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TITLE: A 240-kA SWITCH WITH POTENTIAL APPLICATION IN ELECTROMAGNETIC-LAUNCH SYSTEMS

AUTHOR(S) E. M. Honig

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Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

A 240-kA SWITCH WITH POTENTIAL APPLICATION IN ELECTROMAGNETIC LAUNCH SYSTEMS*

E. M. Honig
Los Alamos National Laboratory
Los Alamos, NM 87545

Summary

Electromagnetic (EM) launchers have severe switching requirements. Switching demands for railgun systems, for instance, include current conduction from hundreds of kA to a few MA, conduction times of a ms to a few s, standoff voltages as high as a few tens of kV, recovery voltages of 1-10 kV after conduction, opening and closing duty, and repetitive operation up to about 50 Hz. These demands, particularly for repetitive opening duty, are far beyond the capability of most current switches and switching concepts.

This paper will review the performance of rod array triggered vacuum gap (RATVG) switches and discuss their potential for solving switching problems in EM launcher systems. A new mode of operation for the RATVG switch is proposed. Fundamental considerations for the operation of opening switches and their associated transfer circuits are presented. Methods of recovering the railgun's inductive energy to enable efficient repetitive operation are discussed and new circuits with such capability are proposed.

Introduction

Vacuum switches can conduct large currents in a low voltage, diffuse-arc mode. Furthermore, they are able to open during a short period of zero current and recover with a rate of rise of recovery voltage (rrrv) faster than any other high power switches.[1] These capabilities provided some of the basic motivation behind research at the General Electric Company (GE) aimed at extending the use of vacuum switches from the distribution class (5-15 kV ac) to the transmission class (at least 72 kV ac).[2] This work, sponsored by the Electric Power Research Institute (EPRI), was prevented from achieving its primary goal by the rapid and successful development of SF_6 puffer-type interrupters.[2] Nevertheless, the significant advances made in vacuum switch technology have important implications for the pulsed power field.

The research at GE was particularly successful in proving the merits of a new type of vacuum switch structure, the rod array type. In this structure, metal rods attached to the anode and cathode end plates are interleaved and overlapped, as shown by the schematic drawing of the G1 tube, Fig. 1.[3] In this tube, the rods are equally spaced around a circle and the arcs burn in an circumferential direction between them. This type of structure rapidly proved its capability to handle large currents while maintaining a diffuse vacuum arc. One early experimental device, in a demountable vacuum chamber, carried a current pulse of 240 kA peak and a total charge transfer of 1275 C "without any traces of melting on the rods for one half-cycle of arcing at 60 Hz."[3] Furthermore, the arc drop did not exceed 70 V.[2] During full power interruption tests with the best of the RATVG switches, the G1 tube, the highest power level attained at GE was 20 GW. The G1 tube carried an ac current pulse of 150 kA peak, interrupted the current flow during a natural ac current zero, and withstood a recovery voltage reaching a peak of 135 kV within 150 μs.[3]

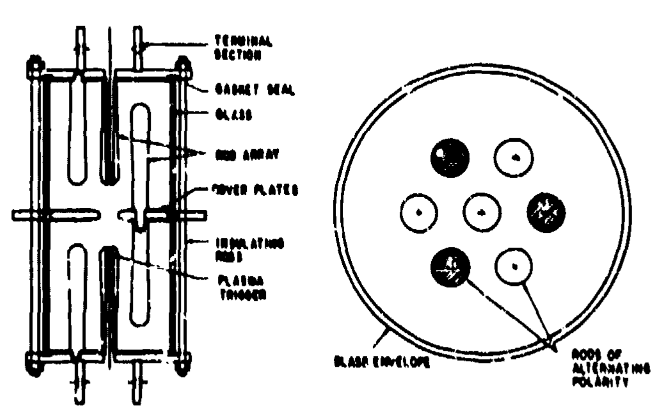

Fig. 1. Schematic diagram of type G1 rod array triggered vacuum gap (RATVG) switch.[3]

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While there are a number of requirements for opening and closing switches in EM launcher systems, one of the most severe applications is for a repetitive opening switch in inductively-driven railgun systems. Since the accelerating force on the projectile is proportional to the square of the current, railguns are best driven by generators capable of providing nearly-constant current. Furthermore, the high peak power and large total energy required during each shot quickly lead to the requirement for an intermediate energy storage system between the railgun and the prime power source. With "current source" characteristics and a high energy storage density, inductive energy storage is a logical candidate to meet these requirements. However, its effective utilization for this application depends on advances in opening switch technology and the development of efficient transfer circuits. This paper will address both requirements.

