FABRICATION OF A COMPACT STORAGE INDUCTOR FOR RAILGUNS

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Summary

A liquid nitrogen-cooled, coaxial, energy storage inductor has been designed and built to be used in conjunction with a compact homopolar generator to form a high-energy-density power supply for use with electromagnetic accelerators.

The low-resistance, lightweight aluminum inductor stores 3.1 MJ at a peak current of 1.0 MA. Minimizing weight rather than size was emphasized in the design, resulting in a 1.23-m (48.6-in.) diameter by 0.91 m (36 in.) long inductor weighing 14.7 kN (3,300 lb). A coaxial design was chosen to eliminate high external magnetic fields without the necessity for shielding. External magnetic fields are undesirable because of effects on nearby components and the possibility of detection. Also, attention has been given to minimizing the partial flux linkages or internal inductance of the coil, thereby minimizing the overall transfer efficiency into a railgun. Details of the design, fabrication, and predicted performance will be presented.

Introduction

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has been involved in the development of electromagnetic accelerators (EM railguns) for several years. In January 1988, a program was started to develop a lightweight, high-current, high-energy-density power supply to drive a field-portable EM railgun. This program is being sponsored by the U.S. Army Armament Research and Development Command (ARADCOM) and the Defense Advanced Research Projects Agency (DARPA). The type of power supply chosen uses a homopolar generator (HPG) as the primary power supply. HPGs are high-current, compact machines. Because of their relatively long output pulse and low terminal voltage, HPGs thus far developed are not suitable for driving an EM railgun directly. This necessitates the use of an intermediate energy storage component, the inductor, and an opening switch to complete the EM railgun power supply.

The circuit configuration of the power supply and railgun is shown in Fig. 1. The HPG charges the inductor to a peak current of 1 MA in 0.25 s, at which time the opening switch S2 is opened, diverting current into the railgun. The inductor then discharges into the railgun in 2 to 4 ms. Because of the high d/dt imposed by the switch S2 and the large circuit inductance, a high voltage is available at the railgun terminals to initiate the arc. The inductor also acts as a current supply to the railgun, minimizing current droop as the back emf of the gun rises.

A major step in the development of the power supply has been accomplished with the successful design and testing of a compact HPG. The 3400-lb HPG developed at CEM-UT stores 6.2 MJ and has generated 1 MA. The next step was to develop a compact energy storage inductor for use in this system. This inductor has been successfully fabricated, and preliminary testing has begun. The 3,000-lb aluminum coaxial inductor, cooled with liquid nitrogen, is designed to store 3.1 MJ at a peak current of 1 MA. The terminals of the inductor can be configured for a five-turn 6.2 kA, or a four-turn 4.0 kA inductance. Because of the coaxial design, external fields are virtually eliminated, reducing EM interference with nearby components and the chance of EM detection. The coaxial inductor-HPG power supply is presented in Fig. 2.

Design

Because of the long charging time imposed by the HPG, the resistance of the coil and bus system must be minimized to keep IR losses to an acceptable level. The overall size and weight of the inductor must also be minimized to satisfy the field-portability requirement. This implies high magnetic fields and, therefore, high stress levels on the conductors. In this type of power supply, switching transients and railgun voltage appear across the conductor terminals, so the design should be capable of withstanding the highest anticipated circuit voltage.

For the purpose of analysis, the total inductance of the coil is divided into two components -- the inductances resulting from air-core flux linkages and the partial flux linkages (internal inductance) in the conductors. In the theoretical case of an instantaneous discharge, magnetic diffusion effects result in the energy in the partial flux linkages being trapped and dissipated in heating of the conductors rather than driving the railgun projectiles. For the rapid discharge into a railgun, about 4 ms, 70 percent of the energy stored in internal inductance is trapped. Therefore, the internal inductance must be minimized. Finally, the design must satisfy the constraint of eliminating external magnetic fields.

