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Abstract: The design of a lightweight, compulsator driven 9 MJ electromagnetic (EM) launcher has been completed and is presently in the fabrication phase.[1] Scheduled for initial field testing in early 1989, the system will be capable of firing a salvo of nine rounds in three minutes at muzzle velocities between 2.5 and 4.0 km/s. Prime power for the compulsator is supplied by a 5,000 hp gas turbine engine through a gearbox and clutch arrangement, and auxiliary power is provided by a small 750-hp turbine. Electrical power generation and pulse conditioning for the launcher are performed by the compulsator [2], which features a self-excited, air-core magnetic circuit and selectively passive armature compensation designed to minimize peak projectile acceleration. Peak power from the machine is 27 GW and a total of 30 MJ is extracted from the rotor during each firing of the gun. The heart of the generator is a fiber reinforced epoxy composite rotor which operates at a peripheral velocity of 580 m/s and stores about 250 MJ. Present plans include the construction of two rotors, one uncooled and one with actively cooled armature conductors. The gun is also fitted with an autoloading mechanism and a pre-injector which provides an initial 200 m/s velocity to the projectile entering the main gun. System mass, including gun, compulsator, prime power, and auxiliary systems, is less than 22 tons and will be mounted on a 36 ton concrete slab which simulates the mass of an armored vehicle on which the system will eventually be integrated.

Introduction

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has been contracted to design, fabricate, and test the system described as a part of the Electromagnetic Gun Weapon System Program. The goal of the program is to develop a new armored vehicle utilizing an EM gun. As a preliminary step to eventual system integration into a specially designed armored vehicle, this project focuses on field demonstration of a lightweight, repetitive fire EM gun system which includes the pulsed power supply, prime power, thermal management, and auxiliary systems.

A self-excited, air-core compensated pulsed alternator (compulsator) was chosen as the prime power source for the system for several reasons. Its use of an inertial energy store provides very high energy densities compared with other fast discharging energy storage devices. As projectile energies are scaled upward for future applications, the weight advantage of an inertial energy storage device will be even more pronounced. Unique advantages of the compulsator include single element energy storage and power conditioning, naturally occurring current zeros to minimize muzzle flash and eliminate switching requirements, and an opportunity to shape the current pulse [3,4] to more efficiently drive an EM launcher. The compulsator is also capable of very high firing frequencies since operating frequencies are above 100 Hz.

The CEM-UT rapid fire 9 MJ railgun demonstrator is shown in figure 1. The compulsator and prime power turbine are arranged in colinear fashion through a speed increasing gearbox and slip clutch coupling. A small auxiliary power turbine is located beside the prime power device and drives various support systems required by the demonstrator. As shown, the EM gun is mounted above the compulsator and is capable of muzzle elevation. The turbine skid is detachable from the compulsator mount pad for transportation purposes, and measures 2.5 m wide by 2.7 m long. System controls are located along one side of the turbine skid.

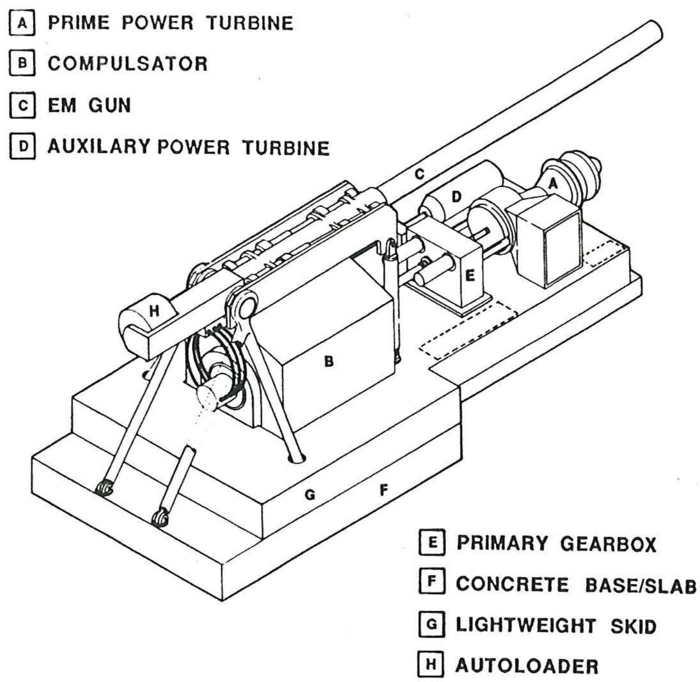


Figure 1. Repetitive fire, compulsator driven 9 MJ railgun field demonstrator (skid isometric)

