EFFECT OF RESISTANCE MODIFICATION ON EML CAPACITOR BANK PERFORMANCE*

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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 Naval Research Laboratory has initiated a program to develop and test materials to achieve these fire rates and lifetimes [2]. The U.S. Naval Research Laboratory has assembled a facility to develop and test materials for the study of barrel lifetime in electromagnetic launchers (EML) for surface-fire support and other missions [3].

The pulsed power system utilizes several modules that can be individually triggered to shape the output current pulse. Each bank module consists of capacitors from General Atomics Electronics Systems. The switching thyristors and crowbar diodes are from ABB. A series inductor is used to limit the peak current, isolate modules from each other, and ensure the current is delivered to the test system. Several launch events have been performed, and the pulsed power systems have operated as intended [3].

The capacitor bank modules were originally designed with minimum output resistance to obtain the maximum L/R decay time into the launcher. Modification of a module to allow for a variable output resistance is highly desirable to modify the output waveform of the bank module system, such as limiting the late-time current. NRL has designed resistance packages that can be easily inserted into a specific bank to modify the damping of the current. The effect of the resistance will be shown at various power levels and the resulting effect on switch action, capacitor voltage reversal, and output current will be demonstrated. Computer modeling of the modifications will also be discussed.

I. INTRODUCTION

The original capacitor bank design sought to maximize the L/R decay time to deliver as much current as possible for a long as possible into a load. The requirements of the system have changed since the capacitor bank was built, as new experiments seek variable pulse shapes. The best way to change the current shape is to modify the output current of the capacitor bank. The peak current is still achieved, but the late-time current is significantly reduced.

NRL has successfully fielded a modular resistor package in the crowbar diode circuit at a number of current levels. A major benefit of the modification is a considerable reduction in diode action, as the resistor creates and over-damped condition. Adding the resistor or inserting a short requires the removal of a few bolts, allowing for fast changes to the system with a minimum of downtime.

A. Experimental Setup

The experimental setup consisted of a capacitor bank with a stainless-steel resistor. There were two recorded monitors, a b-dot monitor on the output and a rogowski coil on the capacitor side of the thyristor switches to record ringing on the capacitors.

The capacitor bank is shown in Fig. 1. The module consists of four capacitors, two fuses per capacitor, a dump resistor, and output inductor, a stack of crowbar diodes, and a thyristor stack.

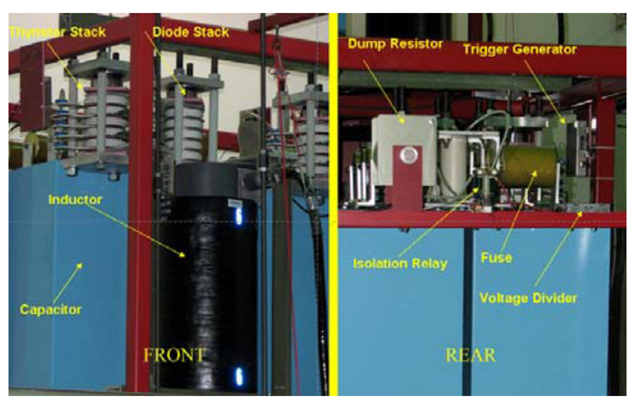

Figure 1. Capacitor Bank Detail.

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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 Naval Research Laboratory has initiated a program to develop and test materials to achieve these fire rates and lifetimes [2]. The U.S. Naval Research Laboratory has assembled a facility to develop and test materials for the study of barrel lifetime in electromagnetic launchers (EML) for surface-fire support and other missions [3]. The pulsed power system utilizes several modules that can be individually triggered to shape the output current pulse. Each bank module consists of capacitors from General Atomics Electronics Systems. The switching thyristors and crowbar diodes are from ABB. A series inductor is used to limit the peak current, isolate modules from each other, and ensure the current is delivered to the test system. Several launch events have been performed, and the pulsed power systems have operated as intended [3]. The capacitor bank modules were originally designed with minimum output resistance to obtain the maximum L/R decay time into the launcher. Modification of a module to allow for a variable output resistance is highly desirable to modify the output waveform of the bank module system, such as limiting the late-time current. NRL has designed resistance packages that can be easily inserted into a specific bank to modify the damping of the current. The effect of the resistance will be shown at various power levels and the resulting effect on switch action, capacitor voltage reversal, and output current will be demonstrated. Computer modeling of the modifications will also be discussed.

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As shown in Fig. 2, the capacitor bank was modified slightly with the addition of the resistor package.

Figure 2. Resistor package installed on capacitor bank.