Opening Switch and Transfer Circuit Fundamentals

There are two fundamental switch opening methods (direct interruption and counterpulse) and associated transfer circuits. With the direct interruption method, the impedance of the opening switch R(t) in the resistive transfer circuit, Fig. 2, is rapidly raised to a value much greater than the load impedance to "choke off" the current flow and force the switch current (loop 1) to transfer to the load (loop 2). The load voltage risetime depends directly on the switch impedance risetime. The switch must conduct the full storage current, undergo a large impedance change, and then withstand the high recovery voltage immediately afterward. In addition, due to conservation of flux during the switching operation, resistive transfer circuits require that the opening switch dissipate the energy associated with the load inductance L_2 and its own inductance L_{switch}. The minimum amount of energy, E_{DIS}, that must be dissipated in the opening switch (for instantaneous switching) is

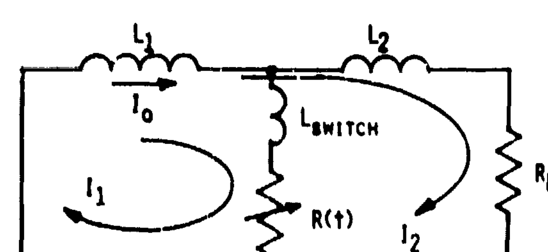

Fig. 2. Schematic diagram of resistive transfer circuit with stray inductances.

related to the energy $E_{Lswitch}$ stored in the switch inductance and to the energy E_{L2} transferred to the load inductance by the equation

$$E_{DIS} = E_{Lswitch} + (1 + X)E_{L2} \quad , \qquad (1)$$

where $X = L_2/L_1$.[4] If L_2 or L_{switch} are appreciable, the transfer efficiency is correspondingly reduced. The switch dissipation increases as the switching time increases (ie., real switching conditions).

With the counterpulse method, the current in the opening switch S_1 (loop 1) of the capacitive transfer circuit, Fig. 3, is momentarily reduced to zero by discharging the counterpulse capacitor C_2 through the switch (loop 2) in the direction opposing the main current. If the current zero time is long enough, the switch recovers and opens. The coil current then flows through C_2, rapidly raising its voltage to a value sufficient to force the current to transfer to the load (loop 3) when switch S_3 is closed. The main switch S_1 is allowed to open naturally during a time of zero current while the severity of the recovery voltage stress is reduced by the parallel counterpulse capacitor. Unlike the resistive transfer circuit, the capacitive transfer circuit has no fundamental energy losses associated with the circuit stray inductances. The energy $E_{Lswitch}$ stored in the opening switch inductance L_{switch} is actually transferred back to the storage coil L_1 by the action of the counterpulse capacitor. The increase in stored energy ΔE_{L1} in L_1 is given by the equation

$$\Delta E_{L1} = (2 + Y)E_{Lswitch} \quad , \qquad (2)$$

where $Y = L_{switch}/L_1$.[4] Therefore, the energy E_C that the capacitor must have to insure sufficient counterpulse current in the opening switch S_1 is given by

$$E_C = (1 + Y)E_{Lswitch} \quad . \qquad (3)$$

Further analysis of the resistive and capacitive transfer circuits for the special case of purely inductive loads and ideal opening switches shows that the same amount of energy must be handled by the resistive and capacitive transfer elements during the transfer operation.[5] The key difference is that the resistor dissipates its energy while the energy in the capacitor is recovered. For purely inductive loads, the operational efficiency of the capacitive transfer circuit approaches 100 %.