During actual firing of the gun, the clutch slips at a specified torque level and isolates the turbine and gearbox from the rapid deceleration of the compulsator rotor. Also during discharge of the compulsator, the stator of the machine is allowed to rotate approximately 10° against a set of dampers. This reduces the peak load transmitted to the skid base, thereby minimizing the mount structure required to sustain these forces. Similarly, the EM gun is mounted on linear bearings and allowed to recoil about 15 cm during firing. A flexible bus arrangement between the compulsator and the gun breech is used to accommodate the gun motion. Conceptual design of the gun is underway at the time of this writing, so details concerning it are not presented in this paper.

System Operation

Operating procedure for the system may be summarized as follows. Preparation begins with cooling of the field-coil conductors to liquid nitrogen temperature and preheating of the bearing oil. Auxiliary systems are then activated after starting the auxiliary power unit (APU) with an onboard battery. Final preparations include charging of a small capacitor used to initiate self-excitation and pressurization of brush actuation accumulators with nitrogen gas. The prime-power turbine, a General Electric model LM500, is subsequently started using a hydraulic motor powered by the APU. Approximately five minutes are required to reach full speed (10,000 rpm). Just before the discharge sequence commences, a projectile is loaded into the railgun injector. An electrical schematic of the system is shown in figure 2.

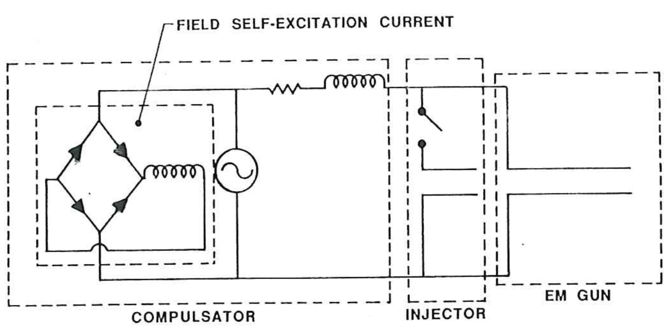


Figure 2. Simplified system electrical schematic

Compulsator discharge begins with self-excitation of the field coil. The field brushes are lowered onto the compulsator rotor output slip rings to close the field coil circuit and the initial excitation capacitor is then discharged into the coil. A set of silicon controlled rectifiers (SCRs) arranged in a full wave bridge are used to rectify the varying frequency ac signal from the compulsator into direct current for the field coil. Full excitation is achieved in roughly 1.5 s and requires 18 MJ from the rotor, dropping its speed by 5% to 9,500 rpm. Just as full excitation is reached, the main compulsator brushes are lowered and the trigger switch closes the injector into the output circuit as the rotor rotates into the proper angular position. The switch is closed late in the voltage cycle so that the current is near zero as the projectile leaves the injector and enters the main accelerator. The subsequent voltage cycle drives the gun current as shown in figure 3, again allowing for a near zero muzzle current. During the acceleration in the main gun, which lasts about 5 ms, the rotor speed drops nominally 8% to 8,700 rpm. The slip clutch in the drivetrain prevents the gearbox and turbine from experiencing this abrupt deceleration. It does, however, slow the drive components during the subsequent 50 ms to match the rotor speed so that remotoring can begin for the next shot. Once the discharge is complete, some of the magnetic energy of the field coil is used to recharge the initial excitation capacitor and the remainder is resistively dissipated. Peak gun current required to accelerate the 9-MJ projectiles varies with the projectile mass as shown in table 1.