The top buss bar was raised to allow a new plate to be inserted under the diode stack. The plate travels over an existing buss bar and connects to the resistor package. An aluminum bar can be inserted between the new plate and the lower plate, effectively removing the resistor package from the circuit, as shown in Fig. 3.

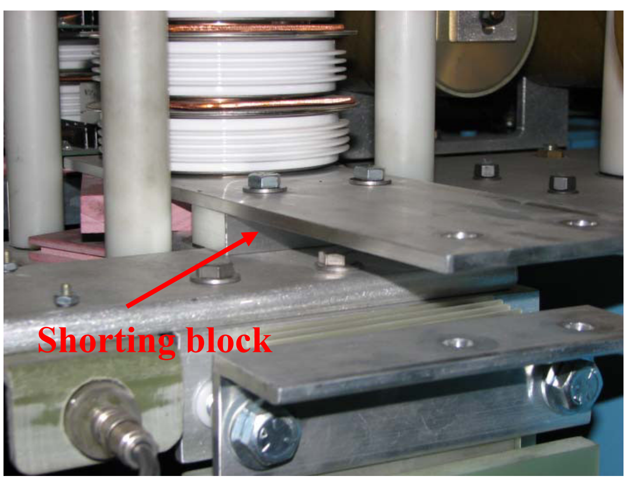

Figure 3. Shorting bar installed on capacitor bank.

The resistor can be reintegrated by removing the shorting bar and inserting new brass cylinders between the new plate and the resistor package, as shown in Fig. 4.

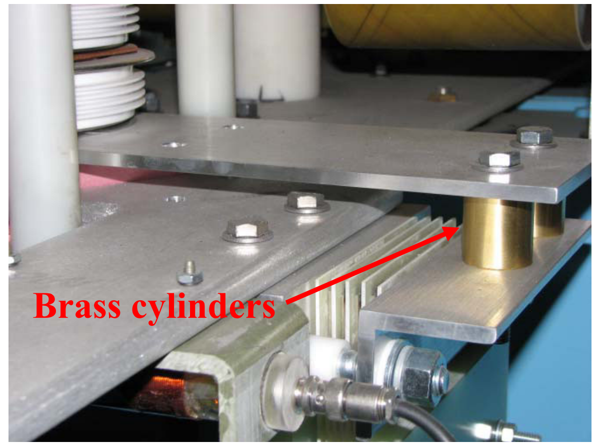

Figure 4. Resistor package electrically connected to capacitor bank.

The load is shown in Fig. 5. The load and switches were allowed to cool for a few minutes for low current shots and up to an hour for high current shots to ensure consistent parameters.

Figure 5. 10-mΩ stainless-steel resistive load

B. Ideal Circuit Model

The ideal circuit model is shown in Fig. 6.

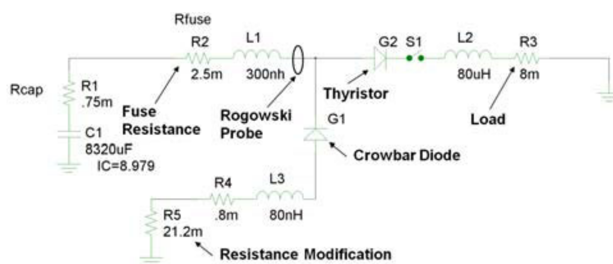

Figure 6. Ideal circuit model created from measured values.

The circuit model treats capacitors, fuses, and semiconductor devices as lumped elements to simplify the model. The diode and thyristor models are default SPICE models with the manufacturer's published on-state resistance integrated in the model

C. Resistor Package Design

The resistor package consists of 304 stainless steel conductors in a G-10 frame. A CAD drawing of the resistor package is shown in Fig. 7.

Figure 7. CAD drawing of resistor package installed on capacitor bank.

The resistor was designed using Eqn. 1, with an initial target resistance of 25 mΩ. Various engineering decisions changed the final dimensions to a value slightly higher.

$$R = \frac{\rho \cdot l}{w \cdot h} = \frac{72\mu\Omega \cdot cm \cdot 6.1m}{1.6mm \cdot 10.2cm} = 27.2m\Omega \qquad (1)$$

The final values used yielded ten 609.6mm x 101.6mm x 0.0625mm plates, which were insulated with G-10 pieces to ensure an effectively continuous 6.096 m resistor. When measured with a milliohm meter, the value is 21.2 mΩ, which is reasonably close to the desired value.

