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Current Interruption in Inductive Storage Systems With Inertial Current Source

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Utilization of inertial current source inductive storage with high power output requires a switch with short opening time. This switch must operate as a circuit breaker, i.e., be capable to carry the current for a time period characteristic of inertial systems, such as homopolar generators. For reasonable efficiency, its opening time must be fast to minimize the energy dissipated in downstream fuse stages required for any additional pulse compression. A switch that satisfies these criteria, as well as other requirements such as that for high voltage operation associated with high
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20. Abstract (Continued)

power output, is an explosively driven switch consisting of large number of gaps arranged in series. The performance of this switch in limiting and/or interrupting currents produced by large generators has been studied. Single switch modules were designed and tested for limiting the commutating current output of 1 MW, 60 Hz, generator and 500 KJ capacitor banks. Current limiting and commutation were evaluated, using these sources, for currents ranging up to 0.4 MA. The explosive opening of the switch was found to provide an effective first stage for further pulse compression. It opens in tens of microseconds, commutates current at high efficiency (> 90%) and recovers very rapidly over a wide range of operating conditions.

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CONTENTS

CURRENT INTERRUPTION IN INDUCTIVE STORAGE SYSTEMS WITH INERTIAL CURRENT SOURCE

I. INTRODUCTION

Multimegajoule pulses of electromagnetic energy at high power level are required in a variety of experimental and development programs. For example, in the inertial fusion program both the laser output and charged particle (electron or ion) beam output must provide power into the fusion target at the tens of terawatts level.[1] Studies such as those involving the simulation of effects of natural lightning on aircraft and other vehicles also require large energy pulsers with output in sub-terawatt range.[2] Utilization of inductive storage for such application is very attractive because of its inherent compactness associated with energy storage in the form of magnetic fields. Additionally, inductive storage can be sufficiently versatile to provide high peak power pulse trains for those applications where sequence of events separated by only tens or hundreds of microseconds apart must take place.[3] Here, current interruption techniques and components, necessary in application of inertial-inductive energy storage to generating terawatt pulse output, are discussed.

II. CONCEPTS AND COMPONENTS

Storage of energy in magnetic fields is practical at a level of the order of 10^7 J/m^3. The current required to produce the magnetic field can be derived from sources such as capacitor banks, chemical storage (batteries and explosives) and from inertial storage such as alternators and homopolar generators. With the exception of the capacitor banks, the energy density of these current sources is compatible with that of magnetic fields. Some of these, e.g. explosive generators,[4] are capable of producing high current output with very short rise time. Although explosive generators are very compact and are suitable for very large pulse energy, they can not be used in many environments (and often destroy the experiment) where periodic pulsing of the system is required. A more practical, nondestructible, version of high current pulser is the PULSAR concept[5] employing the explosively generated plasma for compressing magnetic fields.

Rotating machinery, storing energy in inertial form, has been traditionally used as high current sources with either periodic or single pulse output. Electric power test facilities[6] for 60 Hz output and homopolar generators for single pulse output[7,8] can, in addition, be used with current transformers to adjust output current requirements. More recently, development of hybrid concepts, combining the features of alternators and homopolar generators has been started.[9] Conversion of the mechanical to magnetic energy, generally, occurs in time several orders of magnitude longer than the required duration of

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the output pulse. Furthermore, required time compression leads to high voltage output, which is much higher than available at the output of the current source. Current interruption, using fast-acting opening switches such as circuit breakers provides the method for compression of the pulse by generating an inductive voltage pulse -- effectively amplifying the current source output power.[10] To deal with the resulting high voltage across the source, circuit designs employing, for example, crowbar switches can be utilized. Specific approach is outlined in Section IV. Because the high output voltage also appears across the opening switches, switch restrike voltage and its recovery rates must be high for efficient pulser design. Large circuit breakers have provided interruption characteristics satisfying, to a degree, these requirements. Explosively-actuated switches offer even better capabilities.[11,12] Section III describes further evolution of the design of the exploding switch and provides the new test results of the switch characteristics. These results can be used in the designs of large inertial-inductive storage for generating output pulses in terawatt range. Although the circuit-breakers can, in contrast to the exploding switch, be self-reset conveniently, the relatively small size of the switch and the shorter ($<$20 to 30 μsec) opening time compared with that of a few msec for circuit breakers, make such switches well suited for use in inductive circuits with very large power amplification.