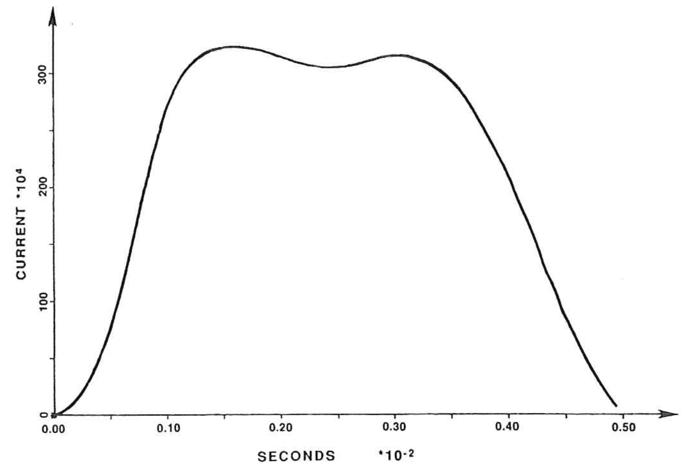


Figure 3. Compulsator current time history during a shot

Testing of a lab based iron-core compulsator driven railgun system [5,6] using a similar firing circuit is underway at CEM-UT. Initial results indicate that this scenario provides reliable timing and controllable muzzle currents once system operation is characterized.

Compulsator Design

A two-pole compulsator was chosen as the best compromise between rotor peripheral speed, peak gun current, gun length, and overall machine mass. A four-pole alternator has some advantages over the chosen design, but would require a larger, lower speed rotor to match the performance of the two-pole design in terms of minimizing peak projectile acceleration and gun length. This would substantially increase the mass of the machine. Six armature turns per pole are necessary to generate the required voltage and the two lap-wound conductors are connected in parallel to minimize end turn length, conductor width, and internal impedance. Compensation for the armature winding during discharge is provided by a stationary compensating winding located on the inner bore of the stator. Some of the important characteristics of the machine are presented in table 2 and an isometric cross section is shown in figure 4.

Table 1. Peak gun current required for various 9-MJ projectiles

PROJECTILE MASS (kg)	MUZZLE VELOCITY (km/s)	PEAK GUN CURRENT (MA)	PEAK ACCELERATION (kgees)
1.13	4.00	3.00	173.90
1.47	3.50	3.10	139.70
2.00	3.00	3.26	113.50
2.88	2.50	3.61	96.70

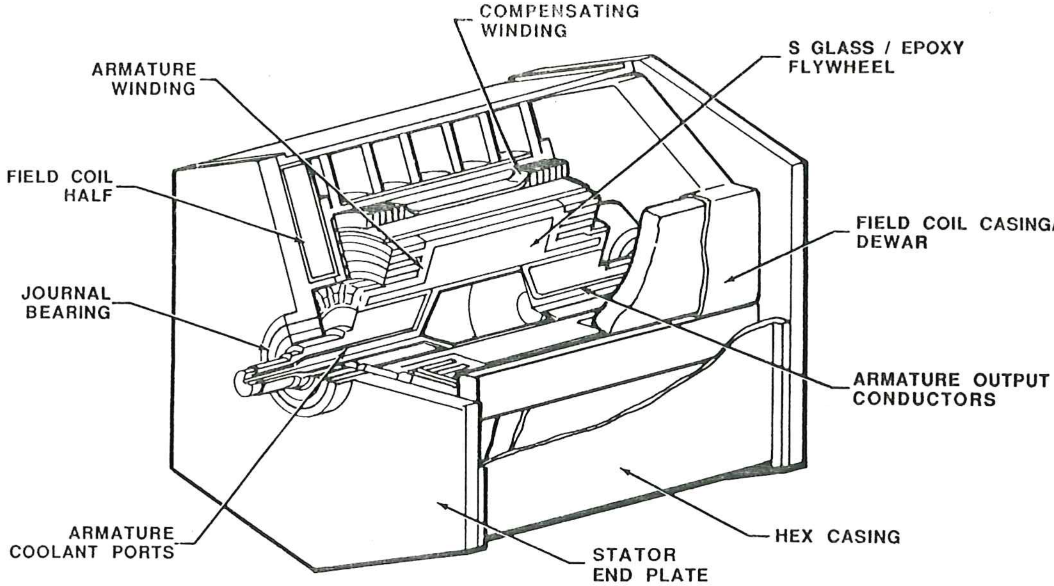


Figure 4. Self-excited, air-core compulsator

Rotor

Primary functions of the compulsator rotor are inertial energy storage and support of the armature conductors near the outer periphery. Design goals of subcritical operation and energy storage of at least 200 MJ were met with the configuration shown in figure 5. Perhaps the most unique feature of the compulsator rotor is the requirement that, with the exception of the armature conductors, it is constructed of entirely nonconductive materials. This is necessary to avoid extreme eddy current losses which would be generated when rotating at high speeds while the field coil is energized. Since this leads directly to the use of many different epoxy composite and other nonmetal materials throughout the rotor, great care was taken to ensure proper radial growth compatibility of the various components as the rotor is spun. Also for electromagnetic reasons, the armature winding must be as close to the outer periphery of the rotor as possible to maximize its inductive coupling with the compensating winding. This effectively limits the maximum banding thickness used to constrain the armature conductors.

