

DESIGN OF A 500-KJ CAPACITOR BANK MODULE 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[1]. 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[2]. 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.

A 500-kJ module is being designed as the basic building block of the pulsed power system for the facility. Each module will supply up to 100 kA to the materials test system. The components being considered are similar to those proposed for a 200 MJ EML pulsed power system[3]. The capacitors are new, 125 kJ/can, 11-kV units from General Atomics Electronics Systems. The switching thyristors and crowbar diodes are from ABB. A series inductor of approximately 80 μ H is used to limit the peak current to 100 kA and isolate modules from each other and to ensure that the current is delivered to the test system. It is expected that the solid-state components used for switching and crowbarring will provide the reliability and flexibility desired for the pulsed power system.

The circuit is analyzed with the dynamic nature of the test system included. The rising inductance of the test must be included in the modeling to accurately reflect the action required from the switching and crowbar elements, and the fuses that are in series with capacitors. The physical layout of the banks is also being designed to provide highly compact modules while providing access for maintenance and repair. Results of the simulations will be presented, along with mechanical layout plans.

I. INTRODUCTION

Practical application of electromagnetic launchers for the U.S. Navy will require that the barrel and armature systems be capable of firing thousands of rounds, at rate of up to 12 rounds per minute[1]. The emphasis on most previous EML systems has been the single shot performance, and a lack of wholesale destruction in the barrel. The EML system being constructed at the Naval Research Laboratory (NRL) has the mission of examining the issues relating to and potential solutions for achieving longer barrel lifetimes[2].

The rail/armature contact operates at a current density, contact velocity and pressure that are outside the normal conditions of other long-lived electric devices, such as electric motors. Thus, there are no readily available engineering data or solutions for this problem. Unresolved issues in railgun barrels would include transition to arcing behavior, thermal management and stress issues, and cyclic fatigue[1]. The facility at NRL is intended as a test bed where these issues can be explored and the environment characterized, and then various approaches tested. The team at NRL includes experts in pulsed power, tribology, metallurgy and surface modification, to bring a wide range of talents, diagnostics and expertise to the problem.

II. TEST SYSTEM GOALS

An EML system is being constructed at NRL to test rail/armature materials and designs to obtain long-lived barrel systems, as an EML is the only device where the relevant materials environment exists. The EML system at NRL is being designed to test at the high current, high pressure and limited acceleration conditions of the naval fire support mission. It is also a design priority that the EML system be able to test with a wide variety of materials, geometries and current waveforms to explore the full spectrum of possibilities.

The barrel is being designed with the following specifications:

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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[1]. 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[2]. 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.					
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- nominal bore of 5 cm and lengths of 4-6 m.
- containment to withstand the stresses of up to 2 MA of current.
- adequate volume inside the containment for bore geometries from round to rectangular.
- ability to tolerate large current at projectile exit.
- access for diagnostics.
- robust process for precise and reproducible assembly.
- quick turn around time for bore access and materials replacement.

The flexibility desired of the barrel also extends to the pulsed power system that drives it. The pulsed power system specifications include:

- peak current of 2 MA at the breech.
- configurable waveform through module timing and module charge voltage.
- robust and reliable.
- operable over a wide range of currents.
- tolerant of failures in barrel and large current at projectile exit.

The pulsed power system is being designed with an ultimate stored energy of 16 MJ, configured as 32, 500-kJ modules. Each module will have a configurable firing time and an option to charge to one of three voltages, to provide the desired waveform flexibility. The initial phase of the project will have 6 MJ of stored energy, in 12, 500-kJ modules.

III. 500 kJ MODULE DETAILS

The basic module is designed to deliver 100 kA to the breech of the EML, from a 500-kJ capacitive store. The switching and crowbarring of the bank will be with solid-state devices, and a large inductor will be used to hold the bank energy and isolate the rest of the bank components from events at the EML. The module size of 500 kJ and 100 kA provides the waveform flexibility desired, and is small enough to be switched within the action limits of a single stack of thyristors and diodes. All of the major components are available from commercial sources. The challenge of the design process thus becomes one of assuring that the components are operated within their allowed characteristics and that the modules will operate independently and deliver the desired current to the EML.

