COMPACT HOMOPOLAR GENERATOR DEVELOPMENT AT CEM-UT

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Presented at the
2nd IEEE Symposium on
Electromagnetic Launch Technology
Boston, Massachusetts
October 11-14, 1983

Publication No. PR-22
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Summary

For electromagnetic launchers (EMLs) to become practical devices, they must evolve from laboratory test beds to field-portable systems. Such systems require the development of compact, lightweight, high-energy, high-current power supplies. Investigation of the candidate systems -- flux compressors, capacitors, inductors, batteries, and rotating machines -- showed the homopolar generator (HPG) to be a device with immediate potential for development. HPGs were selected because of their demonstrated ability to produce the high-energy, high-current electrical pulse required of an EML power supply from a relatively compact lightweight machine. By taking state-of-the-art HPG technology and integrating it with a machine designed specifically for high energy density, a field-portable HPG-powered EML system can be realized.

Introduction

For several years, The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has been engaged in the development of a field-portable EML system. The initial step in developing a field-portable system was to design, fabricate and test a prototype homopolar generator (Fig. 1) which would significantly improve the state of the art in energy and power density.[1] Begun in June of 1980 under the sponsorship of the U. S. Army Armament Research and Development Command (ARRADCOM) and the Defense Advanced Research Projects Agency (DARPA), the project was completed in August of 1982. Utilizing the compact HPG configuration, which minimizes stator iron, the prototype compact HPG inertially stores 6.2 MJ and weighs 3,400 lb_m. This represented a gain in energy density of at least a factor of two over previous HPGs. During the initial tests, the HPG generated a 1.02-MA current pulse, 270 kA more than rated. An analysis indicates that one of these machines will drive an 85-g projectile to 3 km/s in a 4-m gun, or a 10-g projectile to 10 km/s in a 5.5-m gun.

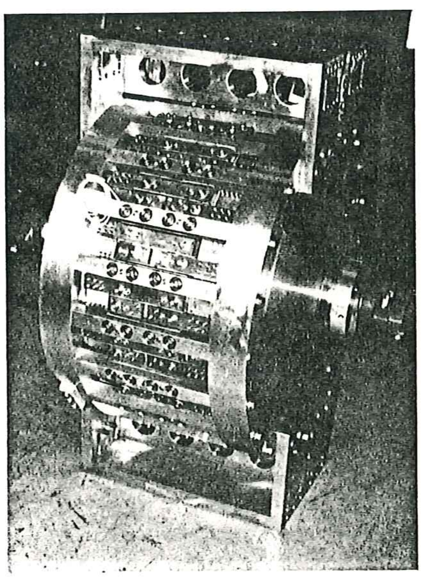


Fig. 1. Compact HPG

Field portability was demonstrated by mounting the compact HPG on a skid with its auxiliaries, which were driven by a single 200-hp electric motor. Replacement of this motor with a gas turbine or diesel engine would result in a field-portable system. This exercise revealed that even though the HPG is compact and lightweight, the size and mass of the system is dominated by auxiliaries. For a truly field-portable system, auxiliaries must be high-performance, pulse-rated devices integrated with the HPG and the host vehicle.

The Center for Electromechanics has continued this program to develop high-energy-density, high-performance HPGs for EML applications. The prototype machine has been upgraded to a current rating of 1.5 MA with improved brushes and thicker conductors. A 3,000 lb_m, liquid nitrogen-cooled, aluminum inductor rated to store 3.1 MJ at 1.0 MA was built to provide power conditioning for the launcher. Tests are presently being run with the HPG charging the inductor to determine the energy transfer efficiency, the effect of the HPG rotor reversal on current collectors, and the degree of HPG armature reaction. A single-shot reusable diverter switch is also under development to complete the power supply. The diverter switch effort is being funded by NASA.

In a parallel effort, an HPG system tester has been built and used to develop components needed to further improve the HPG's performance and energy density. These components include brushes designed to operate at high current density and low voltage drops, and stationary-shaft hydrostatic bearings which have the potential to triple the energy density of the compact HPG prototype. The systems tester will also be used to investigate both brush and bearing performances at higher rotational speeds. Faster spinning of the HPG rotor is the most direct method of improving energy density.

Both the compact HPG/inductor system and the HPG systems tester are experimental devices designed to advance the state of the HPG art. These systems are also being tested to determine performance limits to ultimately provide a technology base to support the continuing evolution of electromagnetic launchers.

