Design, Construction, and Testing of an Inductive Pulsed-Power Supply for a Small Railgun

A. Sitzman, D. Surls, and J. Mallick
Institute for Advanced Technology, The University of Texas at Austin

Abstract—Advances in high-power-density batteries have rekindled interest in using inductive store as a pulse compression system. Although these batteries are considered very power dense, they lack over an order of magnitude of power density to drive a deployable electric gun. However, one can add an inductive circuit to a battery bank to make a hybrid system that has a much higher power density than batteries alone. A battery-inductor hybrid pulsed-power supply boasts several advantages over pulsed alternators, as inductors are static and relatively easy to cool. Inductors are potentially more energy dense than capacitors, making a battery-inductor hybrid pulsed-power supply an attractive alternative to capacitor-based pulsed-power supplies. The opening switch has been a major obstacle in previous inductive store projects, but in simulation, a new circuit topology—the Slow TRansfer of Energy Through Capacitive Hybrid (STRETCH) meat grinder—greatly attenuates the problem. This paper discusses the design, construction and testing of a small-scale STRETCH meat grinder system designed which was successfully used to power a miniature railgun.

Keywords: pulsed power, battery, inductor, capacitor, railgun

I. Introduction

This paper reports the inspiration, design process, and test results of the inductive pulsed-power supply project. There were two major objectives for this project. The first objective was to demonstrate the Slow TRansfer of Energy Through Capacitive Hybrid (STRETCH) meat grinder principles [1] with a physical system. The second objective was to use the system to fire the demonstration railgun at the Institute for Advanced Technology (IAT).

For some time, capacitor-based systems and pulsed alternators have been the focus of research on pulsed-power supplies for railguns. However, both of these systems have major, unresolved problems. Capacitor-based systems are not yet energy dense enough to be used in deployable systems, except perhaps for large ships. Pulsed alternators are energy dense, but they are also very complex and very challenging to build [2].

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Theoretically, the ratio of energy density in capacitors, inductors, and rotating machines is 1:10:100 [3]. However, the type of inductive system described in this paper need only store energy for a single shot, because charging is part of the firing sequence. This is in contrast to a pulsed alternator, which typically stores several shots' worth of energy plus some reserve energy that is necessary for operation. A major technical challenge inherent to inductive pulsed-power systems is the opening switch. Opening high-current inductors produces voltage across the opening switch that is in excess of the capabilities of present-generation solid-state. The STRETCH meat grinder circuit topology addresses this voltage stress and increases the amount of energy transferred to the load [1].

The IAT has constructed a 0.56 m railgun to demonstrate the operating principles of a railgun. Presently, this railgun is powered by a traditional capacitor bank with a pulse-forming network. We wanted to build a second power supply for this railgun based on the STRETCH meat grinder circuit topology.

II. CIRCUIT LEVEL DESIGN

We decided to implement a single unit system to reduce the overall system size, complexity, and cost. This is a first step to a system using parallel operation, as discussed in [1].

The present capacitive pulsed-power supply produces a current pulse with a 1 ms rise to peak and 18 kA peak followed by a 6 ms, nearly inductive-resistive (LR) decay down to 1 kA. To increase the piezometric efficiency of a single unit system, we decided to add a silicon-controlled rectifier (SCR) S1 and a bypass diode D1 so that we could delay the reversal of the current in L1. The modified schematic is shown in Fig. 1.

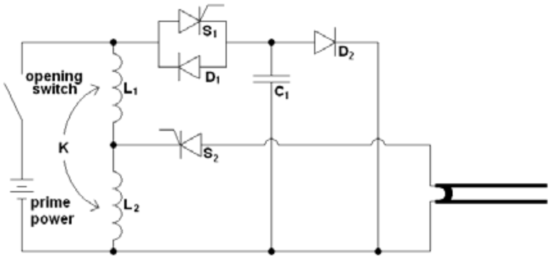

Fig. 1. The schematic for the pulsed-power supply.