In those applications where additional compression of the pulse to submicrosecond time is needed, two methods of steepening the pulse generated by the first interruption of the current have been proposed and tested. One of these employs charging of the peaking capacitor (or pulse-forming transmission line). Designs for MJ pulse output have been worked out in some detail.[13] The second approach uses three-stage opening switches, with the final stage consisting of an array of exploding wires. Such wires provide very fast opening time.[14] Experiments carried out on the TRIDENT pulser at NRL show that such an approach is an efficient method for generating 10^{11} Watt pulses.[15] However, use of exploding fuses is predicated on delivering sufficient amount of stored energy to heat the fuse to vaporization. For given current, vaporization energy is proportional to square root of the time to explosion of the fuse. Thus, the preceding stage must open as fast as possible and must have highest possible restrike voltage recovery rate (as discussed in detail in Section III). An explosively-actuated switch, satisfying these conditions and operating at near the 0.5 MA level, has been developed. Operating with fuse stages, pulses at 600 kV have been formed, generating more than 0.1 TW at the output.

The development of the exploding switch has proceeded following the work of Glukhikh et al,[11] through early phases[12] with much of its understanding based on the technology of circuit breakers. The similarity of the exploding switch function to that of a circuit breaker suggests that these switches are also useful in areas other than in generation of high power pulses, as for example, in protection of power lines and of equipment malfunction.[16] Another important aspect of the exploding switch -- its high voltage capability -- was developed by exploiting high voltage techniques used in designs of large pulse line generators, some with pulse voltages as high as 12 MV.[17] Finally, the high power capability of the exploding switch has been exploited (in conjunction with cascade circuits) in generating high power ($>10^{10}$ W) pulse trains[3] with repetition rate of many tens of kHz.

III. HIGH POWER SWITCHING

A. Staging of Opening Switches

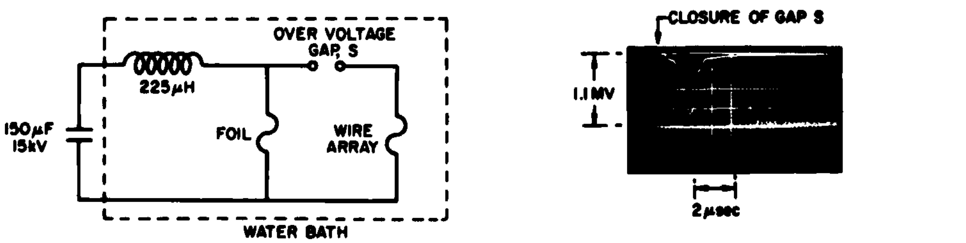
To achieve large amplification factors in inductive storage systems, parallel opening switches are used with consecutive opening. This method requires that each succeeding switching stage have an increasingly shorter opening time, providing in this way shorter commutation times for each succeeding stage. The principles of this method in specific application to generation of high power, high voltage output has been described in ref. 10. Experimental demonstration of this method has been shown for two and three-stage systems in references 13 and 15, respectively. Various aspects of such methods have also been studied elsewhere.[18]

A basic requirement of practical inductive storage system, using inertial current sources, is that at least the first opening stage carry the current for a period several orders of magnitude longer than the output pulse. This requirement imposes a constraint on the choice of the switching element; for example, eliminating fuses from practical consideration for the first stage because of their drain of system energy. On the other hand, any opening switch that operates by drawing on an external source of energy is acceptable. For example, circuit breakers driven by mechanical energy (such as springs, pressure lines),[19] magnetic pulsing[20] or chemical energy[12] have been employed in a variety of applications. Use of chemical explosives provides fast opening times. It has an added bonus that the high pressure generated for switch opening, provides at the same time good insulation when high electric fields are applied across the switch.[21] Further, circuit breakers with mechanical or magnetic actuation can be reset for succeeding operation. Use of explosives for actuation is more restrictive in that respect, since such switches must be replaced for each shot.

