DESIGN AND CONSTRUCTION OF A TWO-STAGE OPENING SWITCH

B. M. Rech, and R. C. Zowarka, Jr.

Presented at the
3rd Symposium on Electromagnetic Launch Technology
Austin, Texas
April 20-24, 1986

Publication No. PR-48
Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

Abstract - Homopolar generators (HPGs) are modern day energy stores (megajoules) capable of large currents (megamps). The generators are typically low voltage and large capacitance, disallowing loads requiring fast rise times to be driven directly by the HPG. An opening switch must be provided to first, in the closed state, transfer energy from the high current source to an inductive energy store and then open to commutate the current to the load. To charge an inductive energy store with large currents for long times (hundreds of milliseconds) indicates a massive switch with many low resistance contacts. At the same time the switch must commutate current to the load in a short time interval (tens of microseconds) indicating a light, fast-acting device. A two-stage opening switch addresses these two conflicting requirements. The first stage is a massive mechanical switch of coaxial geometry with many low resistance galvanic contacts, which commutates through a low inductance to an explosive element second stage. The second-stage switch is then interrupted explosively to provide the microsecond commutation.

The design, manufacture, and testing of the two-stage opening switch were performed at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) Taylor Hall facility in Austin, TX, using a compact homopolar generator (CHPG) and a five-turn coaxial, cryogenic inductor as the pulsed power supply. Initial testing included mechanical actuations and electrical measurements to verify fundamental operation and proper assembly. Testing continued with the CHPG charging the inductor through the switch statically (no commutation) to characterize the current carrying capability of the primary galvanic contacts. Next, tests to check the ability of the first stage to commutate to the second stage by sliding the primary contacts onto the armature insulator were conducted. The fourth phase of testing was a series of two-stage (double) commutations to a fixed load to characterize performance and timing of triggers, voltage hold-off capability, and fixed load commutation times. The fifth and last phase of testing involved the two-stage switch commutating current to a variable impedance (railgun) load.

ELECTRICAL DESIGN

There were three major considerations addressed during the electrical design of the first-stage switch:

1. heating under the switch contacts due to the A^2 -s duty of the CHPG charging the energy storage inductor,
2. the peak constriction current force the contacts would experience, and
3. the energy dissipation required of the contacts in the inductive transfer of energy to the second-stage switch.

The A^2 -s rating for the opening switch was determined using a simulation of the highest energy CHPG-inductor discharge. The total A^2 -s passed through the switch at peak current is $1.2 \times 10^{11} A^2$ -s. If the switch failed to open, the A^2 -s associated with a complete ring out of the homopolar and inductor is $2.7 \times 10^{11} A^2$ -s.

Manuscript received March 17, 1986

The author is with the Center for Electromechanics at The University of Texas at Austin, Austin, TX 78758-4497.

The mechanical opening switch design is based on that of present making switches [1] on the 10-MJ HPG located at the CEM-UT. Data taken from the making switches produced the design parameters of the first-stage switch. The making switch has successfully passed $3.5 \times 10^{11} A^2$ -s and never failed due to thermal effects under the contacts. Therefore, $3.5 \times 10^{10} A^2$ -s is a conservative estimate for the rating of the making switches. During a discharge through a present making switch, the blowoff force due to constriction currents was exceeded. The failure occurred at 260 kA. The contacts were grossly melted and the downforce was measured at 26.7 to 44.5 N (6 to 10 lbf). A second switch in parallel carried 428 kA successfully but the current trace showed a slight instability. Inspection revealed no contact damage and downforce was measured at 66.7 to 88.9 N (15 to 20 lbf). This information was used in subsequent analysis of the contact in the first-stage switch.

Current flows between contacts through constricted areas (domains). This current when flowing in opposite directions toward and away from the constriction area, gives rise to a force tending to separate the contacts. This force, based on Ampere's law, about any domain is

$$F = 2.25 \times 10^{-8} I^2 \ln \frac{R}{r}$$

where

- F = force in lbf
- I = current in amperes (RMS)
- R = equivalent radius of the contacts
- r = equivalent radius of constricted area

The contacts in question are formed by splitting a 12.2 cm (4.8 in.) diameter, 1.9 cm (0.75 in.) high ring into 24 segments. The equivalent radius of the contact is, therefore

$$R = 0.98 \text{ cm (0.387 in.)}$$

To calculate the equivalent radius of the domain, the test results of 260 kA overcoming an 8-lb downforce are applied to the equation below:

$$\ln \frac{R}{r} = \frac{F}{2.25 \times 10^{-8} \frac{I_p^2}{2}}$$

$$r = 0.022 \text{ mm (0.87 mils)}$$

where, the peak current through one contact was taken to be $260,000/24 = 10,800$ A. This result may be further investigated by calculating the current carrying capability of the same contact arrangement loaded with 17.5 lbf as shown below,

$$I_p = \sqrt{\frac{2F}{2.25 \times 10^{-8} \ln \frac{R}{r}}}$$

$$I_p = 15,972 \text{ A.}$$

The total current expected through 24 contacts before instability occurs is 383 kA. This prediction is within 10% of the measured instability at 428 kA. Using this analysis the number of contacts required for a 1-MA discharge is

$$N = \frac{I_t}{\sqrt{\frac{2(F)}{2.25 \times 10^{-8} \ln \frac{R}{r}}}}$$

where

$$I_p = \frac{I_t}{N}$$

I_t = total current
 N = number of contacts
 $F = 20 \text{ lbf}$

Therefore,

$$N = 58 \text{ contacts.}$$

To accommodate the need for more than double the contacts without increasing the mass of the moving parts of the switch, the moving armature was redesigned as a right circular hollow cylinder with brushes on both the inner diameter (ID) and outer diameter (OD). A cross section of the switch with the improved electrical contacts is shown in Fig. 1. The final design incorporates 60 contact fingers, 30 on the ID and 30 on the OD. This increases the contact surface by a factor of 2.5 and should establish a conservative i^2t rating of $0.88 \times 10^{11} \text{ A}^2\text{-s}$ for the opening switch. This rating is scaled from performance of making switches which have not been tested to thermal failure.

A final requirement of the electrical design was to estimate the contact erosion due to the energy dissipation associated with the commutation of current into the second-stage switch. The discharge circuit for the CHPG charging the cryogenic energy storage inductor through the staged opening switch is shown in Fig. 2.

The electrical parameters for the mechanical opening switch circuit and the second-stage explosive switch and buswork are identified in Fig. 3. A computer simulation of this model was performed and the peak charging current was found to be 800 kA. The theoretical energy absorption in a purely resistive opening switch making a step change in conductivity is given by the expression [2]:

Fig. 1. Opening switch showing improved electrical contacts.

$$E = \left(\frac{1}{2} L_C I^2 \right) \frac{L_2}{L_2 + L_C}$$

where

E = energy absorbed
 L_C = inductance of the primary circuit
 I = current
 L_2 = inductance of the secondary circuit

Therefore,

$$E = 10.5 \text{ kJ.}$$

One advantage of staging the switch is the fact that current is held out of the explosive elements until actuation begins. Therefore, the explosively interrupted sheets only carry current for 3 ms. They may be made lighter weight and more easily interrupted (less explosive required). The other advantage of staging the switching is realized when the second-stage switch is connected in parallel with the primary

Fig. 2. Discharge circuit for CHPG charged cryogenic inductor.

Fig. 3. Circuit parameters associated with switch components

switch prior to the first stage opening. The current divider then requires:

$$i_2 = \frac{R_1}{R_1 + R_2} i$$

where

- R_1 = is the resistance of the primary switch
- R_2 = is the resistance of the secondary switch
- i = primary current
- i_2 = commutated current

$$i_2 = 190 \text{ kA}$$

The energy absorbed then reduces to

$$E = 6.1 \text{ kJ}$$

These are approximate numbers. The deposited energy calculated in the simulation is 14 kJ. The simulation incorporates:

- 1) internal inductance of the primary switch,
- 2) a resistive commutation function typical of arcing switches, and
- 3) the make-before-break action into the explosive switch.

Fig. 4. Explosive switch.

Previous experience gained with opening switches indicated that pitting would occur in the last area to break contact (i.e. the opening surface). Thirty contacts share the opening duty and are tipped with copper filled tungsten to reduce potential damage. The opening energy absorbed by the contacts is focused onto the radiused portion of the contact tips.

The major problem with switches previously tested is the pitting of surfaces during the opening duty cycle. This pitting restricts the switch from properly closing for the next charging cycle. To avoid this problem, the proposed design provides that surfaces in contact for charging duty will not be involved in the opening function. To correlate these predictions with actual tests, large viewports have been designed into the switch housing to observe the opening surface during switch testing.

The final component of the staged opening switch is the explosive switch (shown in Fig. 4). Reported performance of this switch [3] indicated an opening time of 10 μ s in a single gap switch interrupting 7 kA/cm of sheet. A switch arc voltage of 2 kV has been obtained using explosive cutting of the current-carrying sheet.

Previous experiments were performed with a total current through the 15.2 cm wide sheet of 50 kA. In higher current tests it has been observed that the developed arc voltage decreases with increasing current. In this design it is required that 200 kA flow in each of the four parallel sheets. During a full current test, it is anticipated that the developed voltage will drop below the 2-kV level. To increase this value and therefore allow this switch scheme to commutate into hypervelocity launchers, more series, explosively produced gaps will be added. This addition will be made as observations of the experimental results require larger switching arc voltages to drive the launchers to higher velocities.

Mechanical Design

The armature design, the mechanical actuator detail, and the free body diagram are shown in Fig. 5. Prior to switch activation, a Mylar® diaphragm is installed and clamped between flat ground surfaces in the O-seal device to provide a pressure seal between

Fig. 5. Opening switch free-body diagram

the nitrogen accumulator and the moving switch piston. The actuator is then charged with regulated bottled nitrogen. In operation the Mylar® will be pierced with a solenoid-driven plunger to rapidly pressurize the actuator and drive it forward. The forward motion pressurizes the volume on the back side of the actuator piston. This volume is sized so that the piston slows after the contacts have moved onto the ceramic insulator which provides a dwell time to allow for second-stage switch initiation and plasma arc acceleration in the railgun. Meanwhile, the actuator piston has continued to move and after 2 to 3 ms, a port on the main shaft is uncovered and the forward volume is exhausted allowing the armature to regain speed. The increase in velocity is required for the subsequent circuit making duty imposed on the contacts.

After the contact is well onto the armature (re-establishing HPG current in the discharge circuit) the exhaust port passes under a seal and the forward volume repressurizes to provide a damping cushion for the high speed mass. At the same time, sealing rods attached to the back of the drive piston vent the rear volume; thus lowering the driving force and reducing stresses on mechanical members. Pressure actuated valves are installed in the front volume to limit the damping pressure and to provide for a smooth braking action. After the experiment and discharge are complete, the volume in front of the guide nose at the center of the armature is pressurized to return the switch to its original position. The guide nose also prevents the actuator piston from binding due to unbalanced forces applied by the contact fingers.

The assumptions applied to the simulation are:

- 1) Neglect flow friction of N₂.
- 2) Neglect charging time of dead space between Mylar® diaphragm and actuator piston. (This volume has been kept small.)
- 3) Neglect expansion and contraction losses through Mylar® diaphragm.
- 4) The pressure drops across all exhaust ports have been designed to be a small value.
- 5) Assume 334 N (75 lbf) for friction due to seal drag.
- 6) Brush drag force was determined experimentally. Friction force = 2,670 N (600 lbf).

The equations describing the switch response for given conditions are:

- 1) Mylar® diaphragm pierced and front damping chamber sealed.

$$X = 1/m [F_D - P_D - FF]$$

- 2) Damping chamber exhausted

$$X = 1/m [F_D - FF]$$

- 3) Damping chamber resealed and drive pressure exhausted

$$X = 1/m [-P_D - FF]$$

Where

X = displacement
m = mass
F_D = driving pressure
P_D = damping pressure
FF = friction contact finger

The approach taken in the electrical design of the first-stage mechanical switch has been to use existing test data on operating switches to size electrical components. A similar comparison is made between the mechanical motion of an operational making switch and the proposed opening switch. The displacement time curve of existing making switches with pneumatic actuation, spring loaded copper contacts, and a similar mass is plotted along with the mechanical simulation result for the first-stage opening switch (Fig. 6). It can be seen that the overall motion is equivalent for the existing design and the proposed design.

During the stress analysis of this design all sections identified as possible problem areas were investigated. The most highly stressed member was the bend in the web of the armature. Analysis of this section is presented as a sample calculation using the following sketch and subsequent relationships:

$$\sigma = \frac{M_U c}{I_U}$$

where,

σ = bending stress
M_U = moment applied to unit section
I_U = moment of inertia of unit section
c = distance to extreme fibers in tension and compression

$$M_U = F_U d$$

where,

F_U = force applied to 1 in. wide moment arm
d = length of moment arm

$$F_U = \frac{F_T}{\pi D} \times 1 \text{ in.}$$

Fig. 6. Opening switch simulated performance results.

where,

F_T = total force (armature mass $\times$ acceleration)
the armature acceleration is calculated in the simulation

D = diameter at which bending occurs

$$I_U = \frac{b_u h^3}{12}$$

where,

b_u = unit width of the section
 h = depth of the section

therefore,

$$\sigma = 18,300 \text{ psi } (1.27 \times 10^8 \text{ N/m}^2)$$

The ultimate strength of chromium copper in a hard state is 36 ksi ($2.5 \times 10^8 \text{ N/m}^2$). From this consideration it is seen that there is a factor of two safety in the strength of the armature web.

Material Selection

All of the conducting paths of the switch are made from ETP 110 copper with the exception of the armature and the contact breaking portion of the primary contacts. The armature is made of RWMA Class III electrode material which is a form of Chromium copper specifically used in industry for high-current electrical contacts. The radiused portion of the breaking contacts is made of copper filled tungsten. Higher melting temperature tungsten was chosen to survive the electrical arcing expected in the transfer of current to the second-stage switch. The ceramic portions of the armature are made from flame-sprayed alumina. This ceramic has been used in the CHPG to electrically isolate the shaft from the rotor. The ceramic is applied to manufacturers suggested tolerance to prevent stress cracks in the insulator surface.

EXPERIMENTAL RESULTS

Data recorded from experiments illustrating typical CHPG current profiles for charging and commutation are shown in Fig. 7. Fig. 7a shows the current profile of a 6.2 μH inductor being charged by the CHPG. The mechanical switch opens and current is commutated through a 48 nH inductance to the second-stage explosive element as shown in Fig. 7b. A single gap in the second-stage element is then explosively interrupted and current is commutated to a 50 nH fixed load in 14.2 μs as Fig. 7c indicates.

Fig. 7. Current profiles during charging and commutation.

In experiments carried out at the Taylor Hall Facility using the CHPG power supply, 49 commutations were performed with the two-stage opening switch. Thirty-eight tests were single commutations in which current was commutated to the second-stage explosive element with the element remaining intact at typical current levels of 225 and 400 kA maximum. Three double commutations at current levels of 135, 250, and 350 kA were performed in which the current in the second-stage element was explosively interrupted and commutated to a fixed load. Eight railgun experiments were performed at a typical current level of 200 kA. One railgun experiment was completely successful in which 160 kA were commutated to the gun with the inductor charged to 200 kA. The system voltage held off by the two-stage opening switch was 1.5 kV. The second-stage element was interrupted with a single gap only.

During the course of the opening switch testing program two major modifications were made to the switch; the removal of the ID set of primary contacts and the removal of the secondary contacts. Analysis of the electromagnetic forces on the contacts indi-

cated the ID contacts would be "blown off" the armature at approximately 680 kA and hence, their removal. In an experiment in which the mechanical switch actuated erratically the second-stage contacts were forced to carry current for a time interval 15 times greater than their design value and they failed thermally. In order to resume testing in a timely manner the second-stage contacts were removed and the explosive switch was installed electrically in parallel with the mechanical switch. This would mean the explosive elements would have to carry current during the CHPG charging cycle. A simulation of the discharge predicted that the explosive elements would not overheat at lower testing levels. During the opening switch test program a making switch on the 10-MJ HPG, upon which the opening switch design is based, successfully carried a 581 kA peak current equal to an i^2t of $7.43 \times 10^{10} \text{ A}^2\cdot\text{s}$. The contacts showed no signs of failure. This information was used to establish a new i^2t rating of $1.16 \times 10^{11} \text{ A}^2\cdot\text{s}$ for the 30 OD opening switch contacts. The last test of the switch testing program was designed to verify the increased i^2t rating of the contacts and ability of the explosive element to carry its share of the current during charge. The i^2t resulting from a 560-kA discharge with no switch actuation (a ringing discharge) is approximately equivalent to i^2t of a 1-MA discharge in which the switch actuates (interruption at peak current). A 6,500-RPM static discharge of the CHPG into the ambient temperature inductor to generate a 560-kA current output, corresponding to an i^2t of $1.2 \times 10^{11} \text{ A}^2\cdot\text{s}$ was performed. The switch contacts showed no gross signs of melting or deformation and the explosive element remained intact showing no signs of buckling or thermal failure.

CONCLUSIONS

The overall performance of the two-stage mechanical switch satisfied the design requirements. The OD contacts alone were able to handle the equivalent i^2t of a 1-MA discharge without melting or gross deformation. Contact erosion and arc damage was minimal. The switch was unable to consistently hold off the voltage generated when commutating to a railgun load. Eliminating the remake feature is anticipated to increase the voltage hold off capability of the switch to allow railgun commutations.

The explosive switch performed as expected using single- and multi-gap elements. Tests included current interruption and commutation. Opening switch modifications are in progress and testing will resume at the Balcones Research Facility in Spring 1986.

ACKNOWLEDGEMENT

This research was funded under ARDC/DARPA Contract No. DAAK-10-82-0185.

REFERENCES

- [1] Paul Wildi, "High Current Making Switch," 6th Symposium on Engineering Problems of Fusion Research, 1976.
- [2] W. F. Weldon and J. H. Gully, "Design, Fabrication, and Testing of a Compact, Lightweight, Pulsed Homopolar Generator Power Supply," Final Report, Contract No. ARLCD-CR-84007, U.S. Army Armament Research and Development Center, January 1985.
- [3] R. D. Ford and Ihor M. Vitkovitsky, "High Recovery Voltage Switch for Interruption of Large Currents," Review of Scientific Instruments, July 1982.