The operation of this circuit is initiated by the closing of the opening switch, which causes the prime power source to develop a current in L1 and L2. Just before the current reaches the desired firing level, the SCR S2 closes. Once the current is at the firing level, the opening switch opens. This causes the current in L1 to decay while the current in L2 increases to support the mutual flux. The leakage flux, along with the back electromotive force (emf) from the railgun, causes voltage in the capacitor to rise. After some

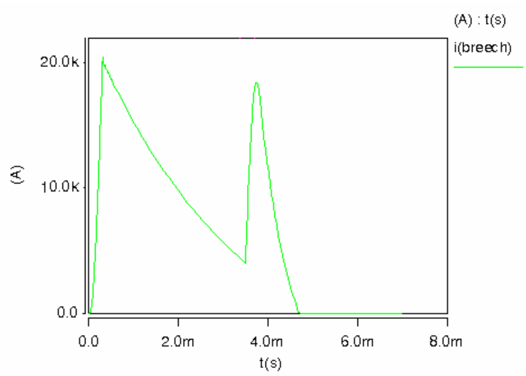

Fig. 2. The simulated output current with a 3.8 kA initial current. The capacitor's output pulse was delayed until 3.5 ms.

length of time, the SCR S1 closes—allowing the capacitor to discharge through L1 in reverse, and through the load in the forward direction. This causes the output current to increase a second time. After the voltage in C1 has decayed to zero, L1 continues to conduct, but through D2 rather then C1. Fig. 2 shows a simulated output current waveform.

The component values for this circuit were selected primarily to accommodate an available opening switch. The opening switch we selected is rated to open 3.8 kA. The output current should peak at approximately 18 kA so that the system is roughly equivalent to the capacitive based power supply. Assuming a coupling of 0.9 and a load of 1 µH we used the theoretical analysis presented in [1] and circuit level simulations to arrive at approximant inductance values for L1 and L2. L1 should be greater then 150 µH and L2 should be less than 8 µH.

III. INDUCTOR DESIGN

The inductor is the most important component in the system. The inductor is made of two coupled inductors, L1 and L2. It is important that L1 not have excessive resistance to minimize the amount of energy lost during charging and to develop the maximum current from the prime power. It is also important that L2 not have excessive resistance, because L2 conducts very high currents. The coupling of the two inductors is critical because the energy of the uncoupled flux of L1 ends up being stored in the capacitor; poor coupling would necessitate the use of a large capacitor.

In order to meet these requirements and simplify construction, we opted for an inductor with Brooks-coil type geometry. Brooks-coil calculations [4] showed that the inductor would need very thick conductors to keep the resistance down to a reasonable level. Initially, we planned to make the conductors out of copper, but we switched to aluminum, in order to reduce the system weight. The aluminum design required very thick conductors, 19.1 mm × 19.1 mm, which increased the total size of the inductor. To give approximately the desired inductance, L1 needed 25 turns, while L2 needed five turns. Finite element (FE) simulations showed that L1 would have about 155 µH of inductance while L2 would have about 6 µH of inductance.

Because the conductors are relatively thick, we decided to cut them from sheet aluminum rather than try to wrap such thick wire. In an effort to simplify construction and keep costs down, we designed a single five-turn spiral part from which the inductor would be made. This part is shown in Fig. 3.

Fig. 3. The spiral part that served as a paradigm from which the inductor was constructed.

The spiral part is 4.83 mm thick and the space between turns is 1.14 mm inches wide. The resistance of each spiral part is about 1.6 mΩ. The two holes on the ends allowed sets of the spiral parts to be pinned together.

We pinned sets of four spiral parts together to make one layer of L1's conductors. To achieve the 25 turns necessary to make L1, we used five layers of conductors. We oriented them such that every set of four spirals is inverted relative to the previous one so that the current is moving in the same direction around the inductor. In order to increase the coupling, we split L2 into six parallel sections. Each section of L1 was "sandwiched" between two sections of L2, as seen in Fig. 4.

