**FABRICATION OF A ROTOR FOR A FIELD BASED, SELF-EXCITED
COMPULSATOR POWER SUPPLY FOR A 9 MJ
RAILGUN DEMONSTRATOR**

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Fabrication of a Rotor for a Field Based, Self-Excited Compulsator Power Supply for a 9 MJ Railgun Demonstrator

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Abstract--Fabrication of a high-speed, self-excited air-core rotor for a field based compulsator has begun and is well under way. The compulsator is to be used as a power supply for firing 9 MJ projectiles from a skid mounted electromagnetic launcher (railgun). The rotor flywheel is made of fiber reinforced epoxy composite and is supported with high strength metal stub shafts which are shielded from the excitation field by water cooled copper sleeves. The rotor features separate windings for self-excitation and railgun firing, and a two-pole configuration for pulse length considerations. The rotor is designed to store 210 MJ at 8,600 rpm, with a rating of 3.2 MA peak current and 20 GW peak power into a 9 MJ railgun load.

The concentric fiber-reinforced epoxy composite rings that make up the rotor flywheel are filament wound on steel mandrels, cured, and interference fit together. The main and excitation armatures and output conductors leading from the armatures to the shaft conductors are constructed of epoxy impregnated aluminum and copper Litz wire. The rotor is approximately 75% assembled; the metal shafts, the excitation winding with its output conductors completed, and several flywheel rings assembled. The main armature has been preformed on a mandrel and is ready for assembly onto the rotor.

A detailed description of the compulsator rotor with design considerations and fabrication techniques are reviewed in this paper, and the current status of the project is discussed. The compulsator stator is being constructed in parallel with the rotor and is discussed in a companion paper presented at the 6th EML conference [1].

ELECTRICAL DESIGN AND PERFORMANCE

Compulsators are excellent power supplies for railguns because power system functions of energy storage, electrical pulse generation, and pulse preconditioning prior to delivery to the gun are combined in a single device [2,3]. This results in a high efficiency system that is able to recover the inductive energy in the gun before the projectile exits the muzzle. Furthermore, burst firing is possible because sufficient energy can be stored in the rotor for multiple shots, allowing prime power to be averaged over several shots and substantially reducing system peak power requirements. 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 a two-pole, self-excited air-core machine was selected based on weight and size constraints. Also, to accommodate relatively low projectile acceleration limits a selectively-passive compensation scheme [4,5] is incorporated in the design which results in a flat current wave form (fig. 1) from the compulsator into a railgun load. The selectively-passive compensation scheme results in a peak projectile acceleration of $980,000 \text{ m/s}^2$ (100 kgees). A cross-section of the rotor is shown in fig. 2 and a list of important rotor parameters, taken from reference [2], are given in table 1.

TABLE 1. SELF-EXCITED AIR CORE COMPULSATOR ROTOR CHARACTERISTICS

Rotor Speed	8,600 rpm
Rotor Energy Storage	210 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
Rotor Mass	4,500 kg

KEY DESIGN ISSUES

During the design and analysis stage of the rotor, several key issues had to be addressed. Of primary concern were radial stresses in the flywheel due to rotor spin and axial stresses resulting from flywheel assembly. In order to

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Fig. 1 Compulsator output pulse shape for a 9 MJ railgun shot

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Fig. 2 Rotor cross-section

maximize the kinetic energy density of the rotor, the flywheel portion is designed with filament wound S-glass and IM6 graphite composites. These materials have a high specific strength that allow flywheel rotation at considerably higher tip speeds than conventional engineering materials. Furthermore, being nonferromagnetic, use of composites in flywheel fabrication results in an air-core rotor. While filament wound composites are extremely strong in the fiber direction, they exhibit very low strength in the directions transverse to the fiber. In the case of a hoop wound flywheel, the fiber direction naturally corresponds to the hoop direction in order to handle the large hoop stresses encountered during rotation at high speed. The directions transverse to the fiber are the rotor radial and axial directions. Radial stresses due to spin can be high in a thick walled ring and can easily exceed the transverse strength of the composite materials used. Thus, a means for controlling the radial stress had to be devised. This was done by designing the flywheel to be constructed of a series of concentric cylinders that are interference fit together. The interference fits result in a radial precompression at rest that offsets the radial tension at speed. The interferences were designed so that the maximum radial stress within any ring and at ring interfaces remains compressive at the maximum rotor speed of 8,600 rpm. This method also ensures that the epoxy layers between flywheel rings (used to bond the rings together during assembly) retain their shear carrying capability (which is drastically reduced by radial tension) during the sudden rotor deceleration due to discharge of the railgun. Likewise, precompression of the armature winding layer at the rotor periphery is accomplished with interference between the armature and a high modulus graphite banding. This is necessary not only for maintaining shear transmitting capability between the armature winding (where the discharge torque is produced) and the flywheel, but also because of strength considerations of the relatively weak aluminum Litz wire/epoxy armature winding.

