OPERATION OF A 5-MJ CAPACITOR BANK FOR EML MATERIALS TESTING*[*]

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Abstract

The U.S. Navy is considering the development of an electromagnetic launcher (EML) for surface-fire support and other missions. The EML system will need to have fire rates of 6-12 rounds per minute and barrel lifetimes approaching 10,000 rounds. The Naval Research Laboratory has initiated a program to develop and test materials to achieve these fire rates and lifetimes. A facility is being assembled to allow testing of rail and armature materials at the high current density, pressure and sliding velocity of the Navy EML. The test system needs to operate over a large range of charging voltages and test configurations. The system also needs to deliver high reliability and reproducibility to accommodate the testing requirements.

The capacitor bank design previously proposed has been fabricated and tested. The module stores 500 kJ at 11 kV charge, using capacitors and fuses from General Atomics, ABB semiconductors and a custom 80μH inductor from Stangenes. A circuit model of the banks, using the no greater than values for internal resistance and inductance of the capacitors, predicted 100 kA output at 11 kV charge. The real devices deliver 100 kA at 10.4 kV charge, with 5% bank reversal. Reinforcements were added to prevent deformation at the inductor tabs, and limit the motion of the conductor plates at high current

A 5-MJ system has been fabricated and installed, using 10 of these modules, stacked in set of two, and another 5-MJ of modules is in fabrication. All ten of the modules passed testing at 1 kV, and 4 random modules passed testing at 8 kV charge, with a 10 m load. 2 more, equivalent 500-kJ modules are being constructed using other 11-kV capacitors. Results of the testing and comparison with the initial circuit models will be presented. Results from initial firings into dummy loads at the breech and low power EML launches will also be presented.

I. INTRODUCTION

The U.S. Navy has begun a research and development program to assess to the use of an electromagnetic railgun for long-range fire support [1]. The deployed system has requirements for sustained rep-rated fire at 6-12 rounds per minute, and a long barrel lifetime, approaching 10,000 rounds. These are challenging performance points for the EML barrel, given that rep-rate and barrel lifetime have never been the focus of sustained research. The Naval Research Laboratory has built a medium scale EML facility, the Materials Test Facility (MTF), to address the materials and design issues related to obtaining the desired lifetime and rep-rate characteristics [2].

The long-range fire support projectiles will require active components for guidance, which will force the EML to operate at lower accelerations and longer barrel lengths. The facility limits the practical length of the gun barrel to 6-8 m. so the MTF is not a one-to-one match to the velocity-acceleration-time profiles of the real EML. However, the facility will be able to match the profiles in first half of EML, and get to the relevant velocities for the second half of the Navy EML, with only modest increases in the acceleration.

New pulsed power systems have been designed, fabricated, tested and operated at the MTF. The design of the pulsed power module was presented previously [3]. The basic module is an 11-kV, 500 kJ device, with solid-state switches and a series inductor that will deliver up to 100 kA into a railgun load. This paper reports on the real devices built from that design. Section II will describe the design in more detail, and present results from a prototype assembly of one module. Comparison of the performance between the prototype and the design shows that conservative values were used for resistances of the capacitors, fuses and inductor, such that the real device and deliver more current at a given bank charge than the design.

Section III will cover the assembly of 5 MJ, 10 modules of production banks. The banks are assembled as two, independent modules in a single, steel mounting structure, then stacked three levels high in the facility. A number of changes were made from the prototype design to ease the assembly of the devices, and to minimize motion of the conductors when the device is pulsed. Section IV presents data from the operation of the MTF, showing the bank performance with a railgun load, and the ability to control

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14. ABSTRACT
The U.S. Navy is considering the development of an electromagnetic launcher (EML) for surface-fire support and other missions. The EML system will need to have fire rates of 6-12 rounds per minute and barrel lifetimes approaching 10,000 rounds. The Naval Research Laboratory has initiated a program to develop and test materials to achieve these fire rates and lifetimes. A facility is being assembled to allow testing of rail and armature materials at the high current density, pressure and sliding velocity of the Navy EML. The test system needs to operate over a large range of charging voltages and test configurations. The system also needs to deliver high reliability and reproducibility to accommodate the testing requirements. The capacitor bank design previously proposed has been fabricated and tested. The module stores 500 kJ at 11 kV charge, using capacitors and fuses from General Atomics, ABB semiconductors and a custom 80ìH inductor from Stangenes. A circuit model of the banks, using the no greater than values for internal resistance and inductance of the capacitors, predicted 100 kA output at 11 kV charge. The real devices deliver 100 kA at 10.4 kV charge, with 5% bank reversal. Reinforcements were added to prevent deformation at the inductor tabs, and limit the motion of the conductor plates at high current A 5-MJ system has been fabricated and installed, using 10 of these modules, stacked in set of two, and another 5-MJ of modules is in fabrication. All ten of the modules passed testing at 1 kV, and 4 random modules passed testing at 8 kV charge, with a 10 m load. 2 more, equivalent 500-kJ modules are being constructed using other 11-kV capacitors. Results of the testing and comparison with the initial circuit models will be presented. Results from initial firings into dummy loads at the breech and low power EML launches will also be presented.

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the pulse shape with the bank firing times. The control and safety systems that support the banks and the MTF are described in another paper at this conference [4]. Section V will present conclusions and plans for future expansion of the facility.

II. DESIGN AND PROTOTYPE OPERATION

The MTF is intended as a facility to obtain the materials information required to obtain the necessary rep-rate and lifetime performance from the EML barrel. This requires that the facility be able to operate for a large number of shots to be able to survey all the materials and geometries of interest, field experiments to better characterize the internal environments of the barrel, and repeat shots to obtain meaningful lifetime data. It also has to execute these tests in performance envelope that matches the Navy EML as closely as possible. These requirements place a premium on the reliability and flexibility of configuration for the pulsed power systems.

The basic module was chosen to be a 500 kJ capacitor bank, at 11 kV [33]. A series inductor of 80 µH was chosen to limit the peak current of a module to 100 kA, and to ensure isolation of the modules from each other, to allow staggered firing of the banks. The current rise time is just over 1 ms, which not an issue for the low acceleration Navy requirements. The limited module size also allows a single thyristor chain and diode chain to carry the action and peak current.

The following primary components are used in the banks:

- 4, General Atomics Model 32923 capacitor, 11 kV, nominally 2040 µF each
- 8, General Atomics Model 94150067 fuse, $1.3\text{x}10^5$ A^2-s carrying action
- 5, ABB Model 5STP52U5200 thyristor
- 5, ABB Model 5SDD50N5500 diode
- 1, custom Stangenes inductor, 80 µH, 100 kA rated.

We also use ABB trigger generators, snubber boards and inductive pickup trigger boards. The only components of the banks that are not commercially available are the buswork and pressure clamping frames for the semiconductor stacks. The values for the fuse action and the inductor were chosen from the design simulations [4], to carry the normal peak discharge current from the caps and limit the peak current and action in the semiconductors.

A prototype module of the bank was built to obtain electrical data with the actual component and to confirm the mechanical assembly details before manufacturing components for multiple banks. The parts for the mechanical assembly were designed in a 3-D CAD program, and no significant interference issues were found. The semiconductor stacks are compressed directly onto the buswork components, to eliminate the resistance and maintenance issues of current joints. The stacks are compressed to the ABB specifications of 90 kN for the diodes and 135 kN for the thyristors. Belleville springs are used at all connections to help maintain contact pressure. Every effort was made to minimize the amount of maintenance required of the banks, since they will be stacked in the lab, and access to the banks is difficult. The bank was tested up to 8 kV, with a 7 m stainless steel load, to verify device performance.

The simplified circuit model of the `as-manufactured' prototype bank is shown in Fig. 1. The circuit has the crowbar diodes between the capacitors and the thyristors. The advantages of this placement of the crowbar diode are that the voltage reversal on the capacitors is minimized and there are no snubbing issues when the thyristors cutout, as there is no capacitive energy stored at that time. The disadvantages are that the thyristors have to carry a large action, since they are in the circuit for the full time, and the diodes have a high peak current when they crowbar. The nonlinear resistance of the fuses helps to damp the ringing in the crowbar loop of the circuit. The values in the model are different than those assumed for the design and from the data sheet values. The design used values from the General Atomics data sheet for the internal resistance and inductance of the capacitors. Conservative values were assumed for the resistance targets of the fuses and the inductor, and the inductance of the capacitor bank connections. The capacitors average 2% higher than the nameplate value, and the internal resistance and inductance came out lower. The other assumed values in the design came out with lower values as well. The net result is that the full output current of 100 kA is obtained at a bank charge of 10.4 kV, instead of the 11 kV. A comparison of the calculated output currents between the design circuit and the actual circuit is shown in Fig. 2. The lower resistance values of the components not only deliver the full current at lower bank charge, but also a longer L/R time, to improve the energy transfer in the EML.

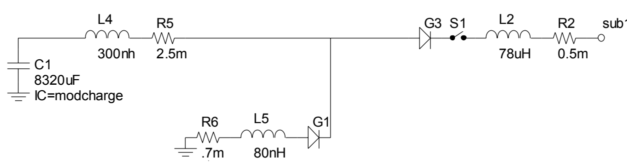

Figure 1. Simplified circuit model of single bank module.

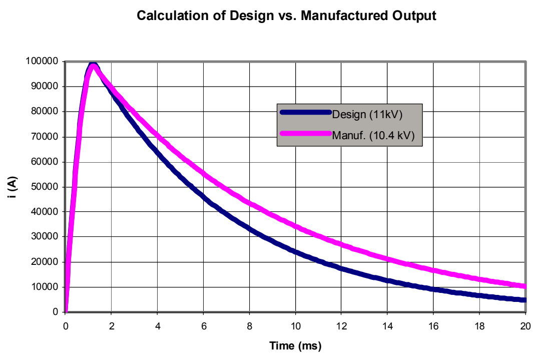

Figure 2. Comparison of calculated design output current at 11 kV charge and manufactured bank current at 10.4 kV charge.

The prototype bank gave us confidence that the larger system would work and resolved some minor issues. Minor changes were made to the buswork to ease assembly of the components, and a PVC bracing plug was added to the inductors to prevent bending of the inner tab of the inductor due to the magnetic forces.

III. PRODUCTION BANK ASSEMBLY.

The production banks are assembled as two, independent modules in a single, steel frame. The output side of a full bank frame is shown in Fig. 3. All 10 modules were tested to 2 kV, and 4 of the modules were test to 8 kV, with no electrical issues found. High speed photography at the output side of the bank showed that significant upward forces were generated on the aluminum conductors on either side of the black storage inductor, leading to large vibrations of the trigger and snubber boards on the thyristor stack. The vertical green fiberglass struts were added to limit the motion, and their efficacy was confirmed with more high-speed photography. The output of each bank goes on a single coaxial cable, model #2198 from Dielectric Sciences.

The banks were stacked three frames high after assembly and testing on the floor. The steel pins on the top of the frame, seen in Fig. 3, assure the alignment of the frames to each other. A 5 ton forklift was used to stack the frame, as seen in Fig. 4. The banks were then wired to the control system [4] and cables run from the banks to the breech of the EML. Removable plastic shields are placed around the lowest bank levels to prevent access to the high voltage components.

Each bank has a B-dot current monitor attached to the ground conductor that is individually monitored by the data acquisition system. The bank monitors and the breech Rogowski monitors were calibrated by firing the banks individually through the breech to a calibrated current shunt attached to the rails. Each bank also has a 550-kJ capacity dump resistor to safe the bank after a shot or if the banks need to be dumped if problems arise.

Figure 3. Two production banks mounted in their steel frame. The black object is the storage inductor, and the thyristor stack is to the left of the inductor, and the diode stack is to the right.

Figure 4. Forklift stack top level of bank frames.

IV. EML OPERATIONS

The EML was operated initial with a 4-m long barrel assembly and nominally 200 g projectile loads. Because of the short barrel, most launches were made by firing all of the banks at t=0, to limit the current in the barrel at projectile exit. Shots were taken at bank charges from 4.5 to 8 kV. The bank voltage was limited to 8 kV, again limiting the residual current at projectile exit. All banks operated properly at 8 kV charge. The EML current and the breech voltage for a nominal 8 kV, 200 g shot are shown in Fig. 5. The projectile exit velocity was 1600 m/s. The gun current and breech voltage for a 7.5 kV shot where the firing of 3 of the 10 banks were delayed to provide a more rectangular current pulse are shown in Fig. 6. This demonstrates that the bank firing times can be controlled and no cross-talk exists that results in premature triggering of banks.

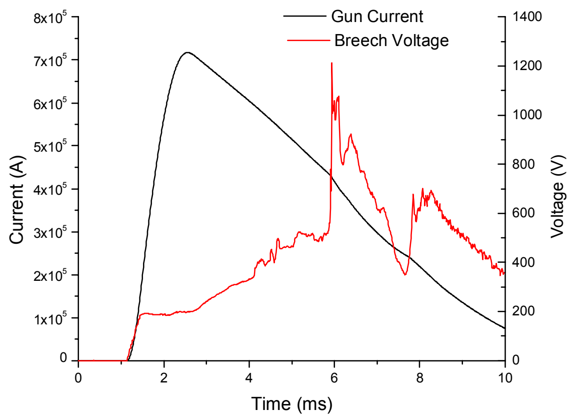

Figure 5. Gun current and breech voltage for operation with 10 banks at t=0, 200 g projectile.

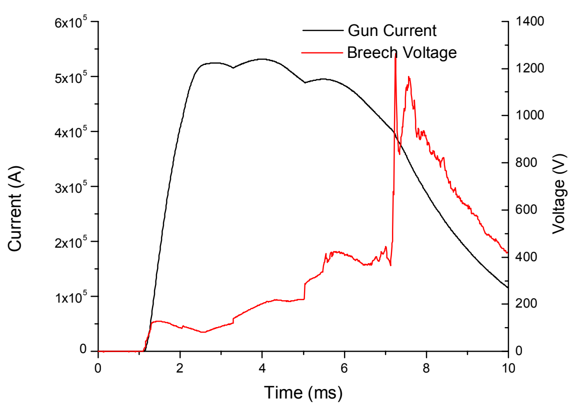

Figure 6. Gun current and breech voltage for operation at 7.5 kV, with staggered bank firing

V. SUMMARY

A 5 MJ, 10 module, solid-state pulsed power system has been designed, constructed and operated at the MTF railgun at the Naval Research Laboratory. Over 50 launch events have been performed, and the pulsed power systems have operated as intended. The solid-state switching allows routine operation of the banks from 200 V charge to full voltage. The standard operating procedure has been to fire a 200-V test shot with a short at the muzzle of the gun before every launch event. This assures that all banks and diagnostics are operational, and then the projectile is inserted and the system fired at full voltage. The system is currently being expanded to 22 modules with 11 MJ of stored energy, for operation of the MTF with 6-m gun barrels.

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