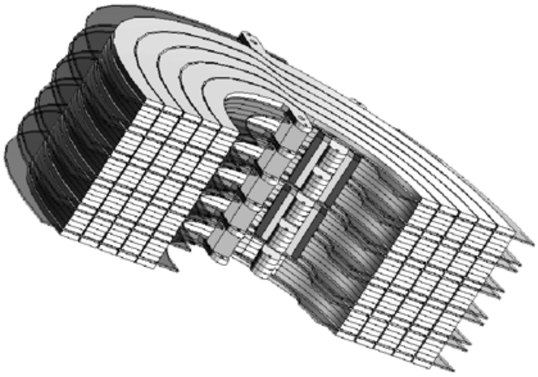

Fig. 4. A cross section of the inductor.

A FE code predicted that this design would have a coupling of 0.92 with conservative spacing between turns. Two pieces of aluminum surrounded by two pieces of steel form a clamp that allows the current to pass from layer to layer in L1. There are four such clamps. Two are visible in Fig. 4, and the other two are on the outside of the inductor. The six spirals that make up L2 are joined by ten aluminum blocks, five at each end.

The original concept was to pot the inductor. However, we decided that the inductor should be designed so that it can be taken apart. To accomplish this, we used sheets of polycarbonate for insulation and designed a containment that bolted the inductor together.

IV. SYSTEM LAYOUT AND CONSTRUCTION

The components of the system were arranged so as to minimize the parasitic inductance and resistance. Fig. 5 shows an exploded view of the system layout.

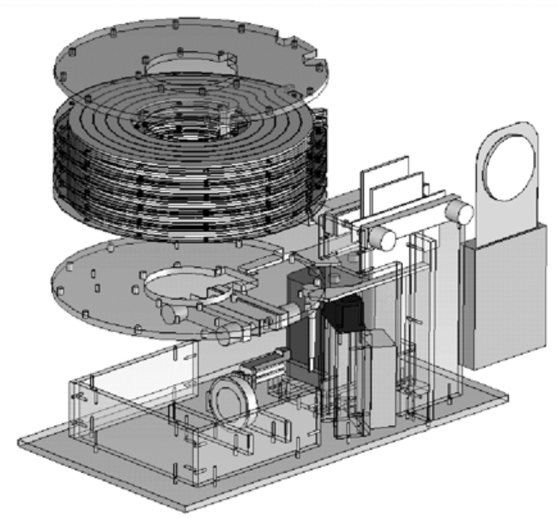

Fig. 5. An exploded view of the inductive pulsed power supply.

The SCR S2 is located just below the inductor. The copper parts just to the right of S2 connect to four coaxial cables that will eventually connect to the breech of the demonstration railgun. The black block contains SCR S1 and diode D1. Behind S1 and D1 are the two capacitors. The schematic called for an 800 μF, 1 kV capacitor. Because of issues with availability, we used a 600 μF, 1 kV capacitor and a 200 μF, 2 kV capacitor to make capacitor C1. The opening switch is an integrated gate commuted thyristor (IGCT), which is shown on the far right of Fig. 5. All transparent parts are polycarbonate. Fig. 6 shows the assembled system.

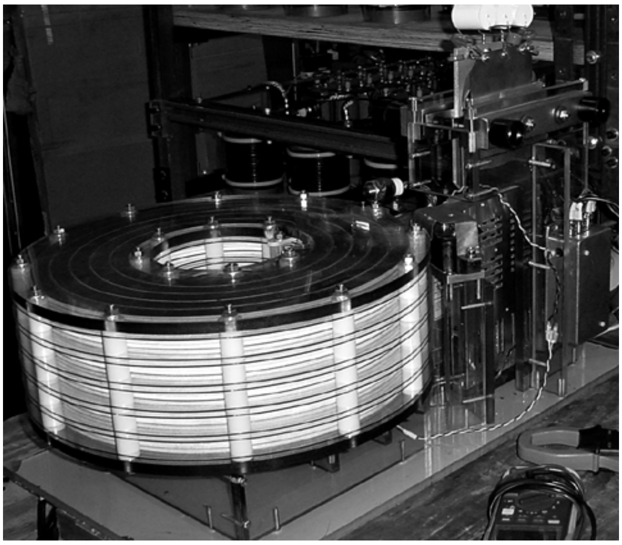
Fig. 6. The completed system.