The implications for railgun switches and systems are clear. At the current levels involved, the energy associated with any stray inductances must be fully considered. If a direct-interruption opening switch is used, then the energy dissipation required by Eq. 1 must be dealt with. The effect of the self inductance of the opening switch and the initial inductance of the railgun and its connections may have enough impact upon the circuit transfer efficiency and the operation of the opening switch to make some direct-interruption opening switch schemes impractical. However, current-zero switches can be coupled with the high transfer efficiency produced by the counterpulse capacitor to

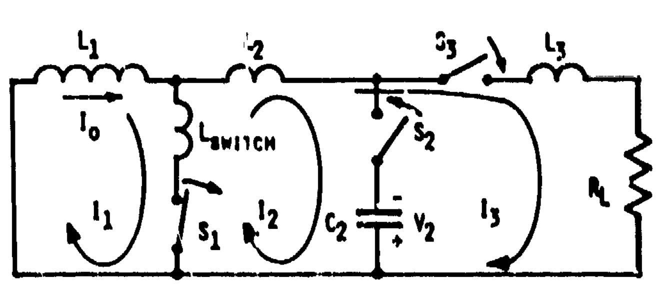

Fig. 3. Schematic diagram of capacitive transfer circuit with stray inductances.

provide an approach that may be more practical. A complete system study will probably be needed to determine the best approach for any particular load.

Operational Potential of the RATVG Switch

To use current-zero type switches to interrupt a dc current, an artificial current zero must be created in the switch. This is usually accomplished by discharging a capacitor through the opening switch in the direction opposing the main current. To keep the capacitor size reasonable, the switch current must be counterpulsed to zero rapidly and held near zero for a short time. For the diffuse-mode vacuum arc, the total counterpulse time need be only a few tens of μs. However, this condition is quite different from 60 Hz ac operation, where the time from peak to zero current is about 4 ms. Standard vacuum interrupters, for instance, use special electrode geometries[6] to allow operation above the diffuse-arc mode region and depend on the long current falltime to return to the diffuse-arc mode before reaching current zero. Consequently, the dc performance of standard vacuum interrupters is usually only about 40-60 % of their ac capability.

By comparison, RATVG switches should perform considerably better than this. According to both visual observations and arc voltage records, the vacuum arc in the rod array structure remained diffuse in all the tests at GE (including the 240-kA pulse),[7] probably due to the large amount of surface area on the rods and the fact that the arcs burn parallel to the direction of the self magnetic field of the total switch current. As long as the arc remains diffuse, current-zero interruptions should occur about as easily with the fast counterpulse technique (dc duty) as for a natural current zero (ac duty). Therefore, the dc interruption capability of the G1 tube is expected to approach its demonstrated ac performance of 150 kA.

The use of a RATVG switch as a current-zero type opening switch in railgun applications depends upon being able to upgrade its current conduction capability while maintaining the arc in a diffuse mode. An increase of 5-10 times over its demonstrated capability of 240-kA must be achieved, but can reasonably be expected for several reasons. First, the previous tests were limited by the test facilities, not the switches. The actual current conduction and interruption limits of the G1 switch are still unknown. Secondly, the originators and developers of the rod array concept feel that increased current capability can be achieved by adding more rods to the structure,[7] such as in the periodic array switch.[2] Finally, the amount of charge transferred by the rod array switch during the 240-kA test is equivalent to passing 1.3 MA for about 1 ms, conditions well within the operating range of railguns. Since it opens on a current zero and uses a trigger system to turn on, the RATVG switch operation is not limited to mechanical time scales. Very high repetition rates should be possible.[4]

The RATVG switch may also be able to operate as a direct-interruption opening switch.[4] By applying a magnetic field transverse to the arc, the arc voltage and switch impedance can be increased, forcing the current to transfer to a parallel lower-impedance load. Transverse magnetic fields have produced arc voltages of 1-6 kV in vacuum interrupters.[8] An axial magnetic field applied transverse to the circumferential arcs in a RATVG switch should be able to do likewise. Such a magnetic field could be produced rather easily and effectively with a simple solenoid. For low impedance loads, such as the initial impedance of a railgun, this method merits further consideration, particularly if a complete interruption can be achieved soon after the transfer. For instance, a switch voltage of 4 kV could force the transfer of 1 MA into a .3-μH load in about 75 μs, with the switch absorbing about 150 kJ.