Prototype Compact HPG

For EML technology to evolve, the community needs a compact, high-performance, relatively inexpensive power supply to drive a variety of EML experiments. CEM-UT is attempting to provide this power supply by developing the compact HPG with an inductor and opening switch for power conditioning. The compact HPG (Fig. 2) was successfully tested in August of 1982 and has subsequently been upgraded. To provide power conditioning, a matched inductor was built, and the second test sequence for the machine is now underway. Because of the successful performance of the machine and the demands of the community, The University of Texas at Austin has licensed an industrial company to produce the machine and the first units are now being completed for sale.

Table 1 summarizes the design parameters of the generator. In the initial tests during August 1982, these design goals were either reached or exceeded. The rotor was motored to 6,400 rpm, slightly faster than the 6,250-rpm design speed, in two minutes and stored 6.5 MJ inertially at this higher speed. Because of a current constriction in the dump resistor load, the maximum energy transferred (4.7 MJ) was from 5,450

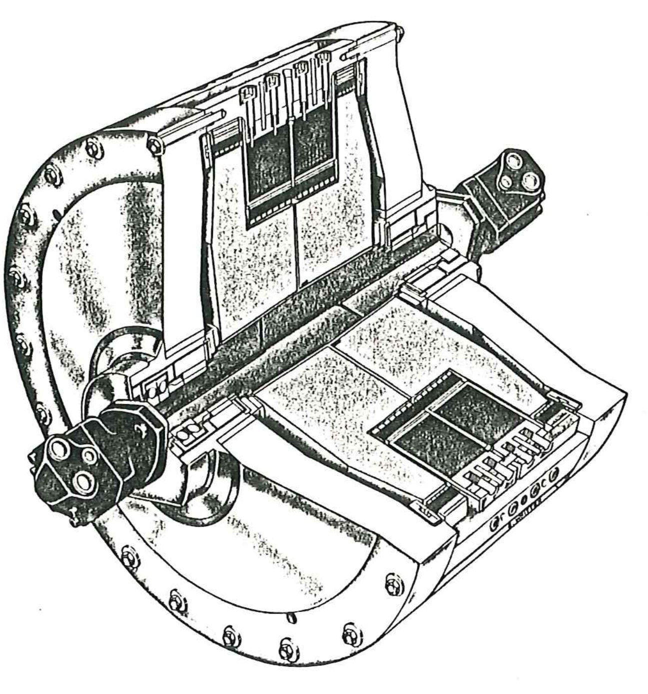


Fig. 2. Section through compact HPG
Drawing courtesy of OIME, Inc.

Table 1. Dimensions and performance parameters of the compact homopolar generator

Stored energy	- 6.2 MJ at 6,245 rpm
Terminal voltage	- 50 V at 6,245 rpm
Effective machine capacitance	- 4,960 F
Internal resistance	- 7.5 μΩ
Internal inductance	- 30 nH
Rated discharge current	- 750 kA
Total generator weight	- 1,545 kg (3,400 lb_m)
Peak discharge torque (at rated current)	- 61,000 N•m (45,000 $ft \cdot lb_f$)

rpm during a 370-kA discharge. In a short-circuit test from 1,360 rpm, however, the machine generated 1.02 MA, 36 percent higher than the design level. At this current level and with the fast current rise time (15 ms to peak), the internal resistance was 10 μΩ. There was no significant armature reaction. The experimental machine components --including rolling-element bearings, disassembleable rotor, pulsed field coils, and a combined current-collection and making-switch system --all performed successfully.

To summarize the initial test results:

- 74 discharges were completed.
- Mechanically, the machine performed as designed. The rotor was motored to 6,400 rpm -- 150 rpm faster than rated -- in 2 min, as designed. No bearing problems due to stray magnetic fields were encountered.
- 1.02 MA -- 270 kA more than rated -- were generated from 1,360 rpm.
- From 5,450 rpm (4.7 MJ stored in the rotor) 370 kA were generated. The load voltage was 34 V. This was the highest-energy discharge.
- A 1.75-T magnetic field resulted from 432 A in the pulsed field coil. An open-circuit voltage of 47 V at 6,250 rpm was extrapolated at this field level. It should be possible to reach the design field level of 2.0 T by increasing the power supply output. A 600-A excitation current was achieved during initial field coil tests.
- The inflatable brush actuators continued to work throughout the tests, even though several of the actuators were later found to have ruptured.
- An internal resistance of 10.9 μΩ -- 3.4 μΩ more than estimated -- was calculated for a 750-kA discharge. This difference was a result of the current's not penetrating into the rotor because of the fast rise time. For a fully penetrated rotor, a 5.75-μΩ internal resistance is estimated, based on data for a 1.02-MA discharge.

