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Abstract: The Center for Electromechanics at The University of Texas at Austin (CEM-UT) is specialized in the development of high power, pulsed rotating machines for a variety of applications including fusion experiments, directed energy devices, and electrothermal and electromagnetic accelerators. For many of these applications, compulsators have emerged as viable power supplies. These machines are low impedance alternators which use flux compression to shape the discharge pulse and increase peak power and, to date, have been constructed from ferromagnetic materials.

In the past several years, tremendous gains in energy and power densities have been predicted based on the use of composite materials. Glass, graphite, boron and Kevlar reinforced epoxy systems have the advantage of superior strength and stiffness, and are much lighter when compared to their metal counterparts. Two major efforts in which composite based (air-core) compulsators are being developed are now coming to fruition. Additionally, conceptual designs of several advanced concepts covering a wide range of pulse lengths and applications have been performed. The purpose of this paper is to report on the status of the machines currently being fabricated and describe the next generation of high performance compulsators.

Introduction

Performance demands in selected applications require that compact, self-excited, air-core pulsed alternators be developed to replace state-of the-art ferromagnetic machines. Due to the high strengths and stiffness-to-density ratios achievable with fiber reinforced epoxy composites, a rotor manufactured of these materials can operate at much higher speed and therefore allow sizable gains in energy storage and output power densities to be realized. It can be shown that mass energy density of a rotor scales with the square of the tip speed, so a composite rotor operating at 800 m/s will out perform a 300 m/s steel rotor of similar configuration by a factor of seven on a specific energy storage basis. Sub-scale tests of graphite-epoxy composite rotors have demonstrated tip speeds as high as 1,200 m/s, which would result in even greater gains. Similarly, power density (or voltage generation) scales directly with tip speed, and further performance gains are realized due to the higher flux densities generally associated with air-core machines. Innovative generator topologies, designed to take full advantage of composite rotor characteristics, can also contribute to substantial performance increases.

Maximum energy storage for a given alternator mass is achieved in the external shell rotor configuration shown in figure 1. The outer portion of this machine, consisting of a composite shell with the armature winding bonded to the bore, rotates at high speed. The field coil and stator compensating winding are located centrally and mounted on a stationary shaft. Since the armature is constrained by the relatively thick shell rotor, higher tip speeds are possible than in conventional internal rotor machines where the winding is banded onto the rotor surface. Also, the armature and field windings may be located in nearer proximity, allowing higher voltage generation for a given level of excitation power and greater pulse shaping capability. Furthermore, excitation field energy is reduced in the shell rotor machine because flux volume is significantly smaller.

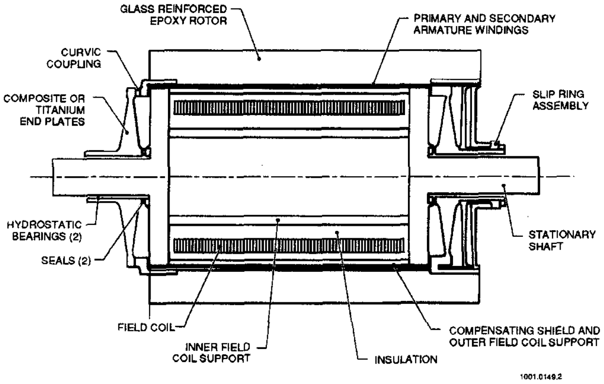

Figure 1. Shell rotor compulsator concept

Of course, the application of an air-core circuit implies greatly increased excitation power and energy and has led to the use of cryogenically cooled field coils in many previous self-excited machines. This generally unattractive feature has been eliminated by including a secondary rotor armature winding which is optimized for the self excitation process. The secondary winding is phase oriented so that it does not couple with the main armature, and is designed to operate at higher voltage to charge the field coil more rapidly than the main winding. Resistive losses in the field coil circuit are thereby minimized, and the need for a very low resistance coil is removed. After self excitation and the subsequent pulsed discharge, the excitation process is reversed and the energy stored in the magnetic circuit is recovered as useable kinetic energy in the rotor. The combination of a field circuit optimized for quick charging and the magnetic energy recovery result in a self-excitation system which is very efficient and can operate repetitively with water cooling alone.