The heat generated by the current flowing through the resistor package is a concern, as it needs to be low enough to ensure all of the materials are below the deformation threshold. The temperature rise was calculated using Eqn. 2, assuming a maximum 350 kJ into the resistor.

$$\Delta T = \frac{E}{Cp \cdot m} = \frac{350kJ}{0.5\frac{J}{gm \cdot ^{\circ}C} \cdot 7.9kg} = 89^{\circ}C \qquad (2)$$

The calculated temperature rise is well below the maximum temperature of the G-10 material, which is 140 °C. As the capacitor bank is only capable of single-shot operation, the package will have sufficient time to cool between tests.

It was discovered during the design process that the resistor package needed additional support to prevent the internal pressures from forcing the material to bow after a shot. The maximum pressure was calculated using Eqn. 3.

$$p = \frac{\mu_0 \cdot I^2}{2 \cdot w^2} = \frac{\mu_0 \cdot (90kA)^2}{2 \cdot (10.2cm)^2} = 493kPa \qquad (3)$$

With an area of 619 cm^2, the maximum pressure is 30.5 kN. The design of the resistor package used six bolts, so the pressure per bolt is 5.1kN. The tensile strength of the grade 2 steel bolts is 10.5 kN, giving a safety factor of just over two. The tensile strength of the 304 stainless steel is 11 kN, giving a safety factor of 2.2. The maximum current the bank will deliver under test condition is 90 kA, so the design will perform satisfactorily.

II. EXPERIMENTAL DATA

Three sets of experimental data were taken, at three current levels, 4.6 kA, 54.7 kA, and 84.1 kA. Each current level was tested with and without the resistance package installed. For each shot, the L/R time was calculated and compared to the simulated data. The diode action was calculated for the measured shots, but the simulation of the diode current was beyond the scope of this work. Simulations of the diode current on this system can be found in [4].

Unless noted, each shot used the same circuit model shown in Fig. 6. A comparison of the L/R decay time and diode action is discussed in Section III.

A. 4.6 kA Shots

For the first shot series, two shots were taken with the bank charged to 500V and discharging 4.6 kA into the load. A control shot was taken first with the short installed and the resistor removed from the circuit. A comparison of the measured data and the simulated data is shown in Fig. 8.

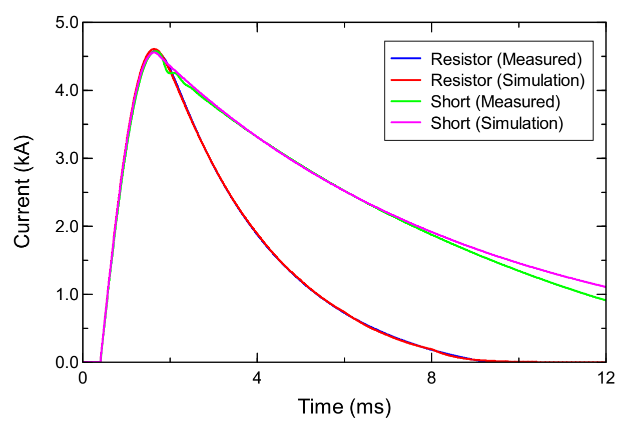

Figure 8. 4.6kA comparison between measured and simulated data with and without resistor installed.

For both shots, the simulated data matched well to the measured data. The L/R time was reduced by 63.2%, with the resistor at 2.58 ms and the short at 7.01 ms. Essentially all of the current was discharged after 9 ms with the resistor, while the current was still at 1.5 kA without the resistor at 9 ms. The simulation circuit for the resistor shot was modified to add resistance as the current decayed, as shown in Fig. 9. No modification was necessary for the simulation with a short.

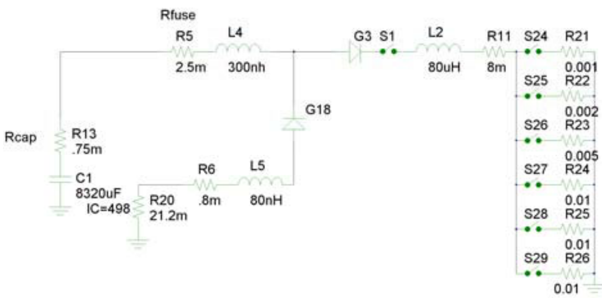

Figure 9. 4.6kA circuit model with late-time resistance modifications with resistor package installed.

A comparison of the diode current between the two shots is shown in Fig. 10.