B. Fuses

Studies of exploding conductors, such as wires and foils acting as fuses, have been motivated by applications in pulse-steepening[10,14] of the capacitor bank output, in commutating to provide a recovery period for circuit breakers,[19] and in capacitor bank protection circuits. The fuse properties have been studied over a broad range of parameters and in a variety of circuit configurations. For example, effects of the time to explosion, (defined as vaporization time) on the amplitude of the restrike electric field were examined among others by Salge et al.[22] Methods for generating very short, high power pulses were demonstrated and their implications in replacing pulse lines in generation of such pulses were discussed in ref. 13. Interaction of the exploding conductors with the surrounding medium was studied to determine the effects of the medium on the fuse characteristics and led to suggestions that chemical reaction energy can be used to contribute to the efficiency of inductive storage systems.[23] Water, as the explosion-confining medium, has been used in Naval Research Laboratory experiments,[12] since it has good characteristics[17] for high voltage applications. Because the restrike phenomena and its scaling are not well understood, new studies such as the dependence of the amplitude of the restrike electric field on the recovery period have been undertaken. The results are discussed below.

The exploding conductor fuses, used as opening switches in inductive storage pulsers, also have properties of importance to system applications. First, in contrast to closing switches, parallel fuse currents self-adjust so that modular approach provides useful flexibility for the system design. In case of systems with stored energies of hundreds of kilojoules and more, the paralleling of fuses provides a means for distributing the explosive forces in a controlled manner so that pulser structural design is made simple. Second, both the inductively self-generated electric fields across the fuse and those that appear as a result of opening of the succeeding stages are in the range that matches that of the exploding switch, as discussed in



A. EXPERIMENTAL APPARATUS FOR TESTING STAGED WIRE FUSES

B. OUTPUT VOLTAGE WAVEFORM OF A SINGLE 5 MIL DIAMETER COPPER WIRE DRIVEN BY AN ALUMINUM FOIL

Fig. 1. Circuit diagram of two-stage opening switch and an oscilloscope trace showing voltage waveform developed across the fuses.

Section III-C. It has been found that the restrike voltage (generated by the succeeding stage) is a strong function of the recovery time and can be as high (20 kV/cm) as that associated with the exploding switch restrike voltage.

The study of the restrike voltage was performed using the circuit shown in Fig. 1. The first stage foil fuse generated inductive voltages in two ranges (90-120 kV and 130 to 170 kV) corresponding to a stress of 3.7 and 4.8 kV/cm, respectively, at switch-out. As the gap S closed and the inductor current was commutated to the exploding wire array, voltages of up to 1.1 MV were generated. The time delay between the foil fuse voltage peak and the higher peak, shown also in Fig. 1, was controlled by changing the number of wires (i.e. the cross-section) of the array. This delay is the time needed for the foil to recover to a given breakdown (restrike) level. Fig. 2 shows the resulting restrike field values. Curves for both levels of electrical stress show that the maximum hold-off capability occurs at 2-3 μsec with values of 22 and 24.5 kV/cm. The implication of such high restrike values is most important in terms of the system efficiency, allowing smaller fuse lengths (i.e. smaller fuse mass) to perform desired switching function.

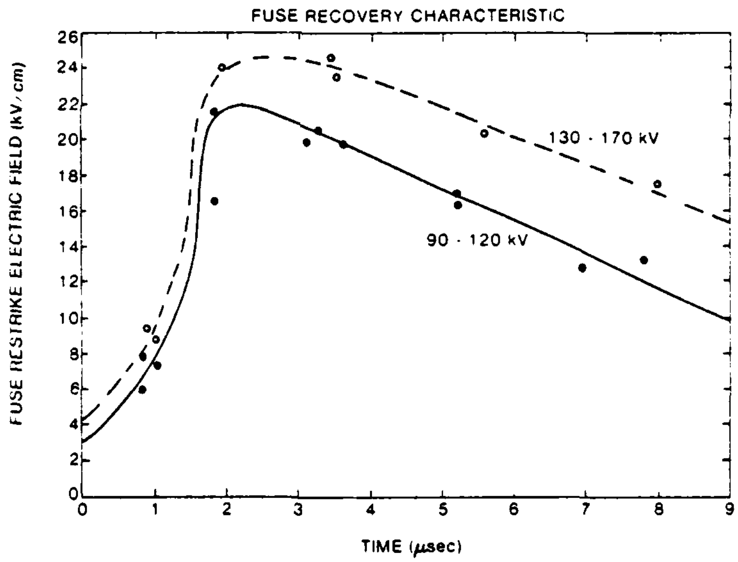


Fig. 2. Dependence of fuse restrike electric field on the recovery time.