Axial stresses in the composite flywheel are also transverse stresses and, thus, are an important consideration. Axial stresses arise from rotor bending and from flywheel

assembly. Bending stresses due to gravity loading are insignificant, as are bending stresses at speed arising from whirling of an unbalanced rotor (for reasonable values of rotor imbalance). Flywheel ring assembly is the main cause of axial stresses in the composite rings. Axial bending stresses can arise in a ring being assembled onto the rotor due to differences in stiffness of the underlying rotor structure along its length. A more significant source of axial stress in the rotor, however, has been found to be Poisson growth of the rotor in the axial direction arising from interference fits. Radial deformation of a ring, due to interference fit pressure, results in axial deformation depending on the material Poisson ratio. The transverse Poisson ratios of the composites used in the flywheel range from 0.3 to 0.45, resulting in significant axial growth of the material below the interference pressure. The axial growth is transmitted further into the flywheel via radial compression and shear forces between rings of different Poisson ratios. The shear force results in an axial stress distribution in the rotor. A careful analysis of the effect of each interference fit was conducted and the results superimposed in order to determine the final axial stress distribution in every flywheel ring. The analysis showed that a substantial amount of stress results but not enough to warrant design modification.

A second important design issue concerned rotor dynamics. At the outset of the design stage, considerable effort was made to ensure subcritical operation of the rotor. The requirement of subcritical operation drove the rotor design severely in several ways, including reducing rotor length by locating the armature end turns on the flywheel face and using a ceramic material to provide lightweight shafts with high bending stiffness. Rotor dynamics analysis using traditional one-dimensional (1-D) beam elements suggested that subcritical operation was possible with these design implementations. On the other hand, they resulted in insurmountable armature end turn stress problems at speed; the reliability of the ceramic shafts, especially during discharge deceleration, was of great concern due to the fairly low tensile strength (~70 MPa) and the brittle nature of the

ceramic material. An in-depth analysis of the rotor bending stiffness using a two-dimensional (2-D) axisymmetric semi-analytical finite element method [6,7] revealed, however, that the rotor bending stiffness predicted by the 1-D beam element model was greatly overestimated, resulting in optimistic critical speed predictions. The 2-D analysis was able to accurately model the radial and shear stiffness of the individual layers comprising the portion of the flywheel at the junction of the shaft with the composite layers. Due to localized radial and shear deformation of the composite layers, bending stiffness in the region where the shaft enters the composite flywheel was significantly lower than the 1-D analysis (which used smeared properties over a rotor section) predicted. Fig. 3 shows the mode shape corresponding to the first bending frequency of the rotor from the 2-D axisymmetric analysis. Based on the results of the axisymmetric analysis, the 1-D beam element model was adjusted to produce similar results for an undamped eigenvalue analysis. Once the eigenvalue predictions of the two analyses coincided, the 1-D model was used to predict rotor and stator system eigenvalues including bearing damping and gyroscopic moments [8]. From the damped, gyroscopic eigenvalue analysis the critical speed was determined and found to be below operating speed. Thus, the rotor was indeed supercritical in spite of efforts to the contrary. This revelation allowed relaxation of rotor length constraints, allowing the armature end turns to be placed on the rotor periphery resulting in greatly reduced end turn stresses. Also, the ceramic shafts were discarded for stronger and more reliable metal shafts.

Additional extensive rotor dynamic studies were conducted in order to determine damped, gyroscopic eigenvalues of the combined rotor/bearing/stator system at speeds above the critical speed and to determine rotor synchronous response to imbalance. The damped eigenvalues were calculated in order to determine bearing support stiffness and bearing damping and stiffness requirements to ensure rotor stability above the critical speed. Synchronous response calculations were done in order to determine sensitivity of the rotor to imbalance and to set minimum balance requirements. Descriptions of these analyses and their results are beyond the scope and space limitations of this paper and will be presented in a future paper.

Another important design concern was eddy current heating of conductive materials in the rotor. Since the entire rotor is immersed in the two-pole excitation flux, extreme

eddy current heating in any solid metal material will occur. Eddy current heating will occur in the graphite composites as well, although to a lesser extent since graphite is only slightly conductive. The reduced propensity to eddy current heating of graphite composites is offset, however, by the severe degradation of composite material properties to quantities of heat that metals would easily shrug off. Eddy current heating in the rotor can be controlled in a number of ways. By selecting materials with very low conductivity, such as S-glass, eddy currents can be eliminated for the most part in the flywheel portion of the rotor. Graphite composite parts are axially segmented in order to break up eddy current paths along the rotor axis. The slits are filled with epoxy impregnated S-glass strands and then cured. Reducing the excitation field charging time by including a 17 kV excitation winding armature (separate from the main armature winding) in the rotor also reduces the overall amount of heating, and the field is rapidly quenched by regenerating the field inductive energy back into the rotor. Eddy currents in the metallic shafts are controlled with a water cooled magnesium zirconium copper (MZC) eddy current shield.