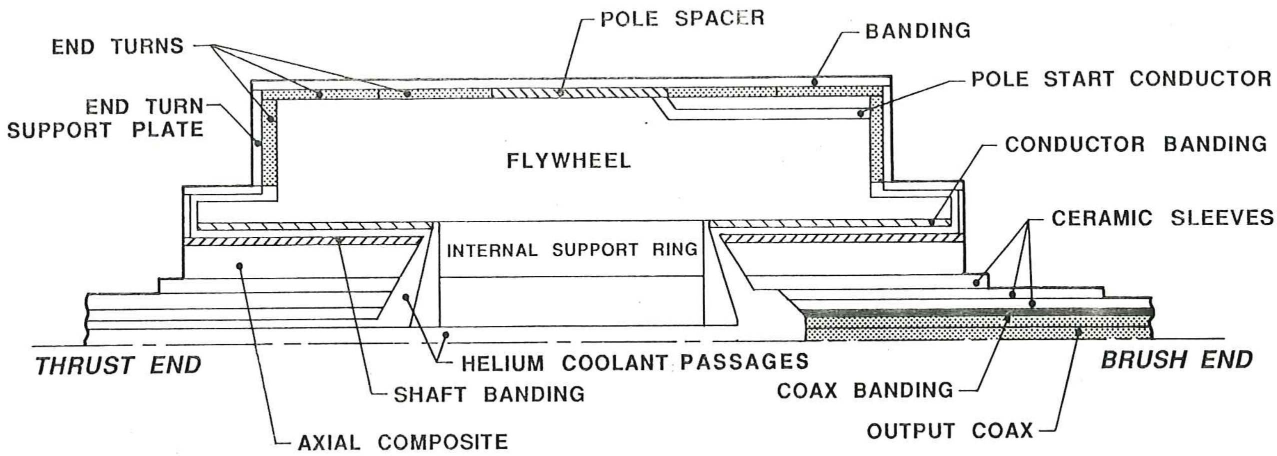
Table 2. Self-excited air-core compulsator characteristics

Rotor Speed	10,000. rpm
Energy Stored	250. MJ
Peak Voltage	8. kV
Peak Current	3.5 MA
Peak Power	27. GW
Pulse Width	5. ms
Maximum Torque	20. MNm
Avg. Armature Shear Stress	15.1 MPa
Mass	12,500. kg

One of the primary issues in design of the rotor involves growth matching and torque transfer between the flywheel and the armature conductors. It is extremely important that this interface be in radial compression as the machine is discharged so that the epoxy bond holding the conductors in place is not compromised. Radial spin growths of the armature/banding and the flywheel must therefore be reasonably close. It is desirable that the flywheel growth be slightly less than that of the armature and banding so it does not load the banding centrifugally. The difference in growth can then be compensated for through the use of an interference fit between the armature and banding. Most of the initial radial interference is relieved at high speed, so stresses in the banding are almost entirely due to the deadweight load of the armature conductors.

To accommodate an uncooled armature design with enough thermal mass to allow nine consecutive shots, a banding material with high strength and stiffness was required. A graphite fiber manufactured by Hercules, UHMS®, was chosen as the best material for this application. Lower modulus fibers could be used, however, assembly of the banding onto the armature with adequate interference to match flywheel growth is questionable. Radial growth of the uncooled armature and UHMS banding combination at 10,000 rpm is approximately 2.41 mm. This effectively established a growth criteria for the flywheel. Hoop wound S-glass fiber reinforced epoxy composite was chosen for its growth compatibility, low cost, and its high strength in both the fiber and transverse directions. Radial tensile stresses produced by rotation are controlled by assembling the flywheel from a series of concentric cylinders which are interference fit together. At assembly, this sets up radial compressive stresses in the flywheel which are relieved as the flywheel rotates.[7]

Once assembled, the flywheel is structurally very resistant to flexure. This allows the use of stub shafts; however, these shafts must also be extremely stiff to ensure that rotor to stator critical frequencies are above operating speed. Fiber reinforced composites can be made very stiff in bending by orienting the fibers in the axial direction; unfortunately, they