C. Exploding Switch

In contrast to the extensive studies of fuses, exploding switch development is relatively recent[11,12] and limited to narrow range of parameters. To become useful in practical inductive storage systems based on inertial current sources, the exploding switch must be capable of interrupting very high currents so that paralleling of the switches, and therefore the system complexity, is minimized. The candidate switch design for operation at 1 MA (with high voltage capability) is the design tested at up to 400 kA.[12] The design is shown schematically in Fig. 3.

The basic operation of the exploding switch shown in Fig. 3 and described in ref. 12 consists of the following steps. Initially, current is conducted by Aℓ cylinder for any period limited only by thermal capacity of the switch parts. The cylinder is loaded with paraffin and an explosive cord is placed on the axis. Initiation of the explosive by one or more detonators leads to a radially outward pressure on the cylinder. Confining cutting rings, alternated with non-conducting rings, allow the cylinder to rupture in controlled areas. The rupturing decreases the current as a result of arc formation in each gap. The arc resistance is controlled partly by extrusion of paraffin into the gap, forcing the arc into contact with hydrogen-rich heat sink. The arc voltage, typically in 0.5 to 1.0 kV/gap can be used to commutate the current into the succeeding switching stage. Removal of the current from the exploding switch leads to rapid cooling of the arc plasma with a consequent increase in the ability of the switch to withstand high voltage without conduction or restrike.

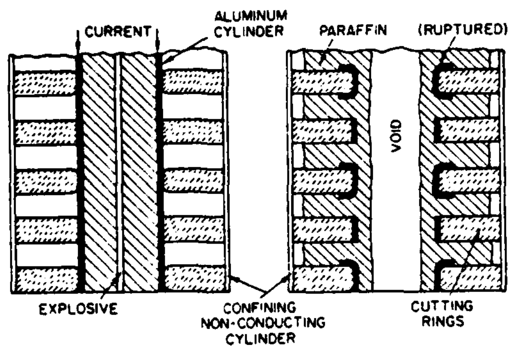


Fig. 3. Schematic of the exploding switch.

The early phase of the switch study[12] dealt with individual gap properties and their behavior when many gaps are connected in series as shown in Fig. 3. This study has shown that interruption time is typically 20-30 μsec (after 50 μsec pressure build-up) for switch lengths of up to 75 cm. Voltage recovery rate is very fast, with 20 kV/gap (corresponding to average field across the switch of 10 kV/cm). For tests where the total number of gaps was such that the detonation wave transit time was less than (or comparable to) the current interruption time, the behaviour of the series gaps does not deteriorate, relative to individual gaps. The interruption behaviour is typical of circuit breaker arcs, most significant aspect being the constancy of the arc voltage with increasing arc current (up to 100 kA). The voltage hold-off design of the switch employed practices such as maximizing the flash-over surfaces and minimizing the enhancement of the electric fields. Although the high pressure generated by the explosive served to increase breakdown voltage[21] during the dynamic phase (i.e. during paraffin flow), exploded switches were also tested at late times by applying external voltage pulses with the final switch configuration hold-off being at least 10 kV/cm. Appropriately designed switches were tested at up to 300 kV.[12]

Use of the switch at higher currents has shown marked deviation from the scaling based on the results obtained at currents of less than 100 kA. Fig. 4 shows the arc resistance recovery as a function