Current Compulsator Projects

Two self-excited, air-core compulsators are now in the final fabrication and assembly phases at CEM-UT. Both machines are two-pole, rotating armature designs which utilize the conventional internal rotor geometry and have specified operating tip speeds in the 500 m/s regime. Secondary armature windings and ambient temperature field coils are also common to both designs. The first is a smaller device, known as the small caliber machine (fig. 2), designed to provide a series of 400 kA pulses at 2 kV to a small bore railgun at a rate of 10 Hz. Initial testing is scheduled for this summer. The goal of the larger machine, the range gun compulsator (fig. 3), is to deliver a sequence of nine, 3.2 MA pulses at 5.8 kV to a 90 mm bore railgun within 3 min. Preliminary testing is scheduled for early 1992. Characteristics and performance information for the two machines is shown in table 1.

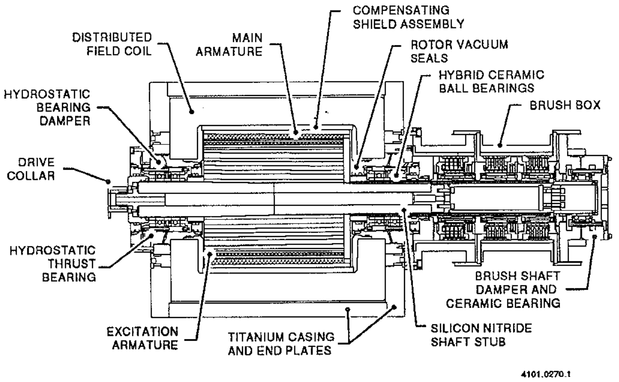

Figure 2. Small caliber compulsator

As noted in table 1, different types of compensation for the armature windings are used in the two compulsators. Uniform compensation, in the form of an aluminum conductive shield, is used in the small caliber machine. No inductance variation with rotor position is seen in this configuration and a sinusoidal output pulse is therefore derived. In order to minimize peak current required from the range gun compulsator, selectively passive compensation was chosen to provide more flat top pulse shape into a railgun load. The advantages of lower peak current are reduced electromagnetic loads in the generator and lower peak acceleration force in the railgun. Selectively passive compensation is accomplished with a two-pole, 26 turns/pole stator winding in which each individual turn is shorted upon itself. An inductance ratio of 2.78 is provided between maximum inductance, where the rotor and stator windings are out of phase, and the minimum inductance position wherein the two winding are aligned.

A driving consideration in the design of these two machines has been management of eddy current losses in the rotor. Although the excitation field is rapidly established and then quenched, eddy current power losses in any unstranded conductive element in the rotor are extremely high. In the small caliber compulsator, due to its higher operating frequency, this has forced the use of a

Table 1. Characteristics and performance of current compulsators

PARAMETER	UNITS	Small Caliber	Range Gun
Machine Diameter	m	0.63	1.82
Machine Length	m	0.86	2.8
Mass	kg	750	19,500
Volume	m^3	0.316	8.0
Maximum Speed	rpm	25,115	8,600
Maximum Rotor Tip Speed	m/s	530	500
Rotor Kinetic Energy	MJ	9.0	210
Peak Power Rating	MW	660	1000
Energy Storage Density	kJ/kg	12.0	10.8
Peak Power Density	kW/kg	880	513
Main Armature:			
Turns per Pole		10	6
Peak Voltage	kV	2.25	5.8
Peak Current Rating	MA	0.4	3.2
Discharge Pulse Width	ms	1.87	6.0
Pulse Shape (railgun load)		sinusoidal	flat top
Compensation		uniform	selective
Secondary Armature:			
Turns per Pole		26	12
Operating Voltage	kV	4.5	17
Current Rating	kA	5.0	42
Field Charging Time	s	0.33	0.8

