HIGH POWER SWITCHES AT THE CENTER FOR ELECTROMECHANICS
AT THE UNIVERSITY OF TEXAS AT AUSTIN

R. L. Sledge, D. E. Perkins, and B. M. Rech

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Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

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Abstract: Railgun experiments require reliable transfer and interruption of large currents in order to provide fast rise times and protect circuit components. The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has developed three high coulomb explosively actuated opening switches which have demonstrated reliability and fast switching in railgun experiments. Two of these switches first provide a low conductivity path to transfer energy from homopolar generators (HPGs) to inductive energy stores and then open to commutate current to the railgun. The first switch is a monolithic aluminum element with machined stress concentrations. The second uses reloadable cartridges mechanically clamped. The third switch is designed to interrupt current in a compulsator powered railgun experiment. In the event of a short circuit fault the switch automatically opens in order to prevent overheating of the compulsator armature windings. This paper reviews the design and excellent performance of these switches.

Design of Monolithic and Clamped Element
Opening Switches for HPG-Inductor-Railgun Circuits

The topology selected for both switches is a parallel plate configuration. The switch designs incorporate multiple gaps in series to increase opening and holdoff voltage, the use of magnetic assistance for arc blowout, and magnetic insulation for increasing the hold-off voltage of the gaps. The monolithic switch also features a unique dovetail stress concentration to facilitate mechanical separation of the gaps. A 21.2 g/m (100 grains/foot (gr/ft)) detonating cord actuates the full scale monolithic switch, which is rated at 1.5 MA. All of the electrical testing of the monolithic switch to date has involved a half scale, 750 kA rated version which is actuated by 10.6 g/m (50 gr/ft) detonating cord. The C-beam switch is innovative in the use of a clamped element which provides the conductive state during charging and is then explosively removed. The C-beam switch efficiently uses 3.2 g/m (15 gr/ft) detonating cord for actuation and features reusable aluminum channel beams and steel wedges to clamp the element.

The mechanical design and testing of the monolithic and clamped element (C-beam) opening switches were presented by Rech, et al., in a previous paper.[1]

The monolithic switch was chosen as the opening switch for the Balcones Homopolar Generator 60 MJ Power Supply at CEM-UT because it preceded the C-beam switch and was fully operational in a smaller railgun test lab at CEM-UT when the decision was made. The switch is instrumental in allowing a wide variety of pulse shaping and power conditioning experiments through the use of staged HPG inductive power supplies. The energy of the system is controlled for each experiment by dialing in the desired rotor speed

and field excitation of the HPGs. Timers execute the staged switching of the inductive stores. Large mass hypervelocity tactical projectiles are propelled using several high energy inductors discharged at once with subsequent generators switched in to support a relatively constant current input. Low mass, extremely high velocity strategic projectiles are accelerated with lower peak currents transferred to the gun at more frequent intervals to provide a constant current waveform.

Electrical Performance of Monolithic
and C-Beam Opening Switches

Twenty-three railgun shots were performed at CEM-UT from September 1986 to December 1987 using the C-beam and half scale monolithic opening switches. A major goal of the experiments was to establish versatility in pulse shaping which would allow optimization of railgun acceleration (as well as the tailoring of current waveforms to the requirements of a wide range of other specific loads) as discussed by Upshaw[2] and Gully[3]. Four different power supply arrangements were used in order to meet the power requirements of each shot and to shape the current waveform to the railguns. These four configurations required the opening switch to maintain gap insulation strength for long times (several milliseconds). Results of some of these experiments are shown in table 1.

Modest current (less than 500 kA) plasma armature experiments in a 1 m long railgun were performed using a single HPG charged inductor as in figure 1. To efficiently power a hypervelocity railgun experiment, switching must be completed quickly with respect to the projectile in-bore residence time. As seen in figure 1, switching is accomplished in less than 15% of the total acceleration time. Experimental parameters for both monolithic and C-beam switches in this test configuration are given in table 1, rows 1 and 2.

Figure 1. Railgun shot involving one HPG-charged inductor.

Table 1. Switching performance of monolithic and C-beam opening switches during railgun experiments

Railgun Shot No.	Power Supply	Circuit	Opening Switch Type	Gaps per Switch	Load Inductance (nH)	Load Resistance (mΩ)	Current Opened (kA)	Current Transferred (kA)	Opening Time (μs)	Peak Switch Voltage (kV)	E _{ABS} (kJ)	Switch Efficiency (%)
GEDI 1 m #20	HPG	See fig. #1	Monolithic	2	266	1.59	408	351	140	3.3	28.9	94.2
GEDI 1 m #23	HPG	See fig. #1	C-beam	2	363	1.70	421	383	140	2.4	34.2	93.6
GEDI 2 m #03	HPG & BANK	See fig. #2	Monolithic	2	366	1.71	391	348	90	3.0	26.5	94.2
GEDI 1 m #24	HPG & BANK	See fig. #2	C-beam	2	360	1.70	388	346	180	1.9	32.3	92.9
TASK B #05	TWO HPG's	See fig. #3	Monolithic Monolithic	4 4	936 662	0.361 0.441	564 592	515 539	85 90	5.1 ---	68.7 ----	92.8 ----
TASK B #06	TWO HPG's	See fig. #3	Monolithic Monolithic	4 4	1,055 703	0.423 0.503	595 624	538 575	100 100	4.7 4.4	82.2 74.4	92.3 93.8
GEDI 8 m #01	FOUR HPG's	See fig. #4	Monolithic Monolithic Monolithic Monolithic	4 4 4 4	850 866 2,083 1,918	0.970 3.75 4.66 2.52	450 155 247 288	387 144 197 232	90 50 95 85	6.5 3.6 5.2 4.4	----- 12.4 33.4 40.0	----- 82.8 81.8 83.9

Plasma armature experiments in longer railguns (2 m) were powered by a single HPG charged inductor in parallel with a capacitor bank in order to maintain a positive di/dt in the gun as seen in figure 2. In addition, this testing demonstrated that individual HPG inductive power supplies could be staged in time. It can be seen from figure 2 that the opening switch does not restrike when the capacitive voltage is applied 250 μs after detonation time (time zero). Typical experimental parameters for the two types of switches are given in table 1, rows 3 and 4.

Solid armature experiments which required high currents (up to 1.4 MA) were powered using two HPGs in parallel and switched simultaneously as shown in figure 3. This testing demonstrated that long duration, high current pulses could be sustained by the power supply and switches for tactical railgun testing (see table 1, rows 5 and 6).

In order to power an 8 m long plasma armature railgun, four HPGs, isolated using ignitrons, were staged. The switches opened consecutively, held off high voltages, and provided a positive average di/dt to the railgun as shown in figure 4 (see also table 1, row 7).

Performance of the switches was evaluated along with other circuit parameters as follows:

R = resistance of the load calculated using $R = v/i$ at $di/dt \approx 0$. The resistance changes with experimental configuration.

• Capacitive effects were negligible.

L = inductance of the load calculated using

Figure 2. Railgun shot involving a capacitor bank in parallel with an HPG-charged inductor.

Figure 3. Railgun shot involving two HPG-charged inductors in parallel and switched simultaneously.

Figure 4. Railgun shot involving four HPG-charged inductors isolated by ignitrons and switched sequentially.

$$L = \frac{v - iR}{\frac{di}{dt}}, \quad \text{at}$$

$dv/dt \approx 0$ with $di/dt \gg 0$. The buswork and railgun inductances change with experimental configuration.

Opening Time = time interval in which switch current changes from 100 to 2% of initial value (90 to 10% was used in Ref [1], but 100 to 2% was chosen to present a more accurate model).

$$E_{\text{abs}} = \int_0^{\text{opening time}} V_{\text{sw}} i_{\text{sw}} dt = \text{energy absorbed in switch during opening time}$$

$$\text{Switch efficiency} = 1 - \frac{E_{\text{abs}}}{0.5 L_{\text{ind}} i_{\text{ind}}^2}$$

where

V_{sw} = switch voltage
 i_{sw} = switch current
 $L_{\text{ind}} = 6.0 \mu\text{H}$ = inductance of inductor
 i_{ind} = initial inductor current

While both switches are rated for currents over 1 MA, the half scale version of the monolithic switch was used for these relatively low current shots, thereby using only half of the chemical explosives of a full scale version. Note that the C-beam performed nearly as well as the monolithic switch but used only 1/3 the amount of explosives.

Monolithic opening switch resistance vs. time is plotted for various currents in figure 5. The data points are incorporated in computer simulations as the switch model during opening. Time zero of this plot corresponds to detonator signal time and the switch begins opening 50 to 60 μs later.

Figure 5. Monolithic opening switch resistance vs. time in railgun experiments. Time zero is detonation time.

Based on the action integral for melting of aluminum[5], initial design calculations predicted thermal failure of the half scale monolithic switch element at a current of 750 kA, corresponding to an I^2t of $1.20 \times 10^{11} \text{ A}^2 \cdot \text{s}$. One of these elements was inadvertently taken to 1.21 MA during a simultaneous

discharge of two HPG's in which one switch did not detonate due to an insufficiently charged firing module. When the other switch opened, most of the available inductor current transferred to the unopened switch element, a path of lower inductance and resistance than the railgun and crowbar circuit. Resultant data allowed the calculation of an experimental I^2t rating as follows:

$$I^2t = \int i_{\text{sw}}^2 dt = 1.32 \times 10^{11} \text{ A}^2 \cdot \text{s}$$

After carrying the excessive current for about 100 ms, the element failed thermally without detonating the chemical explosives. The thermal failure resulted in a fast switch opening similar to an exploding wire fuse and prevented circuit ringing and subsequent HPG brush damage due to rotor reversal. Given this data point, switch elements can be more accurately sized for passive opening and protection of HPG's.

Design of Opening Switch for Compulsator-- Railgun Circuit

Requirements of the opening switch for the Iron Core Compulsator differ from those used in homopolar generator railgun experiments. The compulsator switch is designed only to prevent overheating of the compulsator armature windings by interrupting current in the event of a short in the buswork or a jammed railgun projectile. Because of their fast opening times and ease of integration with electronic controls, an explosive opening switch was chosen for this system.

Since the armature windings of the compulsator are not cooled, only ten full current (1.0 MA) pulses may be transmitted without danger of overheating. Given a frequency of 235 Hz at full speed, 21 ms are available to detect a short circuit and interrupt the current. The fault control monitor used for triggering the opening switch can actually respond as quickly as 4.3 ms, i.e. two consecutive pulses.

The switch is located close to the compulsator to minimize the sites where uninterruptable short circuits could form. The three output terminals from the machine feed into the switch which then distributes the current to coaxial busbars. Given the physical constraints of the busbars and generator terminals, the switch design shown in figure 6 was developed. Two detonators activate a 1.07 m length of 3.2 g/m detonator cord located beneath aluminum conductor elements on the outer face of the switch. Stress concentrations machined into the aluminum elements ensure fracture of the material. Rapid expansion of the explosive gases drive the elements outward opening a 6.35-cm gap.

Further development of the switch elements was based on the following conditions:

- conductive area must be sufficient to prevent overheating of the elements during ten, 1-MA pulses
- the elements must resist the magnetic separation forces developed by the high currents
- when actuated, the element separation must be sufficient to prevent restrike of the 2 kV machine output

The last two conditions were important in considering the length of the elements. Longer elements would yield more separation and higher voltage standoff but would experience greater bending stress.

Figure 6. Compulsator opening switch design.

Loading on the switch elements was determined from conductor repulsion force equations.[4] Assuming an even distribution of current through each one of the 20 elements (50,000 A each) the load on each is 98.6 N/cm. Simple beam calculations show that the 6061-T6 alloy element is strong enough to resist the magnetic forces.

$$F = \frac{5.4 \times 10^{-7} I_1 I_2}{S}$$

where

F = conductor load (lb_f/ft)
 I_1 = current per element (A)
 I_2 = parallel current in back of switch
 S = distance between element and current path at back of switch (in.)

Mechanical testing of samples revealed the importance of the element holding clamps. Radiused corners of 3.3 mm (0.13 in.) or greater were required to prevent bending failure which would result in loose metal in the gap area. Additionally, sufficient clamping force was required to keep the elements from sliding. Elements that slid under the clamps either failed to produce a sufficient gap or did not open at all. Without stress concentrations machined in the center of the element, fracture usually occurred at the support clamp.

Materials tested included 0.76 mm (0.030 in.) thick ETP copper, 0.81 mm (0.032 in.) thick 5052-H32 and 6061-T6 aluminum, 1.60 mm (0.063 in.) thick 5052-H32, 6061-T6 and 2024-T3 aluminum, 1.80 mm (0.071 in.) thick 2219 aluminum, and 2.29 mm (0.090 in.) thick 5052-H32 and 6061-T6 aluminum. The 5052 and 6061 alloys performed well. Their notch sensitivities produced clean breaks at the stress concentrations while they were ductile enough to bend at the clamps. Further tests of 2.29 mm thick elements with stress concentrations of 3.18 mm wide by 1.02 mm deep were performed with favorable results. 6061-T6 aluminum was chosen over 5052-H32 for conductivity, cost, and availability considerations.

Figure 7. Five element sector of compulsator opening switch.

Several switch detonations were performed with no electrical load to obtain consistent conductor separation. During these tests yielding of the elements around the bolt holes was noted on the inner bolt circle. Consequently, a new unitized element (fig. 7) was designed which eliminated this problem and reduced reloading time and the bolt torque required.

In sizing the switch elements, resistive heating was considered. The elements were designed to be reusable in the event of a no-fault compulsator discharge. A temperature rise limit was set and a minimum cross sectional area requirement was determined.

Since the temperature exposure time for ten successive 1.0-MA pulses is only 21.3 ms and switch insulator materials have short term temperature exposure ratings of approximately 260°C, a temperature rise of 200°C was considered acceptable.

The allowable current density for a given conductor temperature rise is given by

$$J = \left[\frac{\rho C_p \sigma}{\alpha t} \ln(\Delta T \alpha + 1) \right]^{\frac{1}{2}}$$

where

J = current density (A/m²)
 ρ = density of conductor (kg/m³)
 C_p = specific heat capacity (J/kg · °C)
 σ = conductivity (mho/m)
 α = coefficient of resistivity (1/°C)
 ΔT = temperature rise (°C)
 t = duration of current flow (s)

for aluminum conductors, yields

$$J = 7.689 \times 10^8 \text{ A/m}^2$$

From this the minimum area A can be determined,

where

$$A = \frac{I}{J} = \frac{1 \times 10^6 \text{ A}}{7.689 \times 10^8 \text{ A/m}^2} = .0013 \text{ m}^2 (2.02 \text{ in.}^2)$$

The actual minimum conductor area is at the stress concentration of the elements where $A = .0014 \text{ m}^2$. Although it appears that this design may be marginal it must be noted that the minimum area requirement was based on a continuous dc 1.0 MA current for the full 21.3 ms.

Electrical Testing of Compulsator Opening Switch

Performance under load was shown by discharging capacitor banks across the switch and triggering the switch to open at peak current. Results of these tests are shown in table 2. Generation of inductive voltage was monitored closely since extremely fast opening times of high currents could cause back voltage in the armature windings far in excess of their standoff rating. Fortunately, at higher currents, switch opening times were found to increase due to arcing between elements. This was evidenced by melting on the corners of the broken edges.

Table 2. Explosive switch capacitor discharge tests

Capacitor Voltage	Current	Opening Time	Switch Volts Generated
(Volts)	(Amps)	(μs)	(Volts)
180	150	28	305
180	900	57	154
180	900	12	364
4,000	117,600	400	615
5,000	252,200	560	708

With these tests completed, the switch was installed into the compulsator busbar system for continued testing. Presently, the explosive switch has been detonated intentionally on almost every compulsator run as a precaution to prevent machine damage in the event of an undetected fault. Switch triggering is performed by a fault control monitor which senses any of three fault conditions: 1) maximum number of current pulses, 2) successive high current positive and negative pulses, and 3) timer for automatic detonation after machine discharge. A nice feature of the fault control monitor is that it senses machine current and waits for it to decay sufficiently before triggering the switch. In this manner, the switch is opened only as it approaches zero current, thus preventing restrike and also minimizing inductive voltages.

Conclusions

The monolithic and C-beam opening switches are advancements in the pulsed power community since they permit charging inductors with I^2t magnitudes of $10^{12} \text{ A}^2\cdot\text{s}$ while consistently and efficiently commutating current to a load in about 100 μs . For experiments with load inductances up to 1.1 μH and load impedances up to 1.7 $\text{m}\Omega$, the energy dissipated in the opening arc is less than 10% of the inductively stored energy, indicating switching efficiencies of over 90%. The monolithic switch has proven its ability to open as an explosive fuse in the event of detonation failure, thereby protecting the generators from rotor reversal due to an underdamped ringing circuit. In railgun experiments the switch has developed voltages of over 6 kV and has opened currents up to 708 kA. Neither switch has been fully tested in terms of maximum current opened or maximum voltage held off.

The monolithic switch was chosen as the opening switch for the Balcones Homopolar Generator 60 MJ Power Supply at CEM-UT because it preceded the C-beam switch and was fully operational in a smaller railgun test lab at the time. The switch is instrumental in allowing a wide variety of pulse shaping and power conditioning experiments through the use of staged HPG inductive power supplies.

The opening switch for the Iron Core Compulsator provides reliable protection from excessive heat in the compulsator armature windings in the event of a short circuit fault such as a voltage breakdown or jammed railgun armature. Although the switch is required to hold off a maximum of 2 kV in the compulsator circuit, the 6.35 cm (2.5 in.) gap would probably hold off order-of-magnitude higher voltages if required in other applications.

The three high power opening switches are mechanically simple, easy to install, and inexpensive to operate and maintain. They have proven to be highly reliable and have consistently demonstrated excellent performance in hypervelocity and extremely high velocity railgun experiments at CEM-UT.

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