DIAMETER 43.6 in (1.11 m)
MASS ~7300 lbs
ENERGY 250 MJ @1047 r/s

Figure 5. Compulsator rotor cross section

have very low shear properties in the transverse direction. This results in excessive shear deflections and reduces the apparent stiffness. An alumina ceramic material was therefore chosen for the overhung portions of the stub shafts and the resulting rotor design will operate at about 75% of its first damped flexural critical. Calculated deflections at the critical speed are small even when large imbalances are assumed. Growth matching between the ceramic shafts and the inner diameter of the flywheel is accomplished with several layers of axially oriented S-glass and graphite-fiber composites which are also interference fit together to control stresses.

Armature

Two separate rotors are being fabricated for this project, one will be fitted with an uncooled armature winding and the other will receive an actively cooled version. The uncooled version is sized to allow nine consecutive discharges before reaching a thermal limit. To allow compatibility of both armatures with either rotor, the cooled armature is dimensionally equivalent to the uncooled version and maintains the same mass density. For the cooled armature, a portion of the conductors have been removed to allow room for cooling passages. In both cases, the 22.86 cm wide by 2.54 cm thick conductors are made up of stranded and transposed 24 gauge aluminum wires. Packing efficiency of the conductors is about 55%. Aluminum windings are physically larger than would be those made of copper, but are much lighter and therefore result in lower centrifugal loading on the banding. Basic geometry of the windings is shown in figure 6. Output conductors are routed in a radial gap between the shaft and the flywheel and eventually to the center of the shaft where they form a coaxial output conductor. The size of these conductors is minimized by using stranded copper wires. Joints between the copper and aluminum wires are of a permanent crimp type design. At the point that the coaxial output conductor exits the shaft tube, it is attached to a pair of brush slip rings. The brush slip ring extension is supported at its outboard end by a small hydrostatic bearing.

A closed loop helium gas system is used to cool the armature winding and output conductors in the cooled rotor.[8] The gas is precooled to -58°C with a liquid nitrogen heat exchanger and pressurized to 7.9 MPa before being introduced to the windings through the thrust end shaft as shown in figure 5. As the gas flows to the outer radius of the rotor, it is centrifugally compressed to about 10.3 MPa before it enters the armature. This increase in pressure, and the heat picked up by the gas in the armature actually helps pump the gas through the circuit. Friction losses exceed the pumping effect by approximately 50 hp, so additional power is supplied by an air motor as shown in figure 7. Compressed air to drive the motor is conveniently available from the compressor bleed port on the LM 500 turbine. A helium flowrate of 0.9 kg/s is needed to allow continuous system firing at a rate of 3 shots/min without reaching a thermal limit in the armature winding.

Stator

The compulsator stator consists of four major components, the excitation field coil, the compensating winding and its support structure, the main stator casing, and the stator end plates which house the rotor bearings. Both the field coil and compensating winding are located and supported by the stator casing, which also provides alignment for the hydrostatic bearings and reacts the discharge loads of the machine.