Applications

There a number of EM launcher applications where switching problems need to be addressed. Current-zero switches will be needed as start-disconnect switches in staged-drive railgun systems to isolate each stage driver after it has done its work and in capacitively-driven induction guns to recover the energy after each pulse. The most difficult switching problem appears to be in the inductively-driven repetitive railgun. This system requires a repetitive opening switch capable of handling and interrupting currents as high as a few MA, withstanding recovery voltages as high as a few to 10 kV, and operating at pulse repetition rates of 1-10 pps and possibly up to 50 pps. The problem of producing repetitive pulses in high impedance loads using inductive energy storage was effectively addressed in a 3-year research and development program at Los Alamos,[4] culminating in a full power demonstration producing a 75-MW, 5-kHz pulse train at a 1-Ω load.[4,9] The problem of inductively driving high-current, low-impedance loads, when coupled with the need to recover the energy remaining in the load inductance after each pulse, is sufficiently different and difficult to require a fresh approach.

The minimum railgun barrel length is achieved by driving the projectile with a constant current at the maximum acceleration permitted. Under conditions of constant-current drive, the energy in the inductance of the rails equals the kinetic energy in the projectile. If the energy remaining in the railgun inductance is not used or recovered, it causes two major problems. First, the operating efficiency will be limited to 50 %, requiring the main inductive energy store to be twice as big as necessary. Secondly, the energy must be dissipated either in the rails or in external resistance. For repetitive operation, the first option quickly leads to unacceptable weight and size requirements on the rails while the second option adds a fairly significant subsystem to the problem.

An alternative to dissipating the energy is to crowbar or short circuit the breech of the railgun to allow the magnetic energy trapped in the inductance of the gun to continue to drive the projectile. The effectiveness of this scheme was investigated using a self-consistent, variable-current computer model. A projectile was assumed to be accelerated to a given velocity using a constant-current source to drive a lossless railgun. After the breech crowbar switch was closed, the projectile was further accelerated by the magnetic energy remaining in the gun. A normalized plot of the energy in the railgun inductance versus projectile position is shown in Fig. 4. Energy is added linearly to the gun inductance until the breech crowbar switch is closed. The projectile position at that time is defined as 1 unit of barrel length and the maximum inductive energy in the gun is defined as 1 unit of energy. After that time, energy is added to the projectile at the expense of the energy in the inductance. The results of Fig. 4 show that the barrel length must be made twice as long to recover 50 % of the gun's inductive energy and made 5 times as long to recover 80 %. It is clear that this scheme rapidly becomes impractical, with the extra energy recovered not being worth the extra barrel length needed.

To fully recover the energy stored in the gun's inductance, one must use resonant circuits. When the projectile has reached its required velocity or has exited the barrel (whichever comes first), a crowbar switch across the muzzle is closed. Let I_0 be the current flowing through the storage inductor L_1 and the load inductor L_2 at that time. By connecting a precharged capacitor C_1 across the inductors, as shown in Fig. 5, one can set up a resonant circuit condition to cause the current in the load inductor to oscillate through zero. All the circuit energy can then be trapped in the storage inductor L_1 by closing a switch across the capacitor. The oscillation in L_2 can be initiated in either direction. If the initial capacitor voltage V_0 is negative, the current in L_2 will be driven towards zero in a manner identical to the counterpulse technique for switches. The initial capacitive energy required to cause a current zero in L_2 is obtained from Eq. 3 (L_2 replaces L_{switch}) giving

$$E_C = (1 + X)E_{L2} \quad , \tag{4}$$

where $X = L_2/L_1$. On the other hand, if V_0 is positive and the capacitor has sufficient energy, the current in L_2 will first swing to a value of $2I_0$ before reversing and coming through zero. The same amount of initial capacitive energy, Eq. 4, is still required. A plot of the energy variation in the capacitor and in the load inductance during the resonant energy recovery process is shown in Fig. 6 for both of these recovery methods (for the case $X = 0.2$). The key differences are that the overpulse method doubles the current in L_2 and takes 3 times longer than the counterpulse method. Which method is best depends on a number of factors, including railgun resistance and stress limits. The counterpulse method imposes less stress on the rails and is more efficient because the current zero in L_2 is produced in less time. However, it requires more switches than the overpulse method.