MECHANICAL DESIGN

Based on the design issues described above, the rotor design has evolved to a primarily fiber-reinforced composite structure with high strength metallic stub shafts, epoxy impregnated aluminum Litz wire excitation, and main armature windings. A high modulus graphite composite banding surrounds the armature in order to precompress and support the armature windings at high speed.

Stub Shafts

The thrust end stub shaft is made of high strength 17-4 PH stainless steel. The thrust end shaft connects to the prime mover drive shaft, and also carries the thrust load through a hydrostatic thrust bearing runner. The current output end stub shaft is composed of a series of concentric coaxial solid copper conductors for the main armature and excitation winding currents, B-stage mica and S-glass insulators, and Invar™; an iron-nickel alloy, for structural strength and stiffness. Invar is used as the shaft structural material because of its low coefficient of thermal expansion, limiting radial growth of the shaft in the bearing journal area from heating of the copper conductors during current discharges into the railgun. High strength stainless steel rings are thermally shrunk onto both shafts to serve as hydrostatic

Fig. 3 Undamped mode shape from 2-D axisymmetric semi-analytic finite element analysis

bearing journal surfaces, and copper coated aluminum slip rings are shrunk onto the coaxial output conductors to provide brush slip ring surfaces for current extraction from the rotor. Use of aluminum for the slip ring material greatly reduces torsional inertia and, therefore, torsional stresses in the output end shaft during discharge deceleration. Water cooled MZC copper alloy tubes are shrunk onto the shafts to act as shields from the excitation field. Eddy currents generated in the shield, oppose the excitation field and protect it from the metallic shaft components. The shields experience a substantial temperature rise themselves, however, and must be actively cooled with a 0.76 l/s flow rate of an ambient temperature water/glycol solution. The coolant is introduced into the stub shafts through a pressurized gallery sealed with carbon ring seals at each end of the rotor. A special composite that can withstand high temperatures surrounds each eddy current shield to protect the flywheel composites from the heated shields.

Flywheel

The rotor flywheel is composed of several composite rings made of S-glass and IM6 graphite that are interference fit together. The flywheel provides most of the rotational inertia storage and serves to support the main armature winding.

Excitation Winding

The excitation winding (fig. 4) used to provide field coil self-excitation current is located between the rotor shafts and the flywheel. It is a two-pole winding that is 90° phase shifted from the main armature winding to avoid EM coupling. The two poles are connected in series so that peak voltage generation is increased and field coil charging times are reduced.

Fig. 4. Representation of excitation winding

The excitation winding is composed of an inner and outer 455 #20 AWG aluminum Litz cable wound in six turns per pole (12 conductors/slot). 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. The inner cable proceeds to the outer cable of the next pole via a center jumper. The aluminum cables are connected to the stub shaft copper wires via crimp and solder joints. The copper wires consist of 32 cables of 7x7 #24 AWG copper Litz wire per terminal. The 32 copper cables are connected to solid copper coaxial conductors by being soldered into holes in the inboard ends of the coaxes and then mechanically crushed. This produces a strong and electrically sound connection. The copper coaxes extend through the center of the connection end stub shaft and extend out the outboard end where they serve as brush slip ring surfaces.

The insulation system utilizes dry fiberglass tape and DMD-70 5-5-5 laminate (polyester mat saturated with 70% epoxy, polyester film core and polyester mat, each 0.005 in. thick). The insulation materials were selected based upon extensive proof tests, the operating voltage of 17 kV, their compatibility with the epoxy system and a design factor of safety of five or greater.

Armature Winding

The main armature winding is in a two-pole configuration with the two poles arranged in parallel so that each conductor carries half of the peak current generated by the machine. The armature winding is composed of lower and upper coils of sixty 110 #24 AWG aluminum Litz cables wound in 3 turns (6 conductors/pole). Fig. 5 shows the armature winding schematic and fig. 6 shows the lower and upper coils per pole. In addition to the interior Litz cable transposition, each coil has major top to bottom radial transpositions as shown by the dotted lines. These transpositions are used to insure uniform current and thermal sharing during the discharge. The two coils proceed down the rotor faces to the connection area for connection to the stub shaft copper conductors. End-to-end symmetry in the winding ensures that axial forces produced from interaction of the end turn currents with the

Fig. 5 Armature winding schematic

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Fig. 6a. Armature winding layout

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Fig. 6b. Armature winding layout

excitation field are balanced, resulting in no net thrust to the thrust bearing during railgun discharge. Graphite support plates are used to control radial growth of the flywheel end regions at speed in order to limit radial and hoop stresses in the transition conductors located on the flywheel faces. The aluminum Litz wire experiences a temperature rise of 12°C per shot, thus, no cooling is required for a nine shot burst.

