ARRADCOM/DARPA
COMPACT HOMOPOLAR GENERATOR

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Introduction

If electromagnetic (EM) rail guns are to be used to propel substantial projectiles, large amounts of energy must be delivered in a fast, high-current pulse. Homopolar generators (HPGs) store megajoules (MJ) of energy in the inertia of a flywheel and then electromagnetically convert this energy into megaamp (MA) current pulses that typically have a duration between a thousandth of a second and a second. These machines appear to be the most likely power supply for military rail guns, space launchers, and other large EM propulsion schemes. However, HPGs now exist only as large prototype fixed installations. In order to serve as field power supplies, HPGs must be suitably designed for production, have reduced auxiliary requirements, and generate more power and store more energy per unit mass than the present generation of HPGs.

The Center for Electromechanics at the University of Texas at Austin (CEM-UT) conducted a study comparing various HPG operating schemes and machine configurations. The study concluded that R. A. Marshall's all-iron-rotating (AIR) concept (figure 1) in which most of the magnetic circuit is rotated, maximizing energy density, is the best HPG configuration for powering a military rail gun.

![Diagram](image)

Fig. 1. Basic geometry of the AIR homopolar generator
Energy densities up to 30 MJ/m\(^3\) for a 533 kg machine producing a 73-MW, 1.5-MA pulse appear feasible. These parameters represent substantial improvements in the areas of concern. In addition, improvements in compactness, weight, and simplicity inherent in the AIR concept should result in substantial cost reductions.

A contract has been awarded to CEM-UT by ARRADCOM to build a prototype AIR HPG in the 3-5-MJ range for a power supply for an experimental portable rail gun. The immediate project objective is to design a machine that is both an implementation of state-of-the-art technology in pulsed solid brushes and--due to by being more compact, lighter, and less dependent on auxiliary power supplies--portable. The long-range objective is to mount the generator on a truck and use it to power an experimental rail gun in the field. Another aspect of the contract is the development of a new face current collector. If successful, a counterrotating rotor AIR HPG with face brushes that are actuated by the magnetic attraction of the rotors can be designed. This machine would be torque-compensated, more powerful than the single-rotor AIR HPG, and because of simplified brush actuation, would represent a substantial reduction in complexity.

CEM-UT has successfully operated a 5-MJ, 0.56-MA HFG using pulsed solid brushes since 1974.\(^2\) The machine has been a reliable power supply for laboratory experiments.\(^3\) CEM-UT has developed state-of-the-art technology in the use of solid brushes for collecting and transferring large currents.\(^4\) In addition, all CEM-UT generators use room-temperature field coils, which are desirable for portable machines. These technologies are required for the successful development of the AIR compact, lightweight HPG power supply.

AIR Configuration

The AIR design is a new implementation of the basic HPG magnetic circuit. HPGs are usually voltage-limited and voltage is directly proportional to the operating magnetic-field level. Since the relative magnetic permeability of iron ranges from a few hundred to a few thousand times that of air, excitation-power requirements force most HPGs to be
built of ferromagnetic material. The magnetic circuit for a ferromagnetic (iron-cored) HPG can be thought of as a simple solenoid of insulated copper or aluminum conductor imbedded in an iron or steel cylinder as shown in figure 2. In order to use the magnetic material most efficiently, it is generally constructed in a "constant flux density" configuration such that the area in the base of the solenoid, \( A_1 \), is the same as the cross-sectional area of one side-plate \( A_S \) and also the same as the area of material on the outside of the solenoid, \( A_0 \).

Fig. 2. Basic magnetic circuit for homopolar generator.
This basic magnetic circuit may now be divided as shown in figure 3 into a disc rotor and a larger stator or "back iron" whose function is to return the magnetic flux from one side of the rotor to the other. This is the disc HPG that is typified by the 5-MJ HPG built by CEM-UT. It can be readily seen that this configuration uses relatively little of the ferromagnetic material to store energy inertially. In fact, although the CEM-UT 5-MJ HPG stores approximately 60 MJ/m³ in its rotor, its overall energy density including field coil, stator, bearings and brushes is only about 6 MJ/m³. However, this disc configuration does have the advantage of having the lowest effective capacitance, which gives it the advantage of offering the fastest discharge time of any HPG rotor configuration.

Fig 3. Magnetic circuit for disc homopolar generator
Figure 4 shows how the basic HPG magnetic circuit may be divided to generate the "drum" configuration that uses a larger percentage of the ferromagnetic material in which to store energy. The drum HPG offers higher overall energy density and efficiency at the expense of increased discharge time.