A. Bank Components

The components of the 500-kJ modules are similar to the ones being used to build the banks for the larger Navy program[3]. The basic components of the module are:

1. 4, 125-kJ, 11-kV capacitors, from General Atomics Energy Products,
2. 5 thyristors, model 5STP52U5200 from ABB,
3. 5 diodes, model 5SDD50N5500 from ABB,
4. 80 μ H, 100 kA storage inductor, from Stangen Industries.

B. Circuit Model and Results

The circuit model of a module is shown in Figure 1. The 4 capacitor units are modeled as 8, equivalent parallel caps, to capture the action in the fuse elements. The program being used is the CASTLE code[4]. 12 modules are connected in parallel to a simple railgun model. The model uses the simple railgun force equation to determine the motion of a projectile, and change the inductance and resistance of the railgun circuit element as a linear function of the position. The railgun model is used as an appropriate dynamic load to assess the action in the thyristor and diode stacks. The nominal parameters used in the railgun model were L' of 0.45 μ H/m, mass of 400 g and a barrel length of 6 m.

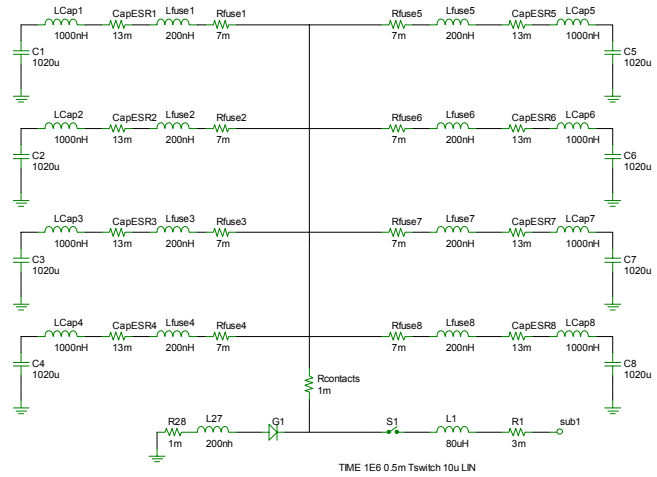


Figure 1. Model of 500-kJ module.

Results of a representative calculation are shown in Figure 2. Seven of the 12 modules are triggered at $t=0$, and the firing of the additional five modules is spread out to approximate a constant current to the load. The action on the thyristors and diodes are the greatest for the first modules fired, and least for the last unit fired. This comes from the greater rate of change of inductance later in the pulse, and the termination of current when the projectile exits.

The results of the calculation are used to assess the action in the semiconductors and fuses. The peak action in the early bank thyristors is $2.9 \times 10^7 A^2s$, or 84% of the rated value with a thyristor junction temperature of 110 $^{\circ}C$. The system is single-shot, so the junction temperatures should be closer to 25 $^{\circ}C$, and the safety margin even greater. The corresponding value for the last bank is $2 \times 10^7 A^2s$, or 58% of rated value. The action in the diodes are all less than 50% of rated values. The fuses at the capacitors see a carrying action of $1.23 \times 10^5 A^2s$. Thus, the circuit model indicates that all of the components of the module are being operated well within their peak current and action limits

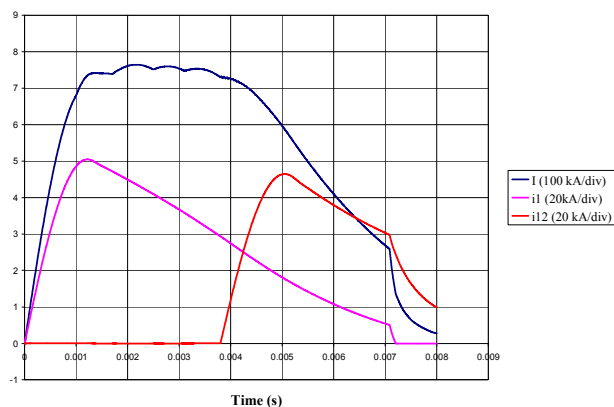


Figure 2. First and last Module currents and total current for simulation.

The circuit calculated has the crowbar diodes placed across the capacitors only, and the thyristors are in the circuit for the entire pulse. This arrangement provides the minimum voltage reversal on the capacitors, but maximizes the action in the thyristors. It also has the advantage that it minimizes the stress on the thyristors at current turn-off, since there are no capacitive elements in the circuit. Snubbing will still be placed across the thyristors, but the purpose is principally to ensure equal voltage division across the stacked thyristors, as opposed to snubbing the turn-off voltage spike. The fuse elements at the capacitors serve both as protective elements in the event of a capacitor failure and to limit the ringing in the circuit when the crowbar diodes actuate.