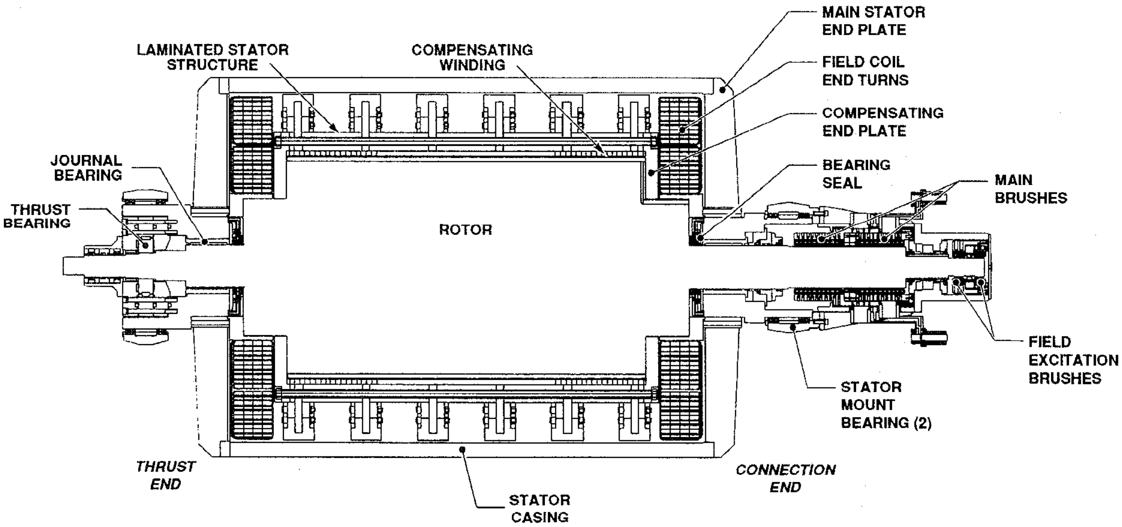

Figure 3. Range gun compulsator

non-conductive silicon-nitride ceramic shaft. The range gun machine makes use of water-cooled copper eddy current shields, which surround the two metallic stub shafts.

At this writing the small caliber machine is in final assembly. Figure 4 shows the field coil and stator structure, and the completed rotor for the machine. Fabrication efforts are ongoing with the range gun compulsator, with assembly scheduled for late 1991. Figure 5 shows the completed rotor shaft with the excitation winding in place, and several composite flywheel rings ready for installation. Major stator components, including the laminated structure and the partially assembled field coils are shown in figure 6.