![Magnetic Circuit Diagram]

Fig. 4. Magnetic circuit for drum homopolar generator

The AIR configuration shown schematically in figure 5 offers a substantial increase in stored energy density at the expense of certain other performance parameters. Figure 5 illustrates that virtually all of the ferromagnetic material is used to store energy inertially in this configuration. The field coil in the AIR configuration may either be stationary or may be split and rotated with the two rotors.
Fig. 5. Magnetic circuit for all-iron-rotating homopolar generator

This HPG configuration was chosen for the portable rail gun power supply because of the importance of energy density in power supplies used for military rail-gun applications.

Preliminary Machine Design

Once the AIR concept had been selected a preliminary design effort identified problems, determined feasibility, machine size, and configuration. Two machines that use conventional solid brushes can be designed: a torque-compensated one with counterrotating rotors and one with a single rotor. Then, two other higher-performance machines can be visualized that incorporate the new CEM-UT face-brush mechanism, which uses many small, cantilevered copper fingers for contact.
CEM-UT pursued the design of a single-rotor machine using copper-graphite brushes (conservative) and a counterrotating rotor, face-brush machine (advanced). (See fig. 5.) All of the above machines advance HPG technology by use of the AIR concept, while the face-brush design advances component performance. By bracketing the AIR concept with an advanced and conservative design, insight into the advantages, disadvantages, and possible combinations of machines was obtained.

Table 1 summarizes the operating parameters of the HPG configurations developed during the preliminary design and compares them with the CEM-UT 5-MJ homopolar generator. The single-rotor AIR HPG (column 2) using brush technology developed at CEM-UT demonstrates a dramatic improvement in energy and power density over the existing CEM-UT 5-MJ HPG. The inclusion of the as yet unproven (at high speeds) CEM-UT proprietary face-brush mechanism into the counterrotating AIR HPG design (column 3) results in a further improvement in power and energy densities in a totally torque-compensated generator. (See fig. 5.) The dual values in the last two columns of table 1 indicate the developmental nature of the proposed program. The first values represent the conservative ratings when the machine is operated at a rotor surface speed of 200 m/sec, which is a practical limit imposed by state-of-the-art brush materials. The second figure represents the performance of 300 m/sec, which will be explored under controlled laboratory conditions. It is anticipated that the final "field rating" for the proposed HPG will be somewhere between these two values.

The single-rotor AIR machine can be built using today's technology. The counterrotating, face-brush AIR HPG requires a demonstration of the face-brush concept at high speeds and development of a high-speed bearing system capable of sustaining the high magnetic-attraction forces between the two rotors while remaining compatible with the field-portability requirement.
COUNTERROTATING ROTORS

SINGLE ROTOR

Fig. 5. A-I-R Concepts Selected for Preliminary Design
<table>
<thead>
<tr>
<th>Parameter</th>
<th>CEM-UT 5-MJ Disc HPG</th>
<th>Counter-rotating-rotor AIR HPG</th>
<th>Single-rotor AIR HPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored energy (MJ)</td>
<td>5</td>
<td>2/5</td>
<td>2.6/5.9</td>
</tr>
<tr>
<td>Open-circuit voltage (V)</td>
<td>42</td>
<td>35/55.5</td>
<td>32/49</td>
</tr>
<tr>
<td>Peak current (MA)</td>
<td>0.56</td>
<td>0.75/1.5</td>
<td>0.75/1.5</td>
</tr>
<tr>
<td>Peak power (MW)</td>
<td>12</td>
<td>26/83</td>
<td>24/73.5</td>
</tr>
<tr>
<td>Brush-current density (kA/cm²)</td>
<td>2.41</td>
<td>6.2/12.4</td>
<td>3/6</td>
</tr>
<tr>
<td>Collector-current density (kA/cm²)</td>
<td>.54</td>
<td>3.1/6.2</td>
<td>1.8/3.6</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>.83</td>
<td>.15</td>
<td>.20</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>7,150</td>
<td>444</td>
<td>533</td>
</tr>
<tr>
<td>Power/weight (kW/kg)</td>
<td>1.67</td>
<td>58/187</td>
<td>45/138</td>
</tr>
<tr>
<td>Power/volume (MW/m³)</td>
<td>14.45</td>
<td>173/553</td>
<td>120/367</td>
</tr>
<tr>
<td>Energy/weight (kJ/kg)</td>
<td>.7</td>
<td>4.5/11</td>
<td>4.9/11</td>
</tr>
<tr>
<td>Energy/volume (MJ/m³)</td>
<td>6</td>
<td>13/33</td>
<td>13/30</td>
</tr>
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</table>
Proposed Program