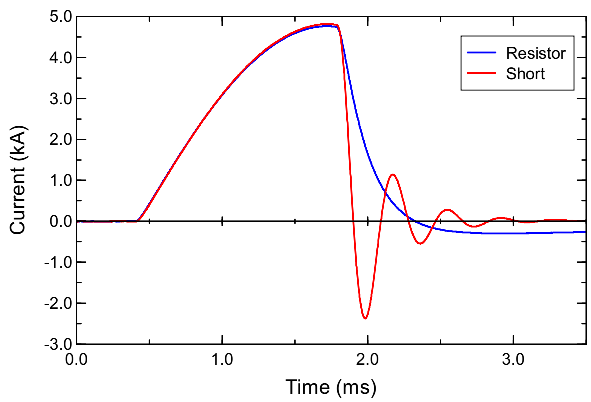

Figure 10. 4.6kA comparison of diode current between shots with and without resistor package installed.

With the resistor installed in the circuit, an over-damped condition is entered, with the ringback substantially reduced. Ringback with the short installed is 49.3%, while ringback with the resistor installed is 6.23%. The calculated diode action was 67.8 kA^2·sec with the short and 29.1 kA^2·sec with the resistor, which is 42.9% of the action in the shorted shot. This series indicates that even at low current levels the extra resistance in the crowbar circuit makes a substantial difference in diode stress levels.

B. 54.7 kA Shot

For the second shot series, the bank was charged to 6000V and 54.7 kA was discharged into the load. A comparison of the measured and simulated data with and without the resistor installed is shown in Fig. 11.

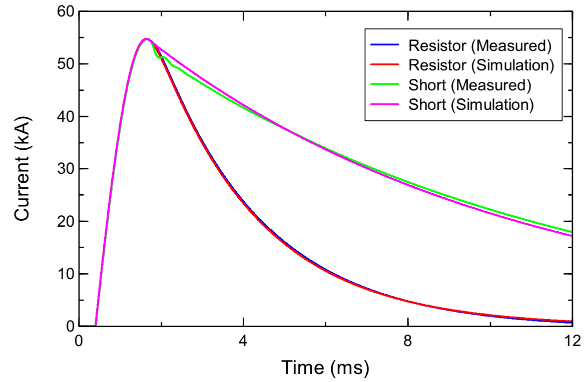

Figure 11. 54.7 kA comparison between measured and simulated data with and without resistor installed.

For both shots, the simulated data matched well to the measured data. The L/R time was reduced by 70.2%, with the resistor at 2.77 ms and the short at 9.29 ms. Essentially all of the current was discharged after 12 ms with the resistor, while the current was still at 17.97 kA without the resistor at 12 ms. The simulation circuit for the resistor shot was modified slightly from the base model to account for late-time current. The thyristor on-time resistance was changed from 0.15 mΩ to 0.0015 mΩ, while no modification was needed for the short simulation.

A comparison of the diode current between the two shots is shown in Fig. 12.

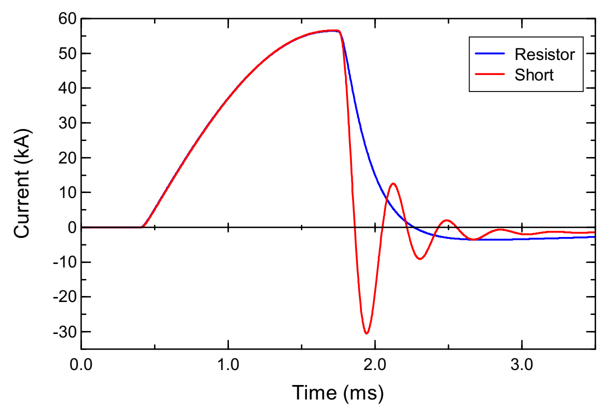

Figure 12. 54.7kA comparison of diode current between shots with and without resistor package installed.

With the resistor installed in the circuit, an over-damped condition is entered, with the ringback substantially reduced. Ringback with the short installed is 53.9%, while ringback with the resistor installed is 6.3%. The calculated diode action was 13.75 MA^2·sec with the short and 3.90 MA^2·sec with the resistor, which is 28.4% of the action in the shorted shot. This series indicates that at moderate current levels the extra resistance in the crowbar circuit makes a substantial difference in diode stress levels.

C. 84.1 kA Shot

For the third and final shot series, the bank was charged to 9000V and 84.1 kA was discharged into the load. A comparison of the measured and simulated data with and without the resistor installed is shown in Fig. 13.