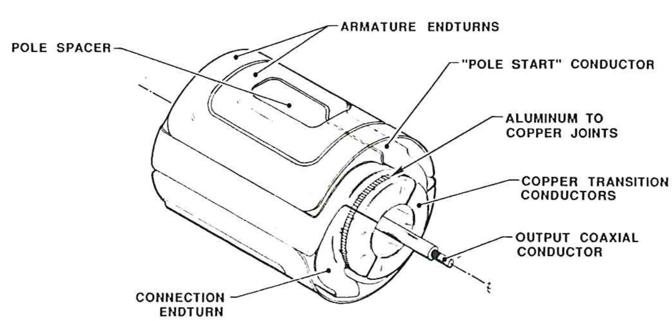


Figure 6. Compulsator rotor armature winding

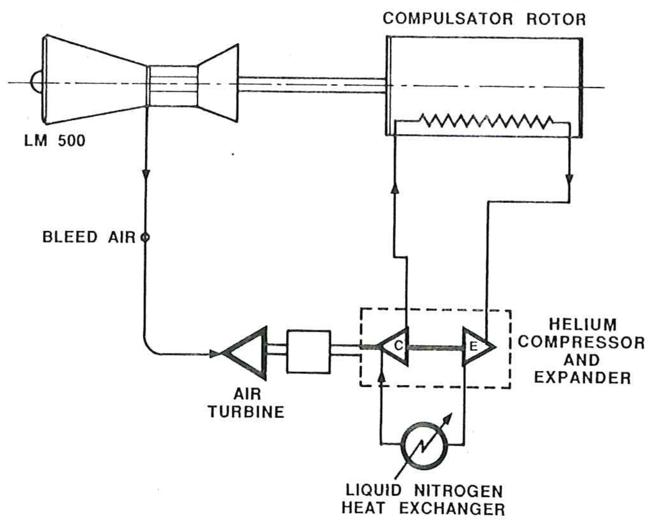


Figure 7. Helium gas delivery circuit for rotor armature cooling

The field coil provides the magnetic field required to generate voltage in the rotating armature conductors. Basic geometry and characteristics of the field winding are shown in figure 8. The coil consists of 500 turns in all. A peak current of 11.5 kA per turn produces an operating flux density of 2.8 T in the armature winding region. In order to minimize the excitation power requirements, the aluminum field coil conductors are actively cooled to -196°C with liquid nitrogen, thereby reducing the coil resistance to about 15% of its room temperature value.

A unique fabrication technique is planned for the field coil. Each of the two coil halves consists of 24, 1.9 cm thick 1145-H14 aluminum plates cut into a rectangular helix using a high pressure waterjet cutting machine to minimize kerf width and thereby increase conductor packing efficiency. Once the 24 plates are bolted together to put all the turns in series, the assembly is enclosed in a 2219-T6 aluminum containment vessel which provides structural support and liquid nitrogen distribution manifolds. The containment vessel is wrapped with fiberglass and installed into a vacuum casing for thermal insulation. The two coil halves are assembled around the compensating winding and fastened rigidly in place to the stator casing.

In order to flatten the compulsator current pulse into the railgun, a special compensating winding is used to create the necessary variation in armature winding inductance with rotor angular position. Induced currents in the compensating winding, however, interact with magnetic fields produced both by the field coil and the armature current, and result in large radial and tangential forces on the compensating winding conductors. These loads are reacted directly to the stator structure through a hoop wound graphite/epoxy cylinder and a series of laminated flat plates distributed axially along the stator which are bolted to the external casing. The stator casing is then compliantly mounted to the main skid with a series of dampers.

The compensating winding is a two-pole configuration with 26 turns per pole and is constructed of stranded and transposed aluminum Litz wire with a 25 cm square cross section. Each individual turn in the winding is shorted on itself, so all the turns are in parallel.[9] The end turns of the compensating winding are distributed over the inner bore of the stator radially above the armature end turns and the inside of the end plates in such a manner as to maximize inductive coupling with the armature winding and distribute discharge loads as uniformly as possible. The axis of the compensating winding is tilted approximately 57° relative to the axis of the field coils to provide the proper timing and inductance variation for producing the flat output current pulse shape best suited for driving a railgun. The compensating winding, its end turns opposite the rotor face, and its supporting structure also form the rotor chamber which is evacuated to about 1 torr during operation to minimize rotor heating due to windage losses. High speed, contacting face seals located just inboard of the journal bearings serve to seal the rotor chamber.

Positioning of the casing, field coil, and compensating winding with respect to the rotor is accomplished by the two stator end plates. These aluminum structures provide extremely stiff support for the radial hydrostatic bearings and also react a portion of the axial discharge loads imposed on the compensating winding end turns. In order to insure a first rotor to stator lateral critical frequency above operating speed, the combined stator end plate and bearing stiffness must be at least 4.38 GN/m on each end. Two 8 pocket hydrostatic radial bearings are used to achieve this requirement and an additional smaller 4 pocket bearing is used to provide dynamic stability for the overhung brush slip ring extension. Axial position of the rotor is maintained and axial subcritical operation is insured by a 10 pocket hydrostatic thrust bearing located on the drive end of the machine. The thrust bearing is a multirecess, opposed-pad design which uses orifice compensation. This bearing must also react transient axial loads in the rotor during discharge. Compulsator bearing characteristics are given in table 3.