V. Static and Low-Current Testing

Once we had assembled the circuit, we measured the values of several components. L1 and L2 had low-current inductances of 158 μH and 5.89 μH, respectively. Their resistances were 2.2 mΩ and 350 μΩ, respectively. The total inductance was 221 μH, resulting in a coupling of 0.94. The resistances were lower, and the coupling higher, than predicted by the FE code. However, the FE model for the spiral part had 3.18 mm separating the turns, while the cut in the final part was 1.14 mm thick. The thickness was changed to accommodate the use of a water-jet process to cut the spiral parts. The four coaxial cables that connected the railgun or load to the system have a combined resistance of 1.5 mΩ.

Once the static testing was finished, low-current testing began. We used a loop of copper attached to the breach of the demonstration railgun to simulate the railgun. This replacement is accurate for the initial part of the launch, that is, the part of the launch that occurs before the armature has started to move significantly. Originally, we used a Hawker battery as the source. The Hawker is a military-grade 12 V lead–acid battery. The relatively high internal resistance of the Hawker limited reasonable charge times to 70 ms. In 70 ms, the Hawker would develop a 1.2 kA current through L1 and L2. The circuit produced a peak output current of about 6.25 kA and appeared to be operating as expected, so we moved on to the high-current testing.

VI. High-Current Testing

Ultimately, we intend to use batteries as the prime power for this circuit, but we wanted to verify the high-current operation before buying the batteries. We used a large (350 mF) capacitor bank charged to a low voltage in place of the batteries for these tests. With an initial voltage of 123 V, the bank develops a 3.78 kA current in L1 and L2 after 12 ms. Fig. 7 shows the output current as seen through the output CVR from a 123 V experiment. Fig. 8 shows the

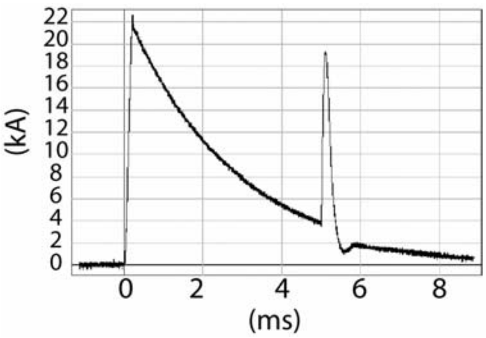

Fig. 7. The output current, as measured with a CVR for a 3.78 kA input current.

IGCT voltage during the same experiment as Fig. 7.

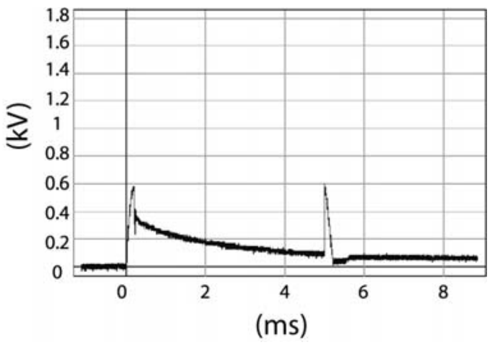

Fig. 8. The IGCT voltage during the same experiment as Fig. 7.

The charging circuit has a significant amount of inductance in it mostly due to the capacitor bank and its connection to the circuit. This inductance causes a transient voltage spike at time 0. A resistive-capacitive (RC) snubber and five metal oxide varistors (MOVs) were added to the IGCT before this test to reduce the transient voltage spike. On a production system, the stray inductance will be minimized so that the snubber will be small, if it is necessary at all.

VII. DATA ANALYSIS

We modified the initial simulation so that it incorporated the parameters gathered from the static tests and an estimated value for the output inductance. Fig. 9 shows the simulated IGCT voltage and the simulated output current superimposed on the experimental data. When we first ran the simulation, with 0.94 coupling, there was noticeable error; the rise times were too long and capacitor C1's voltage was too high. Changing the coupling between L1 and L2 from our low-frequency measurement of 0.94 to 0.975 resulted in very good agreement between the simulated and experimental data. Other simulation parameters were varied to verify that they did not have the same effect as varying the coupling. In the future, we would like to run simulations of the inductor on a more advanced FE code so that the effects of the switching action and non-uniform current distributions can be analyzed.

