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Abstract - A limitation of iron-core homopolar generators (HPG) is that the magnetic field strength and thus terminal voltage of the generator is dependent on the saturation limit of the material in the magnetic flux path. The Center for Electromechanics at The University of Texas at Austin (CEM-UT), in cooperation with GA Technologies, Inc. in San Diego, California, has designed and fabricated a 500 V, 500,000 A, 3.25 MJ, air-core pulsed homopolar generator. GA Technologies designed and constructed the 5 T, superconducting, solenoidal field coil. The stator subassembly, consisting of the rotor, bearings, stator, and output current conductors was designed and fabricated at CEM-UT.

This experimental machine will be the first pulsed HPG with a superconducting field coil. Aspects of the machine design as well as the machine test program are discussed. Brushgear and bearing performance in high magnetic fields are also covered.

INTRODUCTION

Pulsed, high-current, high-energy electrical power supplies, with various scientific, commercial and military applications, have been under development at the CEM-UT for over 13 years. One type of power supply, the pulsed HPG, has been extensively studied with operating prototypes designed and fabricated by CEM-UT to demonstrate significant technical achievements in defining the state of the art for the machines[1]. Because of their high output current (MA) and high peak power output (tens to hundreds of MW), HPGs have been identified as candidate power supplies for electromagnetic launchers (EML).

For present-day iron-core HPGs to drive EMLs, power conditioning equipment, typically an energy storage inductor and circuit opening switch is required. HPG charged inductor[2] and opening switch systems have been designed and built, but to date, repetitive, reusable opening switches have yet to perform at current and voltage levels desired by the EML community[3].

HPG terminal voltages in excess of those on typical iron-core machines (20 to 100 V) are required if an HPG is to directly power an EML. Terminal voltage may be increased by building an air-core HPG with magnetic-flux densities greater than those which can be achieved in iron at saturation (about 2.0 T). The limiting factors for increasing the terminal voltage then become;

- the maximum average magnetic-flux density developed by the field coil at its structural and electromagnetic limits,
- the number of voltage-generating, electrically-isolated, series-connected rotors,
- the maximum field or field gradient in which the brushes may operate,
- the area of each rotor which couples the induced magnetic field,
- and the maximum speed, within their mechanical limits, at which the rotors may rotate.

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The high voltage homopolar generator (HVHPG) was proposed as an experiment to explore the techniques and demonstrate the technology required to build HPGs which may directly drive EMLs. After design, fabrication, and experimental verification of the machine performance, several of these machine modules could be built and connected together electrically, or a single large machine built to result in an HVHPG power supply optimized for an EML.

Design goals for the HVHPG include;

- open circuit voltage of 500 V,
- peak output current of 500 kA,
- 3.25 MJ of stored inertial energy, and
- average magnetic-flux density of 5 T.

This high-voltage, high-current, low-capacitance machine will be a valuable experiment for air-core machines and a new addition to the pulsed-power community.

HVHPG DESIGN CONSIDERATIONS

Parametric Study

To achieve the stated design goals of the project, a parametric study of many machine configurations was performed. Number, size, and possible geometries of the rotors were tabulated and qualitatively evaluated on the basis of electrical performance, mechanical integrity, simplicity, fabrication, and impact on the design of other hardware in the machine. A single shaft, four-pass rotor assembly was chosen (Table 1,2) over other designs because it;

- required only one set of radial bearings,
- made four current passes through the magnetic field, at 125 V/pass, combined to produce 500 V,
- did not require current crossovers between the voltage generating rotors,
- with a 0.318 m (12.5 in.) major radius, it could be fabricated with machinery readily available to CEM-UT,
- was relatively simple to electrically insulate between rotors, and
- had an acceptable stress state in the rotors at full speed and full discharge current.

Table 1. Operating parameters for the HVHPG

Description	Value	Units
Terminal Voltage.....	500	V
Equivalent Capacitance.....	26	F
Internal Resistance.....	See Table 2	
Internal Inductance.....	See Table 2	
Maximum Rotor Speed.....	6,627	rev/min
Maximum Slip Ring Speed (outer brushes).....	220	m/s
Rotor Mass Moment of Inertia.....	13.5	kg·m ²
Maximum Stored Energy.....	3.25	MJ
Maximum Output Current.....	500	kA
Maximum Average Field Strength.....	5	Wb/m ² (T)
Average Current Density in the Coil [4].....	4.3x10 ³	A/cm ²
Stored Energy in the Coil [4].....	12	MJ

Table 2. HVHPG transient electrical characteristics.