A repetitive energy transfer and energy recovery circuit requiring only 4 switches and employing the counterpulse technique for both switch opening and energy recovery is shown in Fig. 7. The storage current I_0 initially flows through L_1, S_1, and S_2 (loop 1) while C_1 is charged to a voltage V_0. When the projectile is injected into the barrel, C_1 discharges through the railgun (loop 2) to automatically counterpulse the current in switch S_2 to zero. With S_2 open, the current from L_1 flows through S_1 and C_1 to drive the projectile while also reversing the polarity of C_1. When C_1 has been charged to a voltage V_1 and energy slightly greater than $(1 + X)E_{L2final}$ (where $X = L_{2final}/L_1$), switch S_3 is closed to bypass the capacitor. After the projectile has reached its

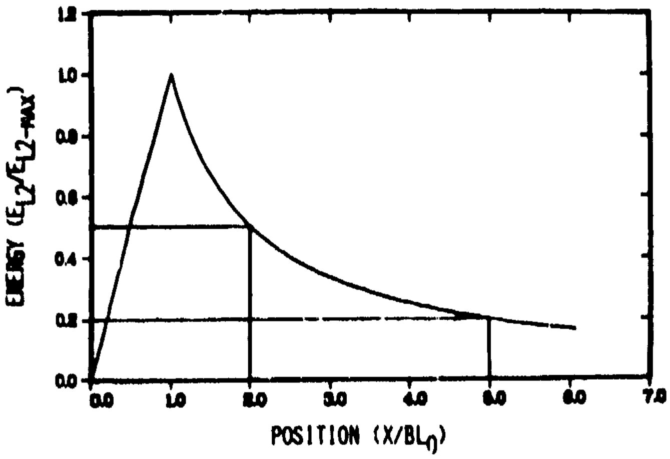

Fig. 4. Normalized plot of inductive energy in railgun barrel versus projectile position.

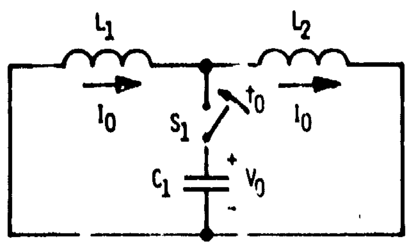

Fig. 5. Schematic diagram of resonant circuit needed to fully recover energy from inductive loads.

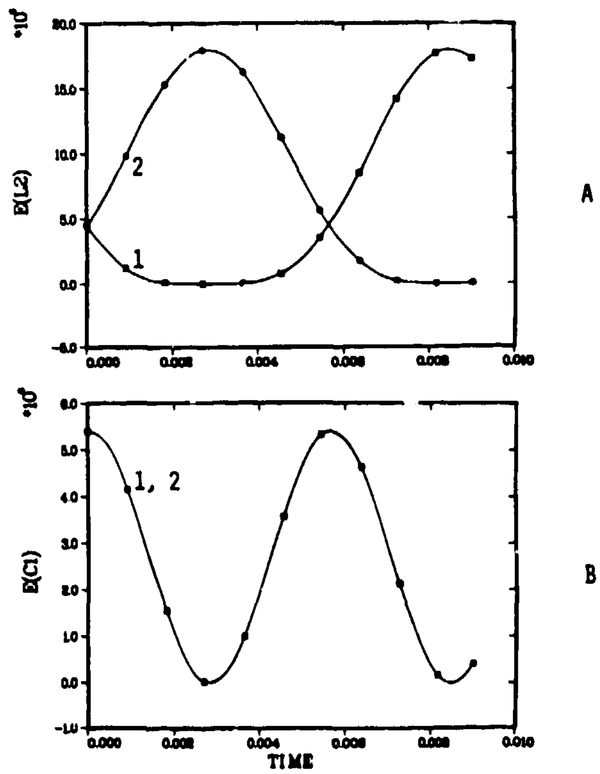

Fig. 6. Plots of the energy variation in the load inductor (A) and the transfer capacitor (B) during a resonant energy recovery with the counterpulse (1) and overpulse (2) methods.