The detailed design[1] and initial test results[2] for the compact HPG have previously been presented. During the past year, the machine has been upgraded and a 3,000 lb_m liquid nitrogen-cooled trapped-field inductor[3] has been built to provide an appropriate test load for the HPG and power conditioning for the future EML facility. The inductor was designed to store 3.1 MJ at 1.0 MA. To upgrade the machine, a complete new set of current collectors and armature conductors have been fabricated. An inexpensive, reliable brush actuator, which operates at twice the force and stroke of the original actuator, has been developed. A reliable, repetitive process for fabricating the trailing arm brush assembly resulted in improved fabrication tolerances which should ultimately improve brush performance -- the brushes now contact the slip ring over their entire faces as opposed to ~ 50 percent contact on the first test. To complete the upgrade, a 400-hp hydraulic system was installed in the laboratory; a microprocessor-based data acquisition system was integrated with the machine controller; and a new machine mount that supports the HPG and inductor was built. The HPG and inductor being assembled on the new mount is shown in Fig. 3.

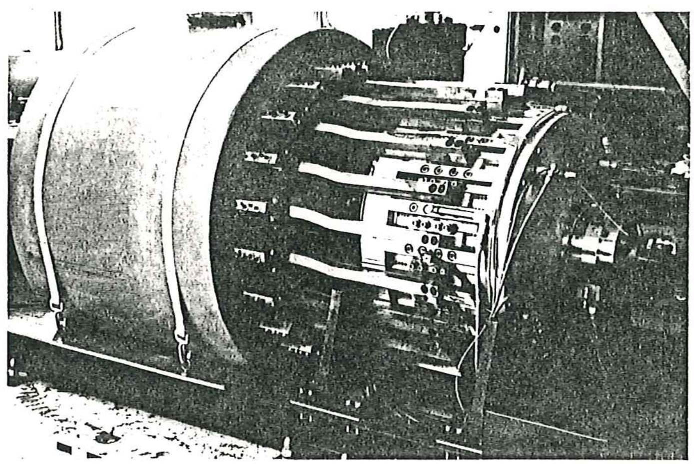


Fig. 3. Upgraded HPG and coaxial inductor in the final stage of assembly

During the second test sequence, now underway, the machine will first be discharged into the inductor before it has been cooled. With the fivefold increase in resistance of the inductor from 6.2 μΩ to 30 μΩ which results with a room temperature coil, a 750-kA transfer current is predicted. This will result in approximately 1.7 MJ being stored in the 6.2-μΩ inductor. Because an opening switch is not available to transfer the current from the inductor into a railgun load, the underdamped HPG/inductor circuit will result in the inductor's ringing back into the HPG, driving the rotor in the reverse direction. With an uncooled inductor at a 750-kA transfer current, it is anticipated that the rotor will ring back up to 1,500 rpm. Although analysis of the trailing arm brush straps indicates that there should be no structural problems with rotor

