EXPERIMENTAL DATA ON HIGH POWER EXPLOSIVE OPENING AND CLOSING SWITCHES AT CEM-UT

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The need for high power switching in pulse power research has lead to the development of fast acting opening and closing switches with current capacity of more than 1 MA. Presented is the performance data of two switches developed for railgun experiments at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). The first is a compact closing switch, explosively actuated, used as an isolation device for staging parallel inductors charged by homopolar generators (HPGs) and as a crowbar to shunt excess energy from railguns during projectile exit. The second is an explosive opening switch which provides a low resistance path during inductor charging before quickly opening to transfer energy to the railgun.

CLOSING SWITCH DESIGN

The original design, as reported by Peterson[1], has evolved into several new closing switches that are used in a variety of ways at CEM-UT. The newest design utilizes a ring of 3.2 g/m (15 grains/foot (gr/ft)) detonating cord to propel a copper throwring (10.31 inner diameter x 12.40 outer diameter x 0.64 cm thick) into a tapered coaxial gap between two steel catch pieces. Prior to detonation, the detonating cord and the throwring are held in a polyethylene cartridge. The steel catch pieces are reusable for many shots with minimal cleaning, however the cartridge and the throwring are expendable. The initiation of the detonating cord is done at two diametrically opposite points and the explosion propagates in both directions from each point. The time required for the switch to detonate is the time required for the cord to burn one-quarter of the way around the ring, about 10 μs. The copper throwring has shallow radiused serations or "scallops" machined on the inner and outer circumferences to provide multiple high pressure contacts as the ring is forced into the tapered gap. The throw rings, CNC-machined from 6.35 mm (0.25 in.) thick C11000 electrolytic tough pitch copper sheet, are annealed after machining for optimal seating in the taper. This versatile design has been utilized for several important switching requirements.

The switch was originally designed to shunt, or crowbar, excess current from the breech of HPG and capacitor bank powered railguns. Proper crowbarring of a railgun breech just prior to projectile exit of the gun is important to minimize damage to the muzzle, prevent projectile tip-off from a large muzzle blast, and eliminate excessive electromagnetic noise from the muzzle arc. Due to the reliable fast actuation of the switch, it has effectively crowbarred plasma armature hypervelocity railgun experiments which require precise timing (fig. 1). The high action capacity of the switch has made it most effective in crowbarring large solid armature tactical railgun experiments which have high exit currents, up to 1.5 MA.

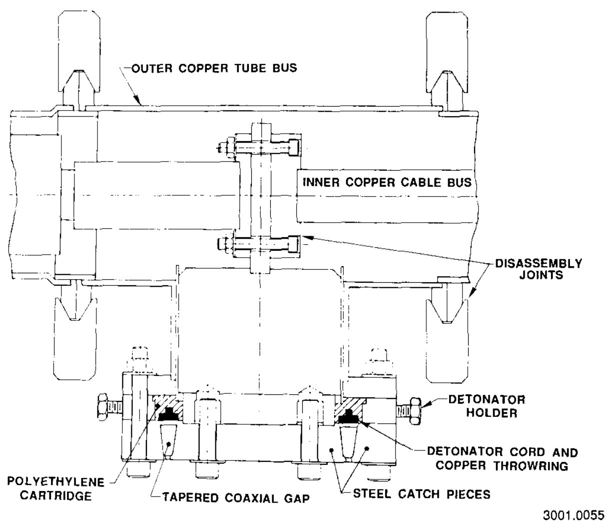

Figure 1. Coaxial version of closing switch which crowbars hypervelocity railgun experiments

Because of the switch's low resistance, it has found an important role in compulsator powered railgun experiments in which current is transferred with precise timing to a solid armature railgun injector. Since circuit voltage is relatively low, the explosive switch has replaced an ignitron, which is more resistive by two orders of magnitude. The switch provides repeatable timing, thereby preventing damage to the injector and railgun.[2]

The staging of parallel HPG-charged inductors allows for shaping current waveforms to the requirements of the specific load (fig. 2). Ignitrons were found to have a Coulomb rating which is not adequate for passing large currents for the extended time periods of these experiments. Two switches in parallel have successfully replaced two ignitrons as the device for isolating and staging (fig. 3). In this role the isolation switch must be able to hold off voltages up to 15 kV generated by parallel opening switches when commutating current. When the switch is closed, it must carry current for the duration of the gun shot as well as the decay time after the breech crowbars close. The isolation/staging switch design has successfully demonstrated its ability to hold off high voltages and pass large currents for long time periods.