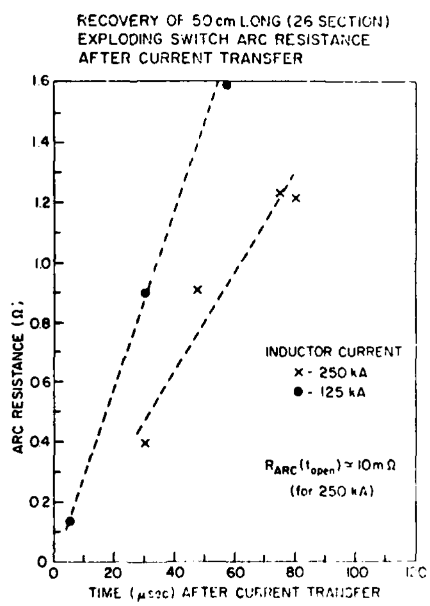


Fig. 4. Arc resistance during interruption of high currents.

of the time between full current interruption and application of high voltage. The resistance is determined by measuring the current reestablished in the switch due to the reapplied voltage. The rate of recovery depends on the current level being switched. At high currents the recovery rate is too slow for efficient storage system designs. As the data of Fig. 4 and the results of ref. 12 indicate, the recovery rate is very fast for small currents. This suggests that to achieve fast recovery rates, switch opening must occur under conditions of no current. To combine both features, i.e. the fast recovery and high current interruption capability, a sectioned switch was developed. This switch is shown in Fig. 5. First 16 gaps are opened 40 μsec before the second set of 27 gaps is opened. Two separate initiator caps controlled by a delay generator are used for this purpose. The gaps that open first limit the current to low value (or, alternately, permit the current to be commutated to a second stage fuse) so that gaps opening later open at low current level. The resulting electrode burning is intense for gaps 1-17 and almost nonexistent in the remainder of the gaps. The two-section switch shown in Fig. 5 with currents up to at least 400 kA has arc resistance higher than 100 Ohms at T_i = 50 μsec, and withstands 600 kV pulses applied at that time.

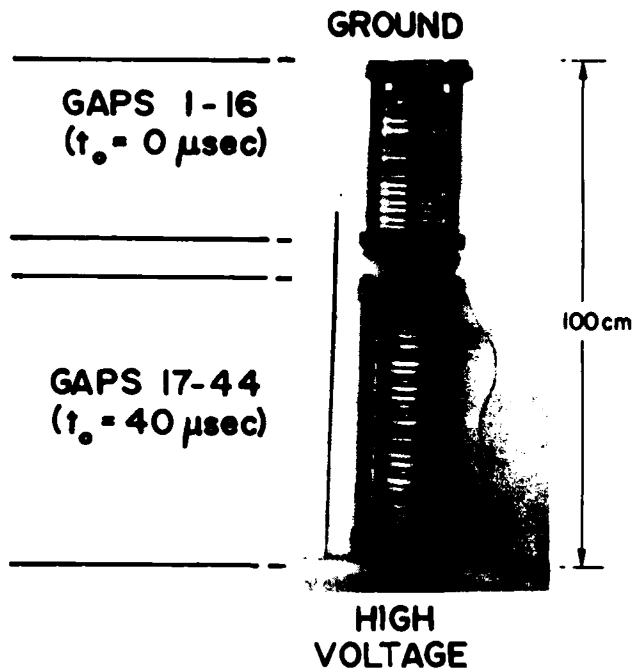


Fig. 5. Two-section exploding switch.

Another important consideration of exploding switch performance is its ability to transfer (commutate) current into succeeding switching stages. In high power applications, these stages consist of fast acting fuses. The resistance of a fuse stage is initially that of the solid metal. It increases to high resistance due to heating and subsequent vaporization in a time given by the current density in the fuse.[24] To determine the transfer, or commutation, time, an idealized circuit of Fig. 6 is used. The current, i_2, through the fuse inductance L and resistance R (which, for most cases, can be the fuse resistance before the onset of heating) is driven by the arc voltage, V, developed by the interruption of current i_1. It is given by

$$V(t) = \begin{cases} V_{max}(t/t_e)^2 & t<t_e \\ V_{max} & t>t_e \end{cases} \qquad (1)$$

where t is time measured from the onset of opening of the switch, and t_e is the "opening time" (of about 80 μsec) and V_{max} is 0.5 kV/gap times the number of switch gaps. For a switch with 26 arc gaps, V_{max} = 13 kV. As long as the arc voltage is independent of current flowing through the explosive switch, the resulting fuse current can be determined without regard for the current or other parameters of the storage coil (with inductance L_o) part of the circuit.