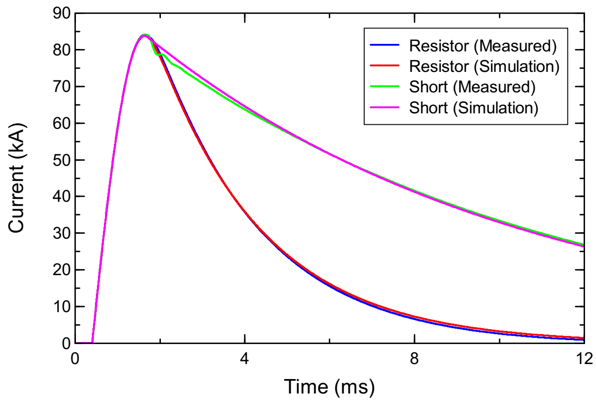

Figure 13. 84.1 kA comparison between measured and simulated data with and without resistor installed.

For both shots, the simulated data matched well to the measured data. The L/R time was reduced by 69.4%, with the resistor at 2.70 ms and the short at 8.83 ms. Essentially all of the current was discharged after 12 ms with the resistor, while the current was still at 26.8 kA without the resistor at 12 ms. The simulation circuit for the resistor shot was modified slightly from the base model to account for late-time current. The thyristor on-time resistance was changed from 0.15 mΩ to 0.0015 mΩ, while no modification was needed for the short simulation.

A comparison of the diode current between the two shots is shown in Fig. 14.

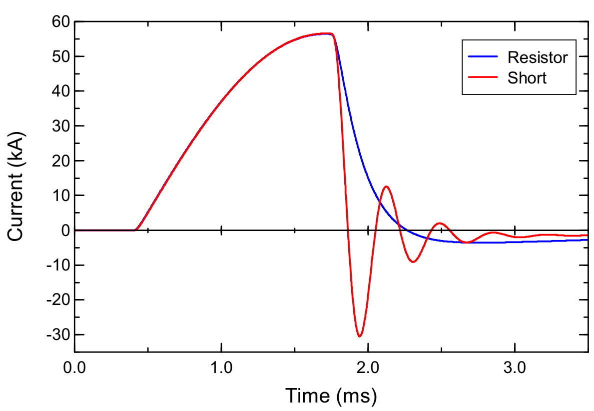

Figure 14. 84.1kA comparison of diode current between shots with and without resistor package installed.

With the resistor installed in the circuit, an over-damped condition is entered, with the ringback substantially reduced. Ringback with the short installed is 49.3%, while ringback with the resistor installed is 6.63%. The calculated diode action was 28.4 $MA^2 \cdot sec$ with the short and 9.0 $MA^2 \cdot sec$ with the resistor, which is 31.7% of the action in the shorted shot. This series indicates that at high current levels the extra resistance in the crowbar circuit makes a substantial difference in diode stress levels.

III. SUMMARY

Three shot series have been fired at various current levels to determine the effect of additional resistance in the crowbar diode stack on diode action and L/R decay time. Each shot series compared a shorted shot to a shot with the resistor package installed. A comparison of the L/R decay time for the different shots is shown in Table 1.

Table 1. Comparison of L/R decay time for all shots.

L/R Decay Time (ms)				
	Resistor (Measured)	Resistor (Sim)	Short (Measured)	Short (Sim)
4.6 kA	2.58	2.61	7.01	7.35
54.7 kA	2.77	2.16?	9.29	8.92
84.1 kA	2.70	2.16?	9.06	8.92

The data recorded strongly shows the effect of the resistor package when installed on the capacitor bank, as well as a close match to simulations. The L/R decay time was consistently much lower than a comparable shot without the resistor in the circuit.

A comparison of the diode action for the different shots is shown in Table 2.

Table 2. Comparison of diode action for all shots.

Diode Action ($A^2 \cdot sec$)			
	Resistor (Measured)	Short (Measured)	Change
4.6 kA	29.1×10^3	68.5×10^3	-42.4%
54.7 kA	3.9×10^6	13.8×10^6	-28.4%
84.1 kA	9.0×10^6	28.4×10^6	-31.7%

As the current is increased with the resistor package installed, the diode action is reduced. At 4.6kA, the action is 42.4% of the action with the short installed, but at 84.1kA, the diode action is only 31.7% of the action with the short installed. With this trend, the maximum charge voltage can be increased to obtain a higher output current without adding additional stress to the diode switches.

Future work on this project will include more realistic modeling of the switch hardware. Using the General Atomics fuse model to account for additional resistance in higher current shots in conjunction with the ABB thryristor SPICE model with provide better modeling as the current level changes. Simulations of the crowbar diode current will also be performed, along with diagnostic improvements to reduce pickup noise on the diode stack's rogowski probe.

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