Fig. 1. EM railgun circuit with intermediate inductive energy store

Fig. 2. HPG-inductor power supply
Within the above constraints, the inductor design must be optimized as to overall system performance. This is defined as the ratio of energy stored in the HPG to kinetic energy imparted to the projectile. Several designs were tested, including those of Brooks coils, toroidal Bitter plates, and pie-segment configurations. This led to the choice of the five-turn coaxial inductor. The work leading to this design has been previously presented. An isometric view of the inductor is presented in Fig. 3. The 6.2-µH inductor has a 1.27-m (48.52-in.) outer diameter and a 0.91-m (35.75-in.) active length. Series 1100 aluminum was chosen as conductor material because of its very low resistivity at liquid nitrogen temperatures (3.4 x 10^-9 Ω-m) and its light weight. This alloy has a 3-cm (1.2-in.) skin depth at the charging frequency of 0.93 Hz. Weight constraints dictated that the conductors could not be this thick, however. The central conductors are composed of a solid 10.16-cm (4-in.) bar and four 2.54-cm (1-in.) thick concentric cylinders. The outer cylinders are 1.27 cm (0.5 in.) thick and are connected to the central coils by 1.27-cm (0.5-in.) thick end plates. Current is fed to the inductor by twenty pairs of 3.49-cm (1.38-in.) by 4.45-cm (1.75-in.) 1100 aluminum bars. These bars are bolted to twenty pairs of copper buses which connect the HPG to the inductor. The empty volume in the central inductor area is charged with liquid nitrogen. Output terminals for future connection to a switch and railgun are formed by coaxial flanges between the outer plate and the center bar.

The inductor is expected to operate at 1 kV, but has been designed to withstand 5 kV. The 0.32-cm (0.13-in.) insulating gap between conductors is vacuum impregnated with high-strength glass-filled epoxy. While this helps to increase the dielectric strength of the inductor, the epoxy is needed primarily for mechanical support. Magnetic fields and therefore magnetic pressures are highest on the inner conductors and decrease with the square of the radius. The direction of the magnetic forces is similar to the forces induced by changing the inner volume with a pressurized fluid. The inner coils are loaded inwards and are supported through compression of the epoxy layers to the center bar. The outer coils are in tension, although the magnetic pressure at this radius is only 1.40 MPa (200 psi), and the five coils with the inner support of the epoxy are able to withstand this load without the need for banding. The highest-stress area of the inductor is located on the end plates at their connection to the inner coils. This welded joint must support the end plate against the 15.2-MPa (2200-psi) magnetic pressure. To reinforce this region, the outer end plates are increased to 2.2 cm (0.88 in.) thick and are further supported by equally spaced (2.0-in) thick radial ribs. Also, a large interior welded fillet was used to reduce stress concentrations. The finite element analysis predicts a maximum deflection of 0.53 mm (0.021 in.).

Fabrication

The coaxial inductor configuration proved difficult to fabricate. The inductor is formed of five large-diameter outer coils, ten circular end plates, four small-diameter inner coils, and the center bar, all consisting of series 1100 aluminum. The outer coils were rolled from 2.54-cm (1.0-in.) thick plate. The coils were rolled by halves, trimmed, and joined together by two axial welds. A large steel spider was used to true the coils to the ± 0.64-cm (0.25-in.) tolerance required after welding. Two sets of 40 rectangular current-feed bars were machined from a solid 1100 aluminum billet 50 x 50 x 137 cm (20 x 20 x 54 in.) donated by the Aluminum Company of America, Rockdale, TX. End plates were turned from 2.54-cm (1-in.) plate, but because the diameter of the end plate was larger than the available stock of 1100 aluminum, the plates were welded from two semicircular sections.

The assembly scheme is shown in Fig. 4. The five-turn inductor is assembled beginning with the inner turn and proceeding outward. Since all joints between turns are welded, the assembly of the entire assembly proceeds. Surfaces were finished only after all welds had been completed. While this made the assembly much more time-consuming, it was the only method to ensure that the 0.32-cm (0.13-in.) insulating gap was maintained.

Coil assembly began by fabricating the inner turn or "bucket." This consisted of the appropriate inner and outer coils joined together by the bottom end plate. The outer current feed bars had been welded to the inner diameter of the outer coil. The top plate was welded to the inner coil, and the three completed exterior surfaces were machined to their final dimension. The second bucket, in which all interior surfaces had been finish machined, was then assembled over the inner coil (step 2) and the top plate was welded to the outer coil (step 3). NEMA type G-7 (glass fiber-reinforced silicone) spacers were used to maintain the correct separation between conductors. The spacers have a stepped cross-section to increase tracking distance. A glass fiber mat was also placed between all gaps to serve as reinforcing filler for the vacuum impregnated epoxy. The G-7 and mat were chosen due to their ability to withstand the temperature encountered near the welds. This is the reason why solid insulation could not be installed at the time of assembly. The last step in the assembly was to weld the next top plate to the inner coil (step 4). This process was repeated three times and then the center bar was installed, thus completing the inductor.