<i>Time to Peak Current (ms)</i>	<i>1</i>	<i>10</i>	<i>12</i>
Inductance (without load, 10^{-9} H)	34.5	46.5	49.0
Resistance (without brushes, $\mu\Omega$)	30.0	26.3	25.0
<i>Machine Output Current (kA)</i>	<i>250</i>	<i>400</i>	<i>500</i>
Brush Set Resistance for:			
One Pass ($\mu\Omega$)	5.9	4.8	4.0
Four Passes ($\mu\Omega$)	23.6	19.0	16.0

Mechanical / Magnetic Interface

The HVHPG was designed as two major component assemblies (Fig. 1). They are the stator subassembly (SSA), and the superconducting field coil[4]. Given the nature of the joint project, with GA building the magnet and CEM-UT building the stator subassembly, it was agreed that the two components be mechanically independent to simplify the task of assembling the SSA into the field coil. Alignment of the SSA concentric to the magnetic axis of the field coil would then be facilitated by a 6.4 mm (0.25 in.) radial mechanical clearance between the SSA and field coil and the SSA positioned by alignment screws with respect to the coil.

High Field Implications

Two major concerns of operating the SSA in the 5 T magnetic field were the electromagnetic effects on the performance of the output current carrying brushgear and bearing systems. The bearings, if uninsulated, would act as small homopolar machines. Voltages generated can be as high as 300 mV to 10 V for the radial and thrust bearings, respectively. For the brushes, any significant radial magnetic fields would induce circulating currents between adjacent brushes. These problems were addressed utilizing insulating ceramics in the bearings and designing the field coil[4] so there is no potential greater than 1 V across any slip ring (Fig. 2).

Operation of the machine in a laboratory environment also had to be considered. Flux plots (results of which are condensed in Table 3) of the far magnetic fields produced by the superconducting magnet showed the HVHPG could not be located within the lab because of the adverse effects it would have on auxiliary systems, instrumentation and control systems, and any ferromagnetic equipment located nearby. In addition, a significant mass of ferromagnetic material in the vicinity of the coil could cause unacceptable magnetic field perturbations in the region of the rotor, inducing parasitic eddy current losses in the rotor while motoring, and excessive loads on the coil support structure. A location outside the lab with good overhead lifting capacity was chosen with a concrete mount fabricated from nonferromagnetic material.

Electric Motoring

Motoring the rotor to full speed is to be accomplished by utilizing a portion of one of the main rotors as a homopolar motor. With the coil at full field, 600 A from an external, direct-current power supply will be passed through the rotor with a set of motoring brushgear. The rotor assembly will then be accelerated to full speed in about 120 s. Electric motoring was chosen over a mechanical motoring system because, like the bearings in the HVHPG, any rotating, conductive components operating in the high magnetic fields would themselves become small HPGs. Consequently, catastrophic damage could be caused by arc-pitting of moving parts in a mechanical motor.

Test Program

Testing of the HVHPG will advance in three stages. First, tests on the bearings, insulation, and brush actuation systems will be made in the absence of any magnetic fields. Flow rate and temperature rise of the bearing lubricant will be monitored and break-away torque of the rotor shaft will be measured. The brush actuation circuit will be pressurized, checked for leaks and the actuation time recorded for input into the timing of the machine discharge sequence. High voltage tests of the insulation in the machine discharge circuit will be performed at all stages of assembly to insure that no shorts between voltage generating sources occur.

Next, with the field coil incrementally energized to full excitation, break-away torque measurements of the bearings will again be performed. Electric motoring hardware will be tested by running current through the motoring rotor, accelerating to relatively low speeds while measuring the corresponding acceleration rates and comparing them to the predicted performance.

Last, the machine will be motored to full speed in increments of 500 r/min. At each increment, the brushes will be actuated, and the machine discharged into a resistive load through an explosive-closing switch. During the motoring and discharge sequences, transient measurements of the HPG voltage, output current, rotor speed, and rotor displacements will be recorded.

STATOR SUBASSEMBLY COMPONENT DESIGNS

Major components in the SSA include the stator, mount, hydrostatic bearings, brushgear, test load, rotor assembly, associated auxiliary systems and instrumentation hardware. The following is a discussion of some of the details of the design and performance of each. Refer to Figure 1 for a cross-sectional illustration of the various machine components.

Stator

The stator is a two-piece, cylindrical structure, divided in a plane along its cylindrical axis, and machined from two large 5052 aluminum billets. Alignment of the split halves is maintained by six aluminum-bronze dowel pins and secured in position by four, 3.8 cm (1.5 in.) diameter Monel K-500® bolts adjacent to the bearing housings. Air-feed manifolds are drilled into each half of the stator to provide air to actuate the brush mechanisms. Figure 3 shows the SSA in the final assembly stage with the brushgear and compensating-turn conductors (CTC) mounted to the fiberglass insulating shells.