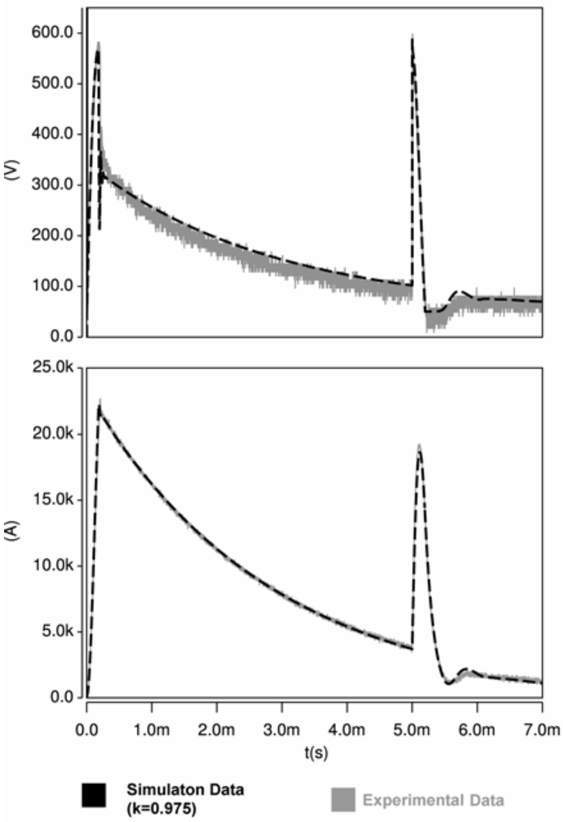

Fig. 9. Top: simulated IGCT voltage superimposed on the data from Fig. 7. Note that the inductive spike due to stray inductance in the charging circuit has been cut off to allow the rest of the data to be viewed more easily. Bottom: simulated output current superimposed on the experimental data from Fig. 8.

VIII. RAILGUN LAUNCH

After we completed the high-current testing, we connected the IAT's demonstration railgun to the power supply and fired several shots. Fig. 10 depicts the entire setup. We used the 350 mF capacitor bank charged to 123 V as the prime power. The setup for firing the railgun was the same as that for the high-current testing, with the exception of the timing of the second current pulse. Delay of the SCR S1 was decreased from 5 ms to 3 ms because the output current will decrease faster when firing the railgun due to the back emf produced by the armature sliding down the rails.

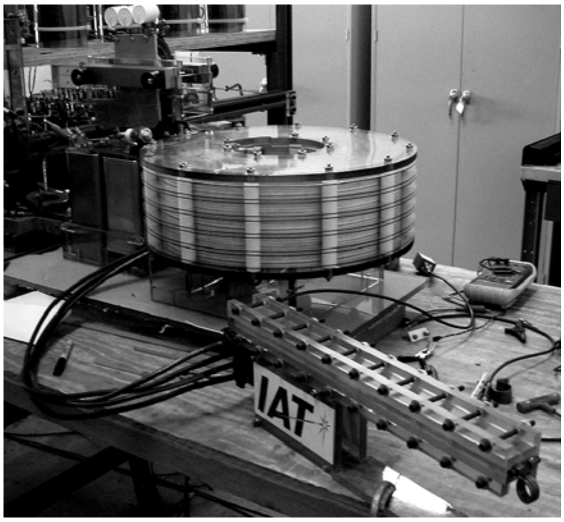

Fig. 10. The inductive based power supply connected to the IAT's demonstration railgun.

IX. CONCLUSION AND FUTURE DIRECTION

Inductive store is a promising alternative to complicated pulsed alternators or bulky capacitors. In this project, we designed, constructed, and tested a working STRETCH meat grinder system that can output a current of over 20 kA. This system was then used to successfully fire a small railgun.

While the power supply described in this paper accomplished its goals, the low currents necessitated by the small scale of system limited the system's energy density. The IAT has another, higher energy, demonstration railgun that is generally fired with a current of over 150 kA using a capacitive power supply. We think that an inductive power supply based on the one described in this paper would provide an impressive size and weight savings over its current power supply.

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