A major difficulty was encountered in determining the proper welding parameters for joining the 2.54-cm aluminum. The coil-to-plate welds carry rated current and must therefore be full-penetration welds to keep the resistance low. In addition, the welds at the inner coils see the most severe stress conditions--stresses as high as 90 percent of the yield strength of the material in the half-hard state--requiring that the welds be completely void-free to minimize stress concentrations. Since the top plates were
welded during final assembly of the inductor, the weld could not be allowed to burn through, possibly shorting to the inner turn. An automated GMA process was established using the joint preparation shown in Fig. 5 which satisfied these requirements. All welds were tested using x-ray and ultrasonic techniques.

The last major step in completing the inductor was the vacuum epoxy impregnation. The inductor geometry and size made this a difficult process. The first problem was to make a vacuum seal over the outside surface of the inductor. This was done by temporarily welding the outside plate to the outer current feedthroughs and to the outer coil. Another seal was required in the interior of the inductor to separate the "inner volume" from the area to be filled with epoxy. The inner volume refers to the void inside the inner turn which is to be charged with liquid nitrogen. This seal need not be vacuum tight but must stop the epoxy flow, and since it connects across a full turn, it must be insulated.

For the vacuum impregnation process it was decided to fill all the gaps between conductors in parallel rather than to flow epoxy around the long labyrinthine path in series. Holes through the end plates and coils were incorporated in the design to allow epoxy flow. The best impregnation results are generally obtained when the epoxy enters the low point of a mold and leaves at the highest. For this reason, the coil was tilted off the vertical axis by 30° to establish a true high and low point and to eliminate any horizontal planes (places where gas bubbles are trapped). One hundred and fifty liters (40 gal) of Dow DER 332 epoxy resin system were mixed and degassed at two torr for one hour. During the impregnation process the inductor and epoxy was held at ten torr. Resin was slowly forced into the inductor, filling it in four and one-half hours. Ninety-five liters (25 gal) were required to fill the inductor.

After a 121°C (250°F) cure, the outside of the inductor was machined to final size, and the temporarily welded seals were removed. Areas filled with epoxy that were revealed during the machining showed that the epoxy was fully cured and apparently void-free.

Upon completion of the final machining, the inductor was placed in a polyethylene tank. The 3.2-cm (1.25-in.) gap between the inductor and the polyethylene tank was pumped full of high-density polyurethane foam insulation. The cured foam forms the thermal insulation and supports the coil when mounted in its normal horizontal position. The inductor is instrumented with resistance temperature devices (RTDs) and strain gages on the outer diameter and the top end.
TABLE 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance (dc)</td>
<td>2.04</td>
<td>μΩ</td>
</tr>
<tr>
<td>Resistance (Charging Frequency)</td>
<td>3.14</td>
<td>μΩ</td>
</tr>
<tr>
<td>Total Inductance</td>
<td>6.2</td>
<td>μΗ</td>
</tr>
<tr>
<td>Internal Inductance</td>
<td>1.74</td>
<td>μΗ</td>
</tr>
<tr>
<td>Peak Current</td>
<td>1.02</td>
<td>MA</td>
</tr>
<tr>
<td>Energy Stored</td>
<td>3.2</td>
<td>MJ</td>
</tr>
<tr>
<td>Energy Transfer Efficiency</td>
<td>51.5</td>
<td>%</td>
</tr>
<tr>
<td>(HPG to Inductor)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge Losses</td>
<td>0.61</td>
<td>MJ</td>
</tr>
<tr>
<td>Energy Available to Load</td>
<td>2.59</td>
<td>MJ</td>
</tr>
<tr>
<td>Inductor Energy Available/Mass</td>
<td>1.73</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>System Energy Available/Mass</td>
<td>0.77</td>
<td>kJ/kg</td>
</tr>
</tbody>
</table>

fabricated a compact inductor for use in an EM railgun power supply. The system, currently being tested, is designed to accelerate an 80-g projectile to 3 km/s. A switch and railgun for use with this power supply are currently being designed. Based on test results, a field-portable, second-generation system, achieving higher energy densities is planned.

References

