A REPETITIVE SWITCHING ARRAY FOR LABORATORY ELECTROMAGNETIC LAUNCHER RESEARCH

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Abstract

A switching array containing up to six switching cartridges has been designed for multiple firing of inductive powered electromagnetic launcher systems. Each cartridge contains both a closing and an opening contact and may be operated at peak current to 1.5 MA for current pulse durations between 1 ms and 300 ms. Contacts are operated by detonating small explosive charges. This paper describes development progress and test results for a 1/2 scale, three shot prototype, and incorporation of results into a full scale, six shot design.

Introduction

Completion of the large battery power supply (BPS)[1] at the Air Force Armament Laboratory (AFATL) and installation of one turn of its planned four turn, 120 MJ inductive energy store, provides a versatile facility for developing and testing high energy electromagnetic launchers (EML), including repetitively fired systems. High energy pulsed inductive storage facilities such as this offer major advantages in size and cost when compared to other multi-megajoule systems. Reliability should also become an important benefit as inductive technology becomes more mature, due to the inherent ruggedness of inductors and the number of components required.

Operational status of the BPS has been instrumental in accelerating efforts directed toward development of inductive store technology,including switching devices capable of multiple launches at megampere currents. In EM launcher applications, typical megampere switches use a mechanical contact (brush) which slides past a conductor and onto an insulator. This type of switch has low arc voltage for commutation, and thus requires a very low inductance (typically 50 nH, 50 micro-ohm) load. It also requires frequent maintenance.

Recently, explosive operated switches have found acceptance in inductive powered launcher systems, primarily due to their high commutation voltage and command triggered firing capability. The technology has been available for many years[2], but was not well exploited. Their first applications for EML included use as small cross-section (2-5 ms conduction time) peaking switches to enhance commutating capability of sliding contact switches, and as separate, fast closing safety crowbar switches.

Both the opening and closing functions were combined into a single switching package, with switches operated sequentially, during development of a staged inductive power supply at Los Alamos National Laboratory[3]. Switch design included command triggering of each contact element, voltage isolation of 20 kV between inductive store stages prior to switch closure, several kV of arc voltage for current commutation, and 20 kV voltage recovery after commutation. This effort demonstrated the versatility of explosive operated switches and provided the technical basis for the switch development described below.

Conceptual Design

The Eglin BPS switch design goals include 300 ms conduction time per shot, operation for 5 shots at peak current to 1.5 MA, and current commutation to a railgun type load (200 nH or less inductance) in less than 200 μs. A voltage withstand capability of at least 10 kV prior to firing as well as after commutation is also desired. The developmental switch would use manually loaded switch cartridges, designed for eventual use with an auto-loader device. Based on past experience and a preliminary dimensional study, 1/2 in. thick aluminum conductor utilizing 50 grain/ft. PETN detonating cord and Reynolds RP80 exploding bridgewire (EBW) detonators were selected as the most suitable conductor/explosive combination for these parameters.

A three shot array was selected for prototype development since it permits full evaluation of performance while minimizing expendable hardware requirements. Switch operation is shown conceptually in figure 1. The switch array comprises three stand alone cartridges, a crowbar contact cartridge, and an array assembly containing cartridge mounting slots and a coaxial cable interface bus. Each switching cartridge contains both a make contact (S) and a break contact (CB), while the crowbar cartridge contains only a closing contact and may be used either to divert residual energy past the launcher after firing or as an emergency system protective switch. Insulated "make" contacts (S1,S2,S3) and crowbar contact (S4) are connected to the current supply bus, while each opening contact (CB1,CB2,CB3) is connected to the current return bus. In this three-shot configuration, it is assumed that the launcher is initially open-circuit, and no current flows until the switching sequence is initiated. Switch operation is as follows;

1) At time (t0), voltage is available from the prime power source, but no current flows.

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14. ABSTRACT
A switching ~rray containing up to six sw1tch1ng cartr1dges has been designed for multiple firing of inductive powered electromagnetic launcher systems. Each cartridge contains both a closing and an opening contact and may be operated at peak current to 1.5 MA for current pulse durations between 1 ms and 300 ms. Contacts are operated by detonating small explosive charges. This paper describes development progress and test results for a 1/2 scale, three shot prototype, and incorporation of results into a full scale, six shot design.

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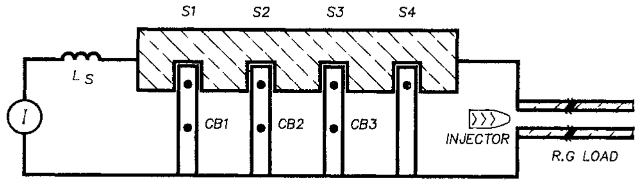

Figure 1. Conceptual repetitive array showing three switching modules and a crowbar.

2) At time (t1), contact S1 closes, initiating current buildup in the inductor via normally closed contact, CB1.
3) At any selected inductor charging time between 1 and 300 ms, the load circuit is completed by injecting a projectile. The opening contact CB1 is then command fired, developing approximately 1-2 kV to commutate current from the switch circuit to the load.
4) The projectile is accelerated for a desired time (typically 3-8 ms), after which contact S2 is closed. This time is generally selected to occur just prior to projectile leaving the launcher, both to relieve accelerating pressure on the projectile and to utilize projectile back EMF to re-commutate current from the load circuit to the switching circuit.
5) This process may be repeated with contacts CB2, S3 and CB3 being sequentially fired to alternately launch projectiles and re-commutate current to the switching circuit.
6) At the end of the firing sequence, crowbar contact S4 is closed, permitting residual stored energy to be dissipated external to the launcher circuit.

Developmental Status

Development efforts include design and selection of suitable switch components, assembling these components into a small scale array for explosive reaction studies, and demonstration of proof of principle by assembling and testing a half-scale, three shot array. Finally, results from the above are being combined into a 5-shot, 1.5-MA full scale switch design. Details of these efforts follow.

Concept Evaluation

Although make and break contacts could be designed as separate components, both their material and electrical performance requirements are similar, leading to the design shown in figure 2, where both components are included in a single conductor. Aluminum 1100 alloy was selected as the switching material of choice due to its low resistivity and formability. A 1/2 in. thickness was found suitable for use with 50 grain/ft. detonating cord.

A small test array measuring 2 in. by 6in. by 10 in. was assembled for evaluating switch sequential firing and timing response, and to identify problem areas including shock damage, sympathetic detonation of explosives, and mechanical stability of components during sequential firing. The array includes three switch modules, each containing a make contact and two break contacts. Each contact uses a two inch segment of 50 grain/ ft. detonating cord and a Reynolds RP80 detonator.

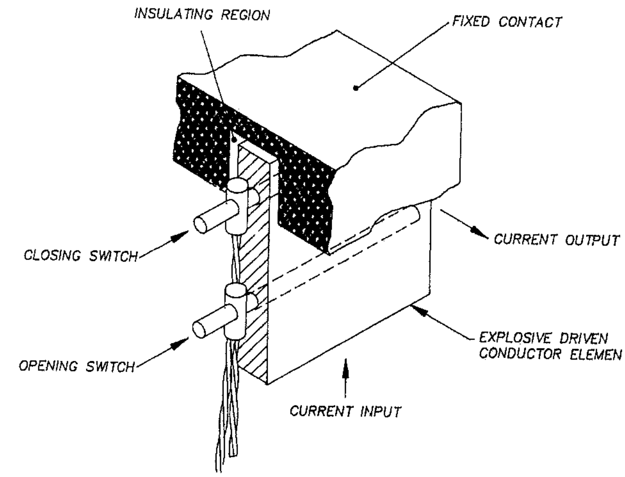

Figure 2. Switch element design having both make and break contacts in a common element.

Switching performance was evaluated using the SUZY capacitor bank for high peak current tests, and a capacitor array containing three independant LC circuits which could be discharged into a common load, for timing and voltage characteristic tests. The prototype battery power supply (PBPS) at Eglin was used for 300 ms conduction tests. These facilities permitted dynamic evaluation of components under expected operating conditions. A summary of test results follows.

Closing contact performance: The fixed contact, separated from the driven contact by insulating film, withstands voltage stress to 10 kV while open. Explosive detonation produces initial contact closure within 10 μs. Firm contact closure is completed in less than 1 ms, producing a large area, low resistance contact. Tests conducted using the PBPS at nominal 100 kA peak current demonstrated that this contact could carry 35 kA per inch width of contact for three hundred milliseconds, without melting. Some tests are continuing, to evaluate contacts under various risetime conditions. Test results show that explosive debris is contained within the switch assembly, when operated within design limits.

Opening contact performance: Initial arc voltage appears 30 μs after completion of explosive detonation and is typically greater than 1 kV. Voltage recovery after detonation is 9 kV per gap. Switch element design incorporates two gaps to increase voltage recovery and to provide redundancy for operating reliability.

Explosive thermal performance: During conduction, Joule heating of the conductor also produces a temperature rise in the explosive charge. A temperature increase beyond 125^{0}C could reduce detonation reliability. Although action calculations were used as a guideline in estimating temperature rise, non-uniform conductor cross-section as well as poorly defined explosive thermal properties created uncertainties in the results. Reliablility of explosive performance was, therefore, verified experimentally. Tests performed using the PBPS for 300 ms conduction time showed that when the conductor is allowed to melt, the resulting action is found to be 4.0 x 10^{16} (A^2-s/m^4), while the calculated value, based on maximum conductor current density, was 2.7 x 10^{16} (A^2-s/m^4). It was determined that the explosive charge could be reliably detonated at action of 2.4 x 10^{16} (A^2- s/m^4) with this conductor design.

Debris catcher performance: The insulating catcher performs the multiple functions of directing the explosive gas flow for arc-quenching, guiding and deflecting explosive debris, and finally halting and capturing debris for containment within the switch array. The design tested uses a polyethylene web sufficiently thick to absorb kinetic energy of the metal fragments, without causing them to rebound into the switch gap. Tests show that the catcher retains explosive fragments without degrading electrical operation.

Timing tests: Results from the above tests show that switch contacts can be operated reliably, to either open or close, over the design range between 1 ms and 300 ms with a timing precision better than 10 μs. Conductor cross section sets the conduction duration, while current commutation and not switch performance, establishes the 1 ms limit.

Half Scale Prototype

Scaling test results to full operating power levels was accomplished by fabricating a three shot switch array designed to operate to 750 kA at current density and conduction time identical to full system operating requirements. This array uses stand alone modules which are assembled and stored for use as needed. The three shot array is shown being installed in the homopolar generator (HPG) test facility at Eglin, in figure 3. A rigid bus connection is used between storage inductor and switch array, since this connection must carry current for the full power supply conduction time. However, a flexible coaxial cable connection is made to the railgun, since the load circuit conducts only during projectile launch time.

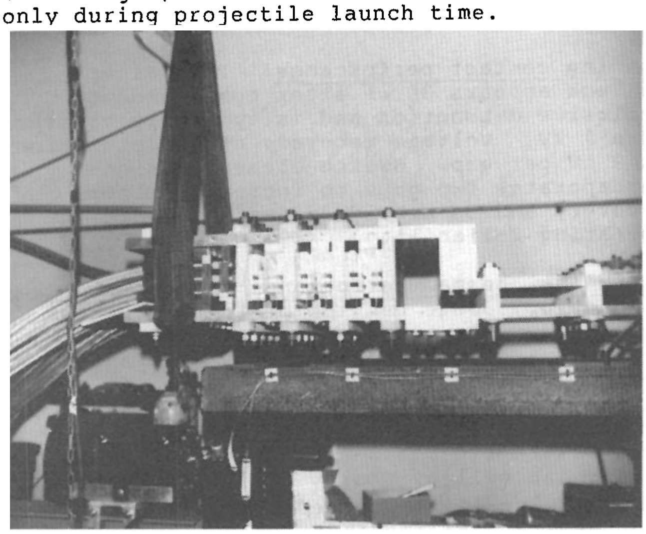

Figure 3. Half scale, three shot prototype switch array installed on the Eglin 5 μH storage inductor.

The assembly shown is 10 in. high by 16 in. wide, and each module occupies a 6 in. slot. Current contact is made between each switch module and the current bus by sliding the module into position and fastening with a row of 1/2 in. steel bolts, top and bottom. Modules are positioned so that the switch module closest to the gun contributes 30 nH to gun inductance, while the most distant module switches into a total inductance of 200 nH. This last value permits switch testing over the previously specified design range. Since the array does not require dis-assembly between shots, installation time is approximately 15 minutes for a full three shot array.

An explosive operated crowbar switch (not shown) has been added to the array to permit current diversion from the gun after operation. This crowbar contact may also be operated as a command fired current diverter with operating time of only 10 μs, in the event of an injector failure or other problem.

In single shot operation, projectiles have successfully been launched at 500 and 750 kA peak current levels, using the Eglin homopolar generator with a 5 μH storage inductor. Sequential switching operations have been demonstrated at 500 kA peak current.

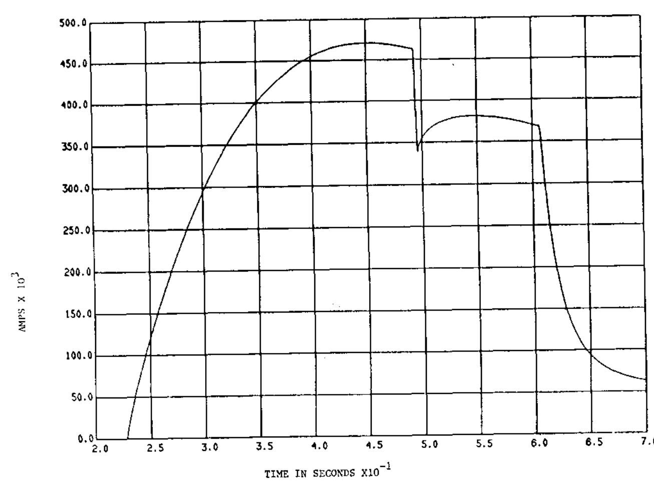

Figure 4. Storage inductor current waveform during a firing sequence which utilizes three separately timed switching functions.

Figure 4 shows the inductor current waveform during a test firing. During this test, the HPG is brought up to speed, field energized, and brushes lowered to provide voltage at the switch bus. On command from the control system, the closing contact of switch module 1 is operated and inductor current rises. At peak current of 470 kA (250 ms conduction time) a projectile is injected into the gun breech and an injector sensing circuit is used to trigger the module 1 opening contact, commutating current to the gun. This corresponds to the drop in current in the inductor from 470 kA to 300 kA. After a programmed time delay of 3 ms, the closing contact of module two, used as a crowbar switch, is fired and inductor begins re-charging from the generator.

The switch output waveform of figure 5 shows current flow in the railgun circuit. A peak current of 460 kA is commutated to the gun breech and decreases to 300 kA as the projectile is accelerated. After a programmed

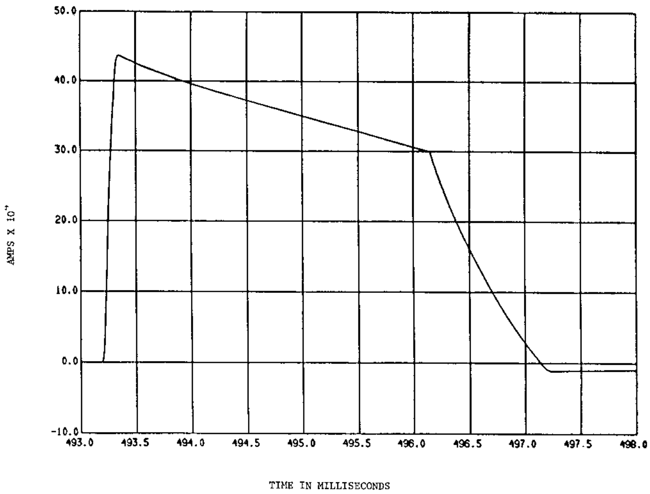

Figure 5. Switch output current waveform during railgun firing.

time of 3 ms, closing contact 2, used as a crowbar contact, is fired and inductor current is re-commutated from the launcher circuit to the switch circuit in 1 ms, and inductor re-charging continues. Inspection showed that the remaining switch module, at the completion of the test firing, was intact and available for continuation of the firing sequence.

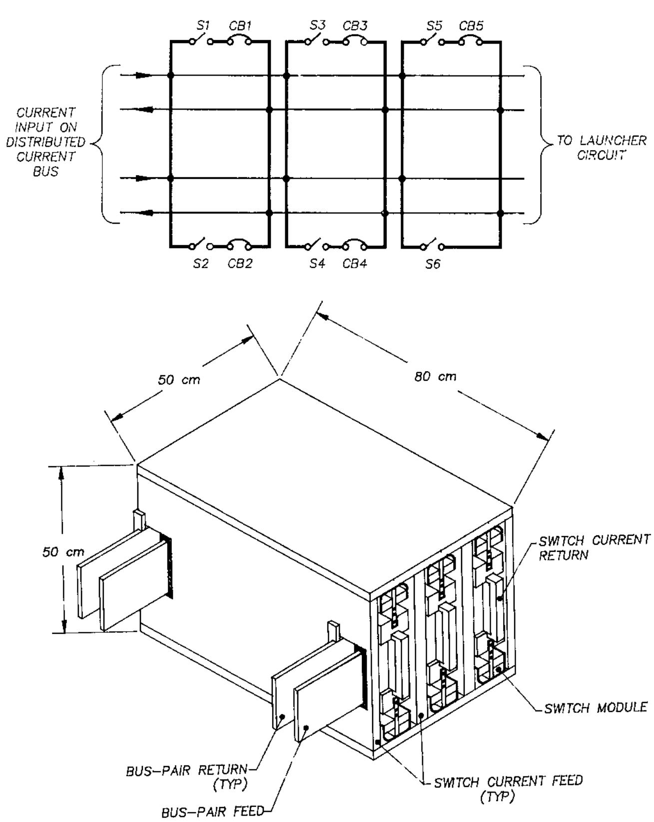

Figure 6 a) Circuit diagram for the full scale five shot plus crowbar switching array. b) Five shot array dimensional layout, with distributed current bus, cartridge configuration, and flexible cable interface shown.

Full Scale Switch Design

The final objective of this development phase is to provide an operational 1.5 MA, cartridge loaded five shot switch for laboratory research applications. This switch will utilize component and module designs described above. Switch electrical schematic is shown in figure 6a and switch configuration is shown in figure 6b.

The switch assembly utilizes a distributed current input bus for magnetic force reduction, and a coaxial cable output for rapid experiment setup and reduced external magnetic fields. This design also equalizes switch module to bus inductance such that no switching module will add more than 50 nH. to the load interface inductance.

The design allows operating flexibility as follows; In routine operation, the array will contain five single shot modules capable of 1.5 MA conduction for 300 ms and a sixth crowbar switch module. Command triggering will permit sequential firing with switching function delays selectable between 1 ms and 300 ms. Use of the crowbar module will leave the load circuit bypassed at the end of a firing sequence, or it may be used at any time during switching operation. Module pairs will have balanced inductance and resistances to the bus, so that they may be operated in parallel combinations to increase either current capacity or conduction time, as desired.

Conclusion

Technical problems have been resolved and component design data base established for modular arrays of opening and closing switches. Half scale tests demonstrated successful operation at designed operating parameters. Scaling results to a 5 module, 1.5 MA array should greatly enhance electromagnetic launcher research capabilities.

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