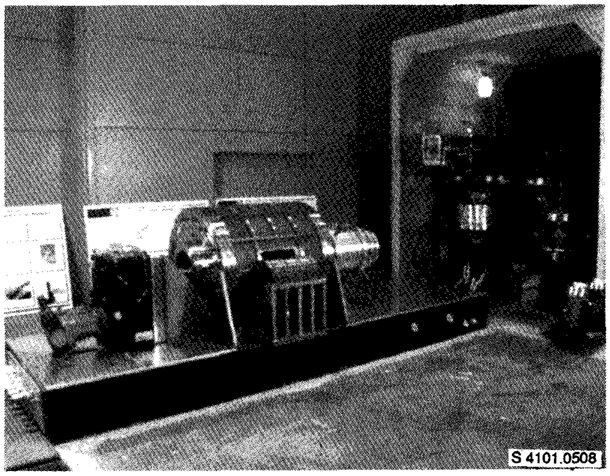

Figure 4. Small caliber compulsator components

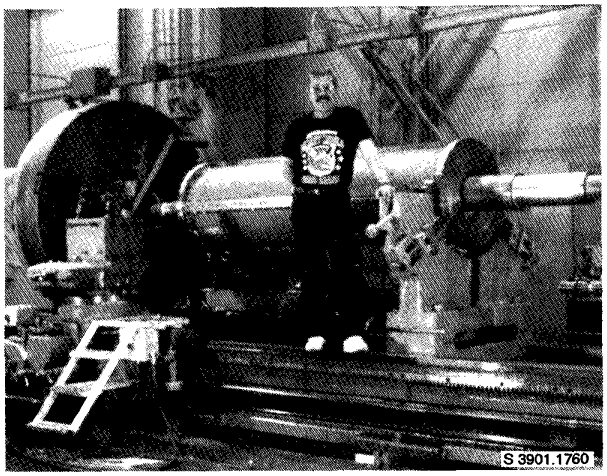

Figure 5. Range gun compulsator rotor shaft

Rotating Shell Compulsator Concept

While the self-excited, air-core compulsators described above represent significantly enhanced performance over iron-based machines, further reduction in generator size and mass are possible with the rotating shell concept. As shown previously in figure 1, this next generation device employs the same features as the machines currently being developed, including ambient temperature field coils and a secondary armature winding, but achieve much higher energy density by spinning the outer portion of the machine. The composite rotor is mounted at either end on end plates, which are supported through high speed ceramic roller bearings by a stationary shaft. Because the rotor is relatively thick to provide sufficient kinetic energy storage, it can easily support the centrifugal load of the armature windings. Transition conductors from the armature windings are attached to the end plate and are connected to output brush slip rings located at the bearing hub. At least one of the rotor end plates is removable for assembly purposes.

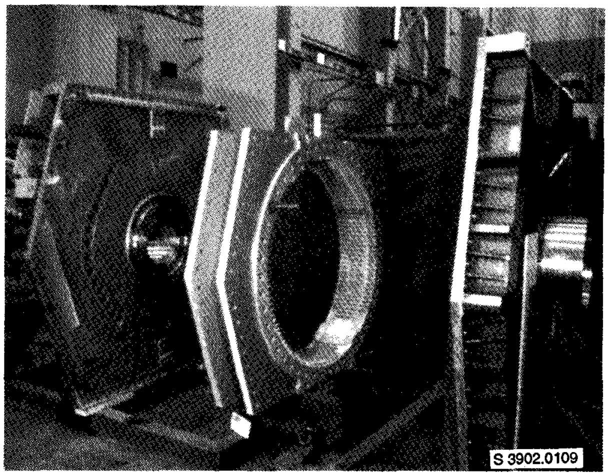

Figure 6. Range gun compulsator stator components

The stationary shaft supports the stator assembly, which includes the compensating shield or winding, and the field coils. A cross-sectional end view (fig. 7) of the machine shows the orientation of the various electrical components. The compensating winding is placed as near to the rotor armature as possible to provide maximum coupling and pulse shaping capability. The field coils are not shielded from the main discharge fields and therefore experience a transient current in addition to the steady excitation current. This transient also helps to compensate the armature winding and thereby indirectly participates in the pulse shaping process. Figure 8 shows the nature of the currents in the armature, compensating and field winding during a discharge into a typical railgun load.

A feature of this machine not included in the machines currently in fabrication is the presence of the quadrature axis excitation winding. The shape of the armature current pulse depends on the relative angle between magnetic axes of the excitation field and the compensating winding. Depending on various railgun parameters such as barrel length and desired muzzle velocity, there is an optimum relative angle between these axes. The quadrature axis excitation winding helps to fine tune the relative location of the two axes, providing optimum performance for a fairly wide range of gun parameters. Since the required range of adjustment is small (~10°), this winding need only supply a small fraction of the direct axis excitation field ampere-turns. This allows the winding to be relatively small and still provide an added versatility in tailoring pulse shape.