In addition to providing structural support for the brushgear and other components in the SSA, the stator is the return current path for the machine. During the discharge, the output current seeks the path of minimum inductance and flows along the surface of the aluminum stator closest to the CTCs. Varying with the pulse width of the discharge, the current diffuses into the skin of the stator at a predictable rate[5] and affects the resistance and inductance of the machine as listed in Table 2.

Mount Structure

As stated in the Mechanical / Magnetic Interface section, the SSA and the field coil are independently mounted to a concrete foundation. This foundation elevates the HVHPG 1.22 m (48 in.) above the iron reinforced concrete in the area. Reinforcement for the foundation is provided with 13 mm (0.5 in.) stainless-steel rods placed on 0.3 m (12 in.) centers in a three-dimensional grid. A welded stainless-steel framework, constructed of plates and tubing and cast with the foundation, is drilled and tapped so that

Fig. 1. Cross section of the HVHPG.

Fig. 2. Contour map of vector-magnetic potential for the thrust bearing end of the HVHPG; first iteration on coil design.

Fig. 3. Stator half with brushgear installed; before final assembly of the SSA.

the SSA may be bolted directly to the foundation. The foundation dimensions were chosen to withstand the peak discharge torque and to act as a substantial seismic mass (totaling 22,700 kg (50,000 lb)) for dynamic stiffness considerations.

Endplates to support the stator from the foundation were fabricated of 38 mm (1.5 in.) stainless steel plate material welded together to provide acceptable radial and axial dynamic stiffness. These plates are doweled as well as bolted to either end of the stator.

Mounting of the field coil will be made directly to anchor bolts cast in the concrete foundation. After the field coil is placed and positioned on the foundation, the SSA is inserted into the coil, its endplates bolted on, and the SSA aligned relative to the magnetic axis of the coil. Once the alignment is verified, non-shrinking grout will be pumped under the mounting surfaces and allowed to cure. After the grout cures, the SSA and field coil will be securely bolted into their positions.

Table 3. HVHPG far-field magnetic-flux densities.

Axial Distance to Coil Center (m)	5.4	6.4	8.4	11.3
Flux Density (G)	82.4	48.3	20.2	7.5
Radial Distance to Coil Center (m)	5.3	6.6	9.3	13.2
Flux Density (G)	41.3	21.1	8.0	3.3

Hydrostatic Bearings

Bearings for the HVHPG are orifice-compensated, externally-pressurized hydrostatic type. Both radial bearings have six circumferential pockets, and a radial clearance of 0.076 mm (0.003 in.) with the shaft. The thrust bearing has four pockets per side and an axial clearance of 0.102 mm (0.004 in.) per side. Radial and thrust bearings operate at 210 bar (3,000 psi) supply pressure. Table 4 lists the flow rates and power consumption for each bearing.

Insulating ceramics were used to avoid arc-pitting in the bearings from homopolar effects. For the radial bearings, a layer of aluminum oxide was plasma sprayed to a thickness of 0.38 mm (0.015 in.) on the journal and seal surfaces. After spraying, the ceramic coatings were diamond-ground to their final dimensions.

Axial electromagnetic loads developed during the discharge will be constrained by a thrust disk made of 99.5% aluminum oxide. It is 38.1 mm (1.5 in.) thick by 178 mm (7.0 in.) in diameter. In addition to its electrical insulating properties, the ceramic has a higher elastic modulus than stainless steel so it is correspondingly thinner.

Table 4. HVHPG hydrostatic bearing operating characteristics.

Parameter:	Flow Rate	Friction Drag	Pump Power	Total Power
Units:	l/min (gal/min)	kW (hp)	kW (hp)	kW (hp)
Radial (each)	42 (12)	10.4 (14.0)	15.7 (21.0)	26.1 (35.0)
Thrust	84 (24)	23.9 (32.0)	31.4 (42.0)	55.2 (74.0)

Brushgear, Compensating-Turn Conductors, and Stator Insulation

Main Brushgear. A high-current-carrying brushgear design, developed in the CHPG program^[1], was adapted to this machine. Table 5 lists some statistics about the brushgear.

Because of the air-core nature of the HVHPG, the brushgear must operate in the 5 T magnetic field. Induced circulating currents between brushes were avoided with a field coil design that minimized radial magnetic fields in the region of the brushgear. Another electromagnetic interaction is a Lorenz force ($\mathbf{J} \times \mathbf{B}$), with a radial component, occurring between the current in the brush straps and the main field of the machine. Use of current compensating straps in the inner brush mechanisms will cancel the radially outward $\mathbf{J} \times \mathbf{B}$ force in them while the outer brushes will be uncompensated to take advantage of the radially inward $\mathbf{J} \times \mathbf{B}$ force to help keep the brushes actuated.

Table 5. Brushgear statistics for the HVHPG.