Auxiliary Systems

Auxiliary support functions for the compulsator are powered primarily by a small 750 hp gas turbine engine which drives a parallel-shaft gearbox that pro-

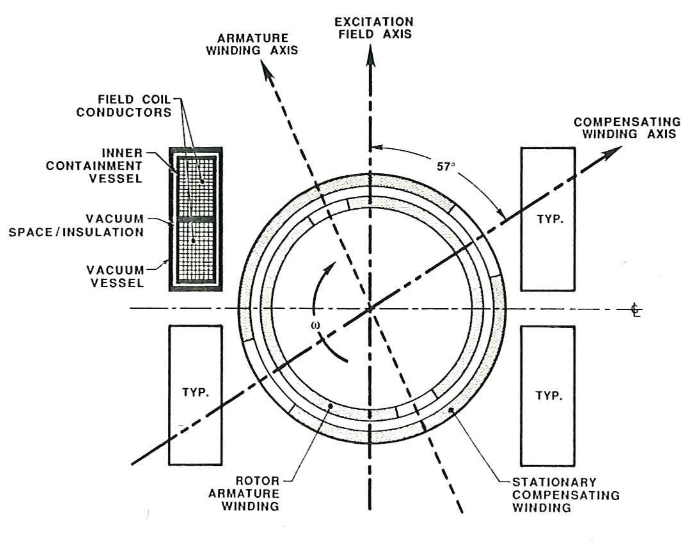


Figure 8. Compulsator mid-plane cross section showing field coil and compensation winding orientation

Table 3. Compulsator hydrostatic bearing characteristics

CHARACTERISTIC	RADIAL*	THRUST*	UNITS
No-Load Stiffness	6.20 35.4	8.18 46.7	GN/m Mlbf/in.
Peak Stiffness	11.54 65.9	12.81 73.2	GN/m Mlbf/in.
Peak Load Capacity	576.0 129.5	467. 105.	kN klbf
Lubricant Type	Mobil SHC 825 Synthetic Turbine Oil		
Lubricant Inlet Temperature	60.0 140.	60.0 140.	°C °F
Lubricant Temperature Rise	32.7 91.	9.44 49.	°C °F
Lubricant Flowrate	164. 43.	186.2 49.2	l/min gpm
Fluid Friction Drag	183.8 246.4	73. 97.8	kW hp
Lubricant Supply Pressure	207. 3,000.	207. 3,000.	bar psi

*Values given are for each of one thrust and two radial bearings

vides power take-off pads at several speeds. Redundancy is provided for critical systems, like the compulsator bearing hydraulics, by pumps driven off the main drive gearbox. Four major systems driven by the APU are skid hydraulics, oil cooling, electrical power, and vacuum pumping. Skid hydraulics provide hydraulic power for main turbine starting, compulsator bearing supply pressure and lubrication oil for various components. Cooling fans and the EM gun auto-loader are also hydraulically operated. Cooling of hydraulic oil is accomplished with two forced air to oil heat exchangers. Total continuous heat rejection capability is 1,100 hp. A small dc generator is also driven by the APU and provides power for instrumentation and controls as well as for other skid requirements. An electric pump is used to maintain the liquid nitrogen level in the field coil by pumping the liquid from a small dewar located on the skid. Evacuation of the rotor chamber is also accomplished with an electric pump, this one a two stage rotary vacuum pump.

Other miscellaneous auxiliary systems include brush actuation, gun cooling, and armature cooling gas delivery. Brush actuation is performed by releasing pressurized nitrogen gas into Viton® bladder actuators. Ambient temperature water is used to cool the gun rails and is pumped continuously through the gun by a gearbox-driven pump during a multi-shot experiment. Major components in the armature cooling circuit include a small turbine which expands the warm, high pressure gas from the rotor, a liquid nitrogen heat exchanger, a compressor, and a small air motor. The compressor is driven by both the expansion turbine and the air motor, which is powered by bleed air from the main turbine.

Conclusions

The self-excited, air-core compulsator now under construction for this effort represents a major leap forward in the development of pulsed power generator technology. To the knowledge of the authors, it represents the highest energy storage density (20 kJ/kg) and the highest power density (2.2 MW/kg) ever achieved in a pulsed rotation electrical machine. In terms of rated peak power (27 GW), it exceeds that produced by existing machines of similar design by a factor of 15. While the ambitious goals of the project introduce some risk and many components in the machine are highly stressed, design analysis and subscale component testing performed indicate a very high probability of success. Major milestones to be completed this year include full speed spin testing of a finished compulsator rotor, assembly and testing of the prime power and auxiliary systems, and fabrication of the compulsator stator. Final assembly of the system is scheduled for early 1989 in time for initial testing for March.

Acknowledgements

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