ROTOR MANUFACTURING ISSUES

Composite rings used in the rotor are fabricated in-house on a four axis McClean-Anderson filament winding machine. The rings are wet wound onto nickel plated steel mandrels using a Shell Epon epoxy system. The rings are typically cured at 110°C with a post cure at 175°C to raise the heat deflection temperature.

Interference fits in the rotor are accomplished using three methods. Conventional thermal fits are used for shrinking together metallic portions of the output and thrust end shafts. For instance, the MZC copper eddy current shields are

shrunk onto the metal shafts using a thermal fit. Thermal fits, however, are not easily accomplished with composite parts because of low thermal expansion coefficients in the fiber direction of most composites, coincident with low temperature handling capabilities of the epoxy matrix. Thus, for interference assembly of the flywheel rings two other methods are employed. Press fits for assemblies involving small interferences are accomplished by axially pressing one ring onto another using a 500 ton press. Care must be taken not to exceed the transverse compressive strength of the material of the ring being pressed on, as well as its transverse shear strength. Since the press load and, therefore, the stresses involved are directly dependent on the amount of friction at the interface, the contacting surfaces of the rings are coated with epoxy to act as a lubricant in order to reduce contact friction. Furthermore, the inherent weakness of composites in shear as well as in the direction transverse to the fiber requires that tooling in the form of a lead-in plug be used to reduce the magnitude of shear and bending stresses in the ring being pressed on as it is deflected outward by the interference. The lead-in plug reduces stresses during assembly by providing a more gradual transition to the deflected position. The length of the lead-in plug controls the amount of shear and bending stress, and so in general, larger interferences require longer lead-in plugs. Since axial space under the press is limited, large interference fits of some of the flywheel rings were not possible due to the lead-in plug length requirements.

The third method of producing precompression does not actually involve geometric interference between rings but the result is the same, with some additional side benefits. The method, called pressurized cure, involves fabricating the rings with a small annulus between them and injecting epoxy under pressure into the annulus, thus, expanding the outer ring and contracting the inner ring, and then curing the epoxy while maintaining pressure [9]. End plates incorporating O-ring seals are used to encapsulate the epoxy in the annulus during the process. The result is an apparent interface pressure at the ring contact surfaces that is uniform along the contact length (unlike conventional interference fits, which can result in variation of the interface pressure depending on the compliance of the underlying structure). No lead-in plugs are required with this method, and since no bending or shear stresses are induced in the ring being assembled, large amounts of interface pressure can be produced without danger of failing the ring. The resultant epoxy layer between the rings remains in hydrostatic compression after curing.

The excitation winding was pre-wound over a nickel plated mandrel in parallel with the fabrication of the rotor stub shafts and inner composite rotor rings. After fabrication of the excitation winding, the winding was transferred from its winding form mandrel to the surface of the rotor subassembly and a clamshell mold was assembled around the excitation winding and the rotor subassembly. End bells were assembled over each shaft extension and to the clamshell mold to control concentricity and axial rotor lengths during the subsequent vacuum impregnation of the stub shaft windings and excitation windings.

The armature winding was wound over a wooden mandrel in parallel with the fabrication of the rotor flywheel. After

Fig. 7. Partially assembled compulsator rotor

the rotor is completed, the armature winding will be transferred to it and the armature winding will be vacuum impregnated with epoxy.

CONCLUSIONS

Fabrication of an air-core, self-excited compulsator rotor is well under way, with the rotor approximately 75% complete at the time of this writing. Fig. 7 shows the partially completed compulsator rotor. The stub shafts, excitation winding and several flywheel rings are in place, and the main armature winding is fabricated and waiting to be assembled onto the rotor. Completion of the rotor is expected for early spring of 1992, with assembly and testing of the compulsator to follow immediately.

ACKNOWLEDGMENT

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ADDENDUM

Since the writing of this paper, a failure of the composite flywheel occurred during fabrication. The failure occurred when pressurized epoxy invaded a pre-existing flaw or crack in the rotor during the pressurized cure assembly of one of the flywheel rings onto the rotor. Once inside the crack, the pressurized epoxy forced the crack tip to propagate radially inward, resulting in failure of the flywheel rings from a 15 in. radius down to a 9 in. radius. In addition, the hydraulic pressure forced the crack to widen by approximately 0.188 in., resulting in axial failure of the excitation winding. A failure analysis and redesign is currently being undertaken and will be presented in a future paper.