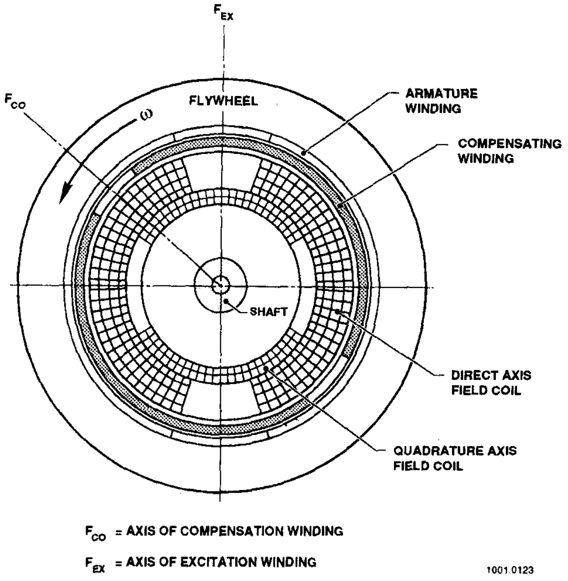

Figure 7. Selectively passive shell rotor compulsator cross section

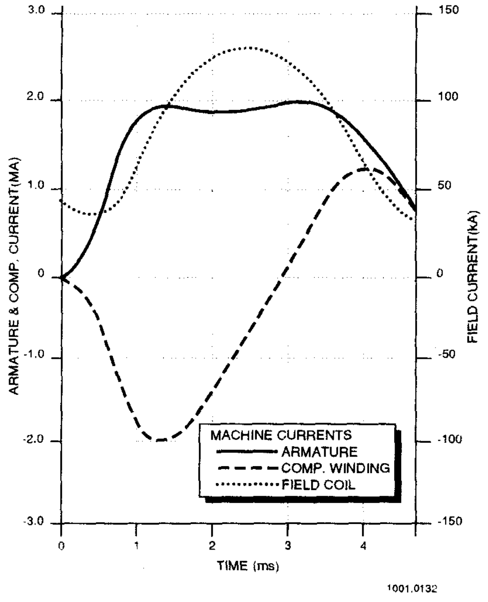

Figure 8. Compulsator winding current profiles

A point design for a rotating shell machine to power a high energy railgun was recently performed at CEM-UT. Although the rotor configuration in the rotating shell design should allow higher speed operation than in the conventional internal rotor geometry, the tip speed was only increased to 600 m/s for the study. This allows a more direct performance comparison of the two machine forms. As shown in table 2, the energy and power densities of the rotating shell compulsator are about 4 and 8 times those of the internal rotor machines, respectively.

Table 2. Rotating shell compulsator characteristics and predicted performance

PARAMETER	UNITS	VALUE
Machine Diameter	m	0.96
Machine Length	m	1.6
Mass	kg	2,759
Volume	m^3	1.3
Maximum Speed	rpm	12,000
Rotor Kinetic Energy	MJ	132
Peak Power Rating	GW	14.3
Energy Storage Density	kJ/kg	47.8
Peak Power Density	kW/kg	5,216

Key Design Issues

Although the rotating shell compulsator concept offers substantial gains in lightweight, compact pulsed power supplies, certain technical challenges remain to be overcome. Support bearing design is complicated by high radial growth, and rotor dynamics are dominated by the rotor end plates which must be relatively compliant to match the spin growth of the shell rotor. Because the shell rotor is more susceptible to ovalling under discharge loading, a 4 or 6 pole design may be needed to make the magnetic discharge pressure on the rotor bore more uniform. In this case, a multi-phase machine would allow tailoring of the pulse shape and length by switching phases to construct the desired waveform. Transmission of the stator discharge torque to ground requires either a large diameter stationary shaft which implies very large journal bearings, or a torsionally compliant mount which allows the stator to rotate under discharge loading.

Acknowledgments

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