary Flux Compressor," presented at the 3rd IEEE Pulsed Power Conference, Albuquerque, NM, June 1-3, 1981.