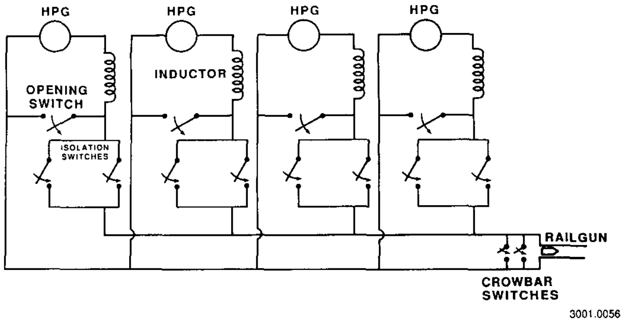

Figure 2. Opening and closing switches required in staging multiple HPG-charged inductors for a high power railgun experiment

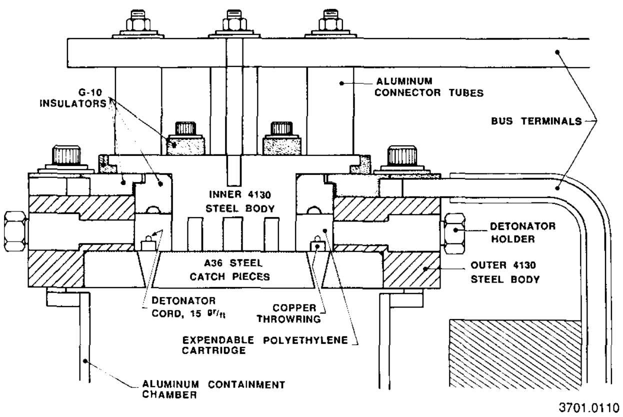

Figure 3. Parallel busbar version of closing switch used in isolating and staging multiple HPG-charged inductors

CLOSING SWITCH PERFORMANCE

Experimental characteristics and peak performance are as shown:

- **Time between detonator signal and current beginning in switch (jitter = ±10 μs)..... 80 μs**
- **Typical di/dt..........................5,000 A/μs**
- **Switch resistance including switch body... 10 μΩ**
- **Switch inductance including switch body... 100 nH**
- **Peak voltage holdoff..................... 14 kV**
- **Peak switch current to date............... 1.14 MA**
- **I^2t rating (peak $\int i^2 dt$ to date)-1.70 x 10^{10} $A^2 \cdot s$**

The I^2t, or action, rating is an indication of how long the switch will carry a high current without thermally damaging the catch pieces, which, at the contact interface, have a lower action rating than the throwring because the catch pieces are made of steel. Based on the total contact area around the scallops and the specific action constant of melt beginning for iron[3], the theoretical I^2t rating was calculated:

$$I^2t = (1{,}216\ mm^2)^2\ (12{,}806\ A^2 \cdot s/mm^4)$$

$$= 1.89 \times 10^{10}\ A^2 \cdot s$$

This compares to the empirical value of 1.70×10^{10} $A^2 \cdot s$. The values are within 10%, suggesting that the throwring seats very well and utilizes the available contact area.

This switch is a candidate for a fusion magnet experiment with requirements of 1.5 MA and 11×10^{10} $A^2 \cdot s$. The use of copper instead of steel as the catch piece material should increase the I^2t capacity of the switch by a factor of six, although a weaker material may withstand fewer shots. Preliminary mechanical tests have been made using copper catch pieces made of readily available copper plate with 1/8 hard temper. Several tests resulted in contact surface deformation of a degree which should not impair performance. A test involving a two fold increase in throwring diameter is also planned.

OPENING SWITCH DESIGN

Design and testing of several explosive opening switches used at CEM-UT were reported by Peterson[1], Rech[4,5] and Sledge[6]. Presented here are higher energy test data and a summary of mechanical improvements for the "monolithic" switch discussed in references 5 and 6.

The parallel plate configuration of the switch, incorporated in the buswork of six, 10 MJ HPG charged inductors, is shown in figure 4. The switch uses an aluminum switch element, 60.96 cm wide, made of 2.54 cm thick aluminum with either four or seven machined stress concentrations. A 10.6 g/m (50 gr/ft) detonating cord shears the 3.96 mm (0.156 in.) thick section of metal above the machined gaps. Seven gaps, instead of the usual four, are employed when switching into higher impedance loads such as plasma armature railguns. Gaps are detonated from each side, using a short length of 3.2 g/m (15 gr/ft) detonating cord which feeds into steel detonator feedthru blocks on either side of a steel containment vessel (not shown) around the switch. The feedthru blocks permit exploding bridgewire detonators to be installed just prior to the experiment, without unbolting the containment.