Note that all of the major components of the module are commercial items. The only custom device is the storage inductor, but even that is readily available from Stangenes. The auxiliary components of the module, thyristor triggers, dump resistors, fuses, etc. are also available from commercial sources. The only components being fabricated by NRL are the buswork, clamps for the solid state assemblies, and the mounting frames.

C. SAFETY AND RELIABILITY

The hazards of the pulsed power system fall into two categories: 1) the inherent danger of high-voltage, energy storage systems; and 2) additional hazards from kinetic energy and shocks from the EML operation. The first category of hazard is exacerbated by the low voltage nature of the system. Since it is air-insulated and in the lab with the launcher barrel, the high-voltage components are readily accessible to personnel. While this eases maintenance, the operation process will include assuring the safeing and grounding of the bank modules after tests, before the lab area is released for general access. The lab area will also be emptied and interlocked before high voltage is applied to the banks. The access controls will also serve to isolate personnel from adverse effects from the EML operation.

The test system at NRL will be used for a wide variety of tests, involving materials and armature designs that are unproven. It is reasonable to expect that many of the tests

will end with less than optimal results, and the pulsed power system needs to tolerate these events. The primary mechanism for protecting the modules is the storage inductor. The inductor limits the peak current of the module, regardless of the events at the EML. It will also present a high impedance to any fast transient events, so that the thyristors and diodes are protected.

A second mechanism is being planned to limit the consequences of abnormal tests. As shown in Figure 2, a substantial number of modules are fired later in time, to shape current waveform. We propose to limit damage from abnormal tests by implementing a real-time ‘performance monitoring’ system that inhibits the firing of any unfired modules, once an abnormal test is detected. For the full 16-MJ system, this could be up to 6 MJ of energy that is kept out of the fault. The method to judge the presence of a fault is the motion of the projectile. If all is going well, the projectile will progress down the EML in a predictable way. However, abnormal tests will result in failure of the projectile to accelerate normally. A set of permanent b-dot position monitoring loops will be installed and used to monitor the time-dependent position of the projectile. If the projectile fails to make it to a given position on time, the system will prevent the firing of any further modules, and dump all of the modules.

The modules should be reliable and low maintenance. The modules will be stacked four levels high in the lab, so access to components for routine maintenance will be difficult. The modules are designed to have no components requiring routine maintenance. All of the switching components are solid state, and all of the high-power resistors are solid ceramic. The buswork will be designed to limit the number of current joints, both for the improved resistance characteristics and to limit the number of connections that will need periodic tightening.

D. CONTROL SYSTEM ISSUES

The full 16-MJ pulsed power system will have 32, independent units, and a simple PLC based system will be used to control the charging and firing of the system. The control system will monitor the interlock status of the experimental area, sequence the charging of the modules so that all modules reach full charge simultaneously, sequence the firing of the modules, and safe the modules after the test. At the module level, the control system concerns are to provide all the necessary control points without coupling EMI back into the control system.

The General Atomics capacitors are two terminal devices, with both of the capacitor electrodes well-isolated from the case of the capacitor. This will keep the capacitor case and the framework they are mounted in electrically isolated from the discharge. We will also keep all control components isolated from the module discharge circuit. The Ross relays and contacts provide full electrical isolation from modules. The ABB thyristor trigger system has fiber optic connections for reporting status and trigger input, and will be powered with an isolated 24 VDC power supply. Isolation of the voltage monitor on the module is the most difficult, and we

proposed to use a voltage-frequency converter, and return the signal to the control system on optical fiber, or use an opto-isolated input to avoid coupling high voltage back to the control electronics.

The control system functions are being integrated into all of the modules, and the expansion from the initial 12 modules to the full 32 is a pre-planned growth of the control system. Control system functionality will be verified during tests of the initial two modules with dummy loads.

IV. SUMMARY

The basic design of a 500-kJ module to power an EML materials test facility at the Naval Research Laboratory has been presented. The principal components of the module will be obtained from commercial sources. Circuit modeling of the module indicates that the components will be operated within their action and peak current specifications, when used in the dynamic EML circuit. Design considerations are also given to control of the modules with a computer-based control system, and mechanism to inhibit the discharge of further modules upon detection of launch faults in the test system.

V. REFERENCES

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