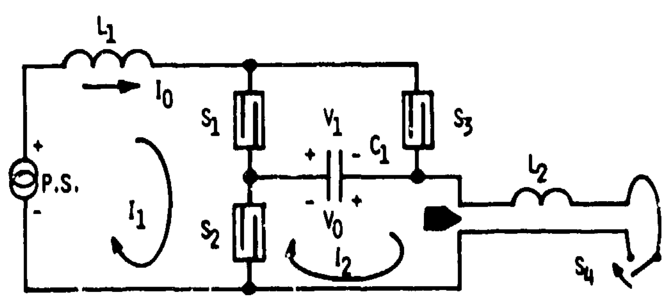

Fig. 7. Schematic diagram of a counterpulse energy transfer and energy recovery circuit for a repetitive railgun system.

desired velocity (or exited the barrel), the muzzle crowbar switch S_4 is closed. The circuit is then placed in the resonant energy recovery mode by closing switch S_2 to allow C_1 to counterpulse the current in L_{2final} to zero and return its energy to L_1, as discussed earlier. By slightly delaying the closing of S_1 to trap the system energy in L_1, the capacitor can be recharged to a voltage V_0 and the entire circuit returned to its original condition (except for the energy imparted to the projectile).

An energy transfer and recovery circuit employing the overpulse energy recovery technique is shown in Fig. 8. The storage current I_0 in L_1 initially flows through switch S_1. If S_1 is a current-zero switch, C_1 must have sufficient initial stored energy to provide a current counterpulse in S_1 and a switch must be provided in series with the capacitor. For simplicity, S_1 is assumed to be a direct-interruption switch and the capacitor does not need to have any initial stored energy. When the projectile has been injected into the railgun, S_1 is opened to force the current to transfer into C_1 and the railgun. The capacitor tracks the voltage of the railgun and must be sized so that its energy at the final railgun voltage will be slightly greater than that required by Eq. 4. When the muzzle crowbar switch is closed to terminate the projectile acceleration, the circuit is placed into the resonant overpulse condition discussed earlier. The capacitor sets up an oscillation in the railgun, forcing its current to double and then swing to zero. Switch S_1 is then closed to trap all the circuit energy in L_1, returning the circuit to its original condition (minus the projectile energy) and completing one energy transfer and recovery cycle.

For both of the circuits just described, the capacitor must be able to store energy in the few-10 MJ range at voltages in the few kV range. This leads to a capacitance in the F range. While this is quite impractical for standard capacitors, it should be feasible using a rotating electrical machine.

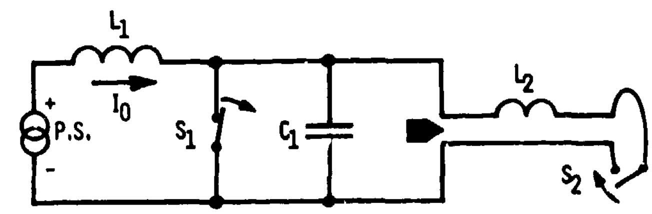

Fig. 8. Schematic diagram of an overpulse energy transfer and energy recovery circuit for a repetitive railgun system.

Suggestions for Future Research

Research should address both switches and circuits. Research and development of the RATVG switch is needed to increase its current rating, to reduce its conduction drop, to investigate its turn-on arc characteristics, and to determine the feasibility of using an axial magnetic field to make it a direct-interruption switch. Systems studies are needed to check the suitability of these transfer and energy recovery circuits for particular applications, to determine whether the required transfer capacitor is feasible, and to improve upon the present concepts.

Acknowledgments

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