Mechanical improvements were required as higher explosive arc and magnetic pressures were encountered. Shown in figure 4 is the present design of the switch. Opening arcs are expanded with explosive gases and magnetic pressure into air and into a polyethylene foam with a density of 96 kg/m^3 (6 lb/ft^3). A copper commutation busbar, slotted for venting of the arc blast, has polyethylene protectors to prevent arc coupling. Also featured is an S-2 glass filament wound, epoxy impregnated, support block required to react the simultaneous blast pressure and magnetic loading on the commutation busbar. A G-10 plate is bolted to and supports the switch element from a magnetic pressure of 200 psi during inductor charging to 1.2 MA.

OPENING SWITCH PERFORMANCE

As of the last reporting, the opening switch had opened currents up to 708 kA and developed voltages up to 6 kV. Switching of current up to 650 kA into loads of up to 1 μH and 1 mΩ resulted in switch efficiencies of 92 to 94%. Switching into loads of higher impe-

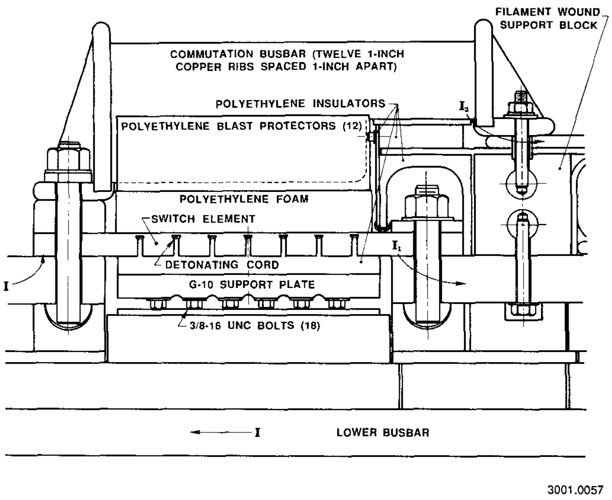

Figure 4. Monolithic element opening switch used in the Balcones 60 MJ power supply

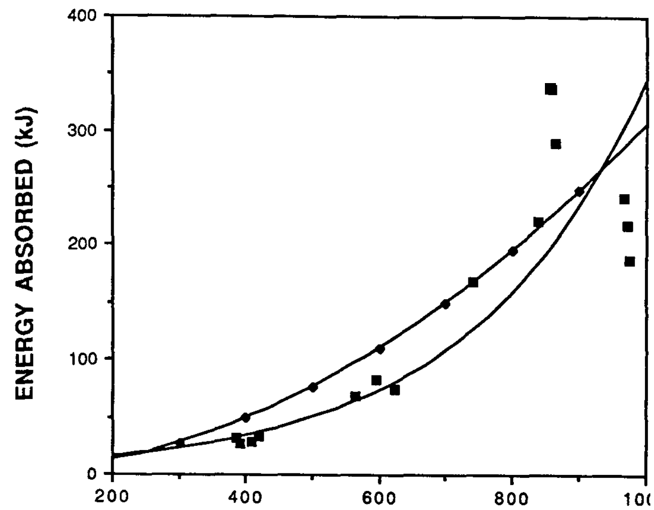

Figure 5. Theoretical and experimental values of opening switch absorbed energy vs. current

dance yielded efficiencies in the low 80's. A switch characterization of resistance vs. time was illustrated along with a table of performance and calculation methods for switching efficiency, load inductance, and load resistance[6]. Opening time was defined as the time interval in which switch current changes from 100 to 2% of initial value. This convention is preferred at CEM-UT over the standard 90 to 10% convention because of higher accuracy. An HPG/inductor/opening switch circuit diagram with electrical parameters was presented by Gully[8].

New performance data are given in table 1. Switch efficiencies are slightly lower (85 to 90%) for currents over 650 kA switching into 1 µH, 1 mΩ loads, as shown in table 1, rows 1, 2, and 4. Plotted in figure 5 are theoretically and experimentally determined values for switch energy absorption at various currents. Experimental values were calculated as follows:

$$E = \int vidt$$

where v is the voltage across the switch and i is the current through the switch during the opening time, using the 100 to 2% convention. Theoretical energy absorption was calculated using:

$$E = \frac{1}{2}I^2 \frac{L_1 L_2}{L_1 + L_2} \qquad [4]$$

where L_1 and L_2 are the inductances of the primary and secondary circuits and I is the initial switch current. For the primary circuit including the 6.5 µH inductor, L_1 = 6.94 µH. The secondary circuit inductance of L_2 = 0.67 µH was calculated for this plot by averaging experimentally determined load inductances, varying from 0.36 to 1.15 µH, for each experiment plotted.

A typical time from detonator signal until the first indication of current decreasing through the switch is 103 µs as shown in Table 1. Although detonating cord length is consistent from shot to shot, jitter times of ±28 µs have been experienced. Reasons for this magnitude of jitter are presently unknown.

New peak current and voltage values are 1.22 MA and 12 kV. In the 1.22 MA experiment, the switch gaps were intentionally melted open by allowing excessive I^2t in the switch before explosive detonation (see table 1, row 6). The switch fully opened in 6.2 ms, before detonation. The purpose of the experiment was to test busbar clamping at peak current, and to determine an accurate specific action constant for the switch element so that it could be accurately sized for passive thermal failure in the event of detonation failure. Passive opening capability is desired to prevent HPG rotor reversal due to an underdamped ringing circuit. The switch element thickness was measured carefully before the test to get an accurate area. Specific action was calculated using area and the value of I^2t up to the time when current began decreasing, as follows:

$$g = \frac{I^2 t}{A^2} = \frac{1.357 \times 10^{10} A^2}{(2{,}262.6\ mm^2)^2}$$

$$= 29{,}016\ \frac{A^2 \cdot s}{mm^4}$$

When switch current reached zero, the I^2t was $1.43 \times 10^{11}\ A^2 \cdot s$ corresponding to a specific action of 30,620 $A^2 \cdot s/mm^4$.

These compare to published action constants for aluminum of:

Table 1. New performance data for the four-gap monolithic opening switch

Shot Number	Power Supply	Load Inductance (μH)	Load Resistance (mΩ)	Current Opened (kA)	Current Transferred (kA)	Opening Time (μs)	Time to first current drop (μs)	Peak Switch Voltage (kV)	EABS (kJ)	Switch Efficiency (%)
3-M #13	two	0.6	1	740	666	120	75	5.7	169	90
	HPGs	- - -*	- - -	729	653	105	75	- - -	- - -	- - -
10-M #1	three	1	0.9	857	737	140	110	7.6	338	85
	HPGs	1	- - -	837	723	150	95	5.8	222	90
			0.9	863	746	140	90	7.5	290	87
10-M #4	four	2	6	971	818	175	95	7.7	459	84
	HPGs	1	4	970	846	175	100	8.5	404	86
		- - -	- - -	992	799	- - -	- - -	5.1	- - -	- - -
		- - -	- - -	971	743	- - -	100	7.8	- - -	- - -
10-M #9	five	0.7	0.8	975	843	145	80	5.8	188	93
	HPGs	- - -	- - -	973	843	150	85	5.6	218	92
		0.6	3	966	822	125	105	6.8	242	91
		- - -	- - -	974	793	- - -	130	7.9	- - -	- - -
		- - -	- - -	970	837	- - -	- - -	- - -	- - -	- - -
10-M #7	one HPG	- - -	- - -	1110	1030	105	100	- - -	- - -	- - -
Switch experiment	one HPG	∞ (no load)	∞ (no load)	1220	NA	6200	NA	1.2	4460	NA

* Insufficient data available

Melt beginning $g = 25{,}238\ A^2 \cdot s/mm^4$
Melt ending $g = 32{,}035\ A^2 \cdot s/mm^4$ [2]

After this test, the specified standard switch area was changed to 2,415 mm^2, corresponding to a maximum I^2t of $1.69 \times 10^{11}\ A^2 \cdot s$ required for proposed railgun experiments. If necessary, the I^2t capacity of the monolithic switch could be increased to $3.89 \times 10^{11}\ A^2 \cdot s$ by increasing the section of metal above the gap to 6.35 mm (0.25 in.) thick. This thickness was sheared successfully using 21.2 g/m (100 gr/ft) cord[5].

CONCLUSION

The explosively actuated closing switch developed at CEM-UT has demonstrated its advantages. Because of repeatable rapid closing and high I^2t capacity it has been used to replace ignitrons in several high power circuits. Due to the switch's compact coaxial design, the assembly is mechanically rigid and easily adapted to both coaxial and flat-plate bus geometries. Direct metal contacts in the switch eliminate large voltage drops inherent to arc initiated closing switches. High current flowing in the closed switch provides a large magnetic pressure that assists in maintaining adequate contact pressure between the throwring and catchpieces.

The utility of the monolithic opening switch has been demonstrated in a multitude of tests. To efficiently power a hypervelocity railgun experiment, switching must be completed quickly with respect to projectile in-bore residence time. For these experiments currents of less than 500 kA were opened in 45 to 95 µs, less than 15% of residence time. The challenge of powering long (10 m) tactical railguns with more massive payloads has been met by opening currents of 500 kA to 1.2 MA in 100 to 175 µs and holding off voltages for long times (10 ms).

Railguns at CEM-UT are successfully powered with compulsators and HPG's employing these fast acting explosive switches. Through the use of staged HPG inductive power supplies, the switches are instrumental in meeting specific experimental requirements by allowing a wide variety of power conditioning and pulse shaping. Both of the switches have proven high I^2t capacity and their ability to transfer currents of over 1 MA.

ACKNOWLEDGEMENT

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