Construction of a single-rotor AIR HPG, using conventional copper-graphite rim brushes and commercially available bearings is a logical first step in implementing the AIR concept. The machine will demonstrate the concept and provide a compact powerful pulsed power supply suitable for field applications. By later building a second single-rotor machine and connecting the two machines with an energy storage inductor, which provides power conditioning and torque compensation, a portable, pulsed power supply for driving an electromagnetic rail gun would be obtained. In addition, the demonstration of the counterrotating rotor, face-brush machine components in a parallel effort would enable the evaluation of a second-generation AIR HPG. At this point, the concept would be fully investigated and development of overall electromagnetic propulsion systems could be intelligently pursued.

Rather than the 2-MJ (at 200-m/s rim speed) machine whose parameters appear in table 1, it has been proposed that a 3.5-MJ (at 200-m/s rim speed) machine be built. To demonstrate field portability this single-rotor AIR HPG would be mounted on a portable frame with its auxiliary systems (field generator and hydraulic pumps) belt-driven by an electric motor. In the event a true field demonstration or application was required at a later date, the auxiliary systems could be belt-driven from a vehicle engine. With a generator-only weight of about 600 kg, the machine will be designed to produce a 37-V, 750,000-amp pulse from a rotor-rim speed of 200 m/s. (See table 2.) It should be noted that from a rotor-rim speed of 300 m/s, the same machine stores 8 MJ and generates 56 V.

Although a counterrotating AIR HPG using CEM-UT face brushes has many attractive features, uncertainties concerning the bearing and collector performance cause this machine to be regarded as a second-generation AIR HPG. Therefore, while the single-rotor machine is being manufactured, a detailed design of an AIR systems test, modeling the counterrotating AIR face-brush machine will be completed. (See fig. 6.) The test consists of a single rotor from the proposed counterrotating machine with appropriate bearings, collectors, and field coils.
mounted on a stationary base. Systems to be tested include thrust bearings, which must withstand the large magnetic attraction; several face-collector schemes; armature reaction; and the field-penetration time constant. This research and development will significantly contribute to future HPG design efforts, demonstrating new concepts and solutions.

Fig. 6. AIR Systems Test
### TABLE 2
Proposed Single-rotor AIR HPG Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conservative rating (200 m/sec)</th>
<th>Advanced rating (300 m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated energy (MJ)</td>
<td>3.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Maximum voltage (V)</td>
<td>37</td>
<td>56</td>
</tr>
<tr>
<td>Maximum current (amps)</td>
<td>750,000</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Rotor diameter (m)</td>
<td>0.610</td>
<td>0.610</td>
</tr>
<tr>
<td>Estimated weight (kg)</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Energy/weight (kJ/kg)</td>
<td>5.8</td>
<td>13</td>
</tr>
</tbody>
</table>

**Conclusion**

Inertial energy storage with homopolar conversion provides the most suitable primary energy store for driving large EM rail guns. An assessment of the state-of-the-art of the various technologies relevant to pulsed HPG design, especially those limiting energy or power density was made. This evaluation concluded that HPG energy and power densities could be substantially improved by eliminating the back iron, which contributes to the mass of the machine but not the stored energy. Furthermore, by designing the current collection system to operate at higher current densities, substantial gains in power density and open-circuit voltage can be realized.

Using this background study as a guide, a comparison of various HPG operating schemes and machine configurations culminated in the selection of Marshall's AIR concept. The AIR concept is most promising in terms of energy and power densities, overall performance, and operating flexibility for interfacing with the EM rail gun. Energy densities of up to 30-MJ/m³ and power densities of up to 140-kW/kg in the AIR HPG appear feasible. These represent substantial improvements in the areas of concern.

Construction of a single rotor 3.5-MJ AIR HPG, using conventional copper-graphite rim brushes and commercially available bearings is a
logical first step in implementing the AIR concept. The machine would demonstrate the concept and provide a compact powerful pulsed power supply suitable for field applications. By connecting two such machines with an energy-storage inductor, which provides power conditioning and torque compensation, a portable pulsed power supply for driving an EM rail gun would result. The demonstration of the counterrotating rotor, face-brush machine components in a parallel effort will enable the evaluation of a second-generation AIR HPG. At this point, the concept will be investigated and overall development of large EM propulsion systems using HPGs in the field will be possible.

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References