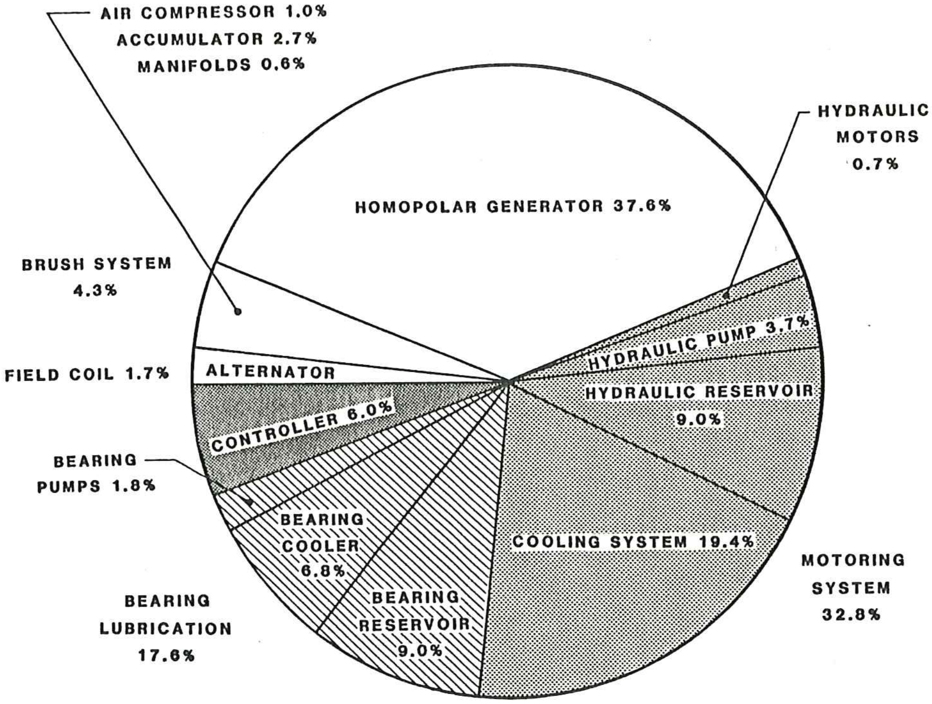


Fig. 4. Contribution of subsystems to HPG system volume

reversal, rotor reversal can be controlled if required by driving the magnetic field down, thus increasing the HPG capacitance and resulting in an overdamped circuit.

After discharging into the uncooled coil, the inductor will be cooled with liquid nitrogen and the tests will be repeated. A 1.0-MA transfer current is anticipated which will result in 3.1 MJ being stored in the inductor, representing a 50 percent transfer of energy from the HPG. These tests will result in the HPG rotor being driven to 3,000 rpm in the reverse direction if magnetic field control is not implemented.

At this point, if inductor tests are successful and an opening switch has not been realized, the inductor will be replaced by dump resistors as a load, and high-current tests will be performed. The resistors have been designed so that a discharge current of 1.5 MA will be achieved from 5,000 rpm (41 V, 4.3 MJ). This is twice the original design current and is the goal of the HPG upgrade.

A program is underway to develop a diverter switch and an EM railgun. These components will be matched to the compact HPG/inductor and will provide a test bed for EML experiments at CEM-UT.

Auxiliary Systems

The size and weight of the auxiliaries significantly affect the overall energy density of an HPG-powered EML system. Auxiliary systems are required for motoring, bearing lubrication, field coil excitation and brush actuation. As shown in Fig. 4, the auxiliaries occupied 62 percent of the system volume in the initial compact HPG machine configuration, in which the HPG and auxiliaries were mounted on a common skid. A single 200-hp electric motor drove all of the auxiliary systems.

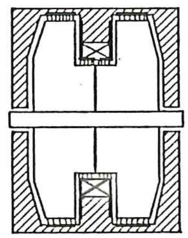
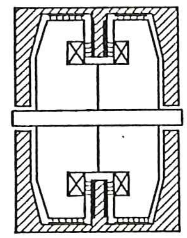
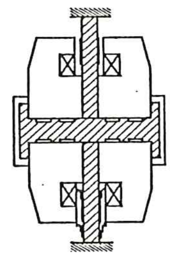
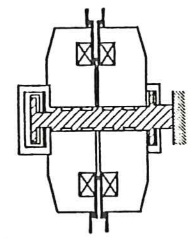
Several approaches can be taken to decrease the volume and weight of the auxiliaries. First, the auxiliaries should be designed for the specific application. For example, the compact HPG takes two minutes to motor to speed and a few seconds to discharge. For its discharge cycle, the HPG is rated at a power level many times that of a conventional electrical machine of similar size. The auxiliaries, because they are off-the-shelf commercial devices, are rated for steady-state, full-speed operation. Therefore, for pulsed systems, high-performance, pulsed auxiliaries are needed. Next, if a field-portable application is being considered, the auxiliaries must be integrated with the host vehicle engine and power take-offs must be provided. Finally, the auxiliary systems must be combined and integrated into the HPG itself. Examples are self-excited machines, power take-offs from the HPG shaft, and integrated hydraulic systems. Although these tasks can certainly be accomplished, they are not currently being addressed, and opportunities for significant improvement of overall system energy density remain.