Description	Inner Brushes	Outer Brushes
Number of Brush Sets.....	4	4
Number of Brushes in a Set.....	168	200
Brush Contact Area, cm ² (in. ²).....	2.1 (0.328)	2.1 (0.328)
Brush Current Density at 500 kA, kA/cm ² (kA/in ²).....	1.4 (9.1)	1.2 (7.6)
Slip Ring Current Density at 500 kA, kA/cm ² (kA/in ²).....	0.6 (3.8)	0.4 (2.5)
Maximum Slip Ring Speed m/s (ft/s).....	106 (348)	220 (722)

Output current compensation occurs in the CTCs. The CTCs are machined from monolithic copper forgings and serve as current collection rings for the brushgear as well as air manifolds for supplying air to the brush actuators. Stainless-steel plates, molded into fiberglass/epoxy insulating shells and glued into the stator halves, transmit the discharge torque developed in the CTCs to the stator. The CTCs are bolted and doweled to the stainless plates and are insulated from the stator by the epoxy/fiberglass insulating shell.

Together, the four inner/outer brush mechanism sets electrically connect the four insulated aluminum rotors electrically in series. As stated earlier, the stator is the return path for the output current, and is connected to the rotor by the first outer brush mechanism at the thrust bearing end of the machine. This mechanism is bolted directly to the aluminum of the stator to make the electrical contact. At the opposite end of the machine, the output current is conducted from the last inner brush mechanism to 18, 25.4 mm (1.0 in.) diameter copper bars which pass through and are insulated from the stator. Output current from the machine is passed from these terminal bars to the load and returned to the stator.

Motoring Brushgear. Electric motoring current is supplied to the motoring rotor via an independent set of motoring brushgear. One face on the rotor at the thrust-bearing end of the machine has two copper-coated motoring slip rings. Eight motoring brushes are used on each of the motoring slip rings and current is conducted to the motoring brush collector rings by four insulated copper bars per ring. The motoring brushes are permanently actuated against the slip rings with a pair of coil springs at the back of each brush strap. Approximately 120 s are required to accelerate the rotor assembly to full speed with a motoring current of 600 A.

Rotor Assembly

A single-shaft, four-pass rotor assembly (rotor) is the voltage-generating portion of the HPG. It is fabricated of four top-hat-shaped, 7050 T736, aluminum rotors shrunk-fit onto a 316L stainless-steel shaft. All five pieces of the assembly are insulated from each other with a 0.38 mm (0.015 in.) thick, plasma sprayed aluminum oxide coating. The rotors were coated on their inside diameters and a portion of either face. The shaft was coated on its major diameter, bearing sump seal surfaces, and journal bearing surfaces. Applying the coatings in this manner provides a minimum of two insulation layers between any two parts and prevents anomalies at any point in one layer from causing a short.

Each of the four rotors and the shaft were machined and sprayed with the ceramic. Afterwards, the ceramic coatings were precisely ground so that there would be a 0.318 mm (0.013 in.) radial interference between the shaft and rotors after the shrink-fit assembly. The four rotors were then stacked and aligned relative to each other and clamped in position. They were then heated to 150°C (300°F) in a forced convection oven and the shaft cooled to -200°C (-320°F) and allowed to thermally stabilize. After stabilization, the shaft was lowered into the rotors until it reached a mechanical axial locating stop. The maximum stress developed by the interference fit occurs in the bore of the rotors at zero speed. A Von Mises equivalent stress of 214 MPa (31,000 psi) was calculated and is 53% of the minimum yield of the aluminum.

A final machining operation prepared the rotor assembly for application of a 0.38 mm (0.015 in.) thick, plasma-sprayed copper coating to be applied to the slip ring surfaces. This coating was chosen to enhance the performance of the Morganite® CM-1S brushes^[6]. Figure 4 shows the rotor assembly during final machining of the copper slip ring coatings, before final assembly of the SSA.

Fig. 4. Rotor Assembly during final machining; before final assembly of the SSA.

HVHPG Experiment Test Load

A resistive test load with an explosive circuit closing switch was designed to simulate the electromagnetic characteristics of an EML directly connected to the output of the machine. The current rise associated with a projectile injected into the "hot" rails of an EML will be simulated by actuating an explosively driven closing switch into a load with a resistance of $700 \mu\Omega$ and inductance of 200 nH . An explosive closing switch is required because the main brushes actuate too slowly (full contact achieved in about 10 ms) compared to the rise time-to-peak current for the machine (as fast as $500 \mu\text{s}$) directly connected to an EML. The explosive switch requires about $60 \pm 10 \mu\text{s}$ to close and prevents arc-damage of the main brushes because they are not used as closing switches. Figure 5 shows the cross section of the explosive closing switch, the coaxial stainless steel resistive load, and the aluminum plates connecting the load to the output terminals of the machine.

Fig. 5. Cross section of the explosive closing switch, coaxial resistive load, and buswork.

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