HPG Systems Tester

For HPG-powered EML systems to continue to evolve, development of individual components, such as HPG brushes and bearings, auxiliaries, inductors, and opening switches must continue. The compact HPG benefited greatly from HPG component development which has occurred at CEM-UT over the past ten years in connection with industrial and energy-related projects. Therefore, in a parallel effort with the compact HPG power supply program, an HPG systems tester[4,5] has been designed and built to provide a facility for development of components needed to further improve HPG power levels and energy densities.

The systems tester, as shown in Fig. 5, is one-half of a full-size counter-rotating HPG, storing 2.5 MJ at 6,900 rpm and generating 20 V. This machine, now entering its initial test phase, incorporates face brushes and a stationary-shaft hydrostatic bearing. These experimental concepts lead to new machine configurations in which higher proportions of the magnetic circuit rotate and support structures are reduced. The present compact HPG has a volumetric energy density of 17 MJ/m^3. By incorporating face brushes, stationary-shaft hydrostatic bearings and actuation of the brushes by axial movement of the rotor, an energy density of 60 MJ/m^3 is possible with no increase in rotor speed. Table 2 shows the gains in HPG energy density that

Table 2. Progression of energy density gains with additional technology required for each increase

	ARRADCOM/DARPA COMPACT HPG	SINGLE-ROTOR HPG w/FACE BRUSHES AND SPINNING FIELD COIL	COUNTERROTATING-ROTOR HPG w/FACE BRUSHES, AND STATIONARY SHAFT BEARINGS	COUNTERROTATING-ROTOR HPG w/FACE BRUSHES STATIONARY SHAFT BEARINGS AND ROTOR ACTUATION
				
VOLTAGE(V)	58	54.6	50	50
VOLUME * ENERGY DENSITY (MJ/m³)	16.9	26.5	45	60
REQUIRED TECHNOLOGY		FACE BRUSHES	STATIONARY SHAFT BEARINGS	ROTOR ACTUATION
GAIN IN ENERGY DENSITY (MJ/m³)		10	20	15

* ALL ROTORS OPERATING AT 250m/s
INCREASE IN ALLOWABLE OPERATING SPEED BENEFITS ALL DESIGNS EQUALLY.

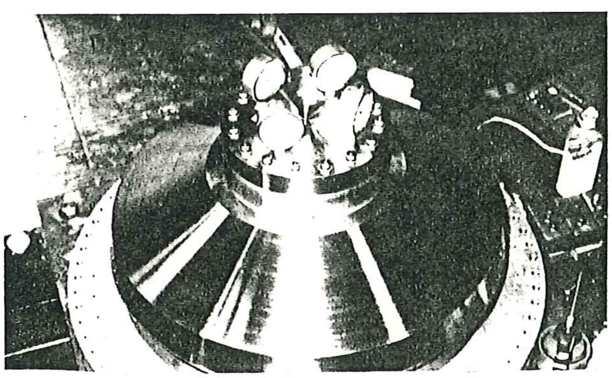


Fig. 5. Systems tester during final assembly

result from the successful development of these components. The systems tester will address face brushes and stationary-shaft bearings. In addition, the copper finger brushes that will be tested in a face brush configuration have the potential for decreasing brush voltage drop and increasing brush current densities. Brush finger current densities of 570 MA/m^2 (367 $kA/in.^2$)[6] have been achieved at low sliding speeds. Higher-current-density brushgear is necessary for transferring higher currents across the reduced slip ring areas of more compact machines. Finally, one of the easiest ways to increase HPG energy density is to spin the rotor faster. The systems tester will be used to evaluate brush and bearing performance at speeds above the present 220 m/s brush slip speed.

Conclusion

Tests have now begun on the experiments described in this paper. The compact HPG is being discharged into the lightweight inductor, which is uncooled for this initial test sequence. After completing inductor tests, in which the design goal is 3.1 MJ stored in the inductor at 1.0 MA, resistors will replace the inductor as a load and high-current (1-1/2-MA) tests will be conducted. Also, an opening switch has been designed and fabricated. Switch tests have begun, using the CEM-UT 10-MJ HPG as a power supply.[7] Finally, brush and bearing experiments on the systems tester have begun. Results of these experiments will dictate the path of CEM-UT's continuing program to develop an HPG EML power supply. An EML facility powered by the compact HPG is scheduled to be built during 1983-84. Component development on the system will continue in order to advance the state of the art and to provide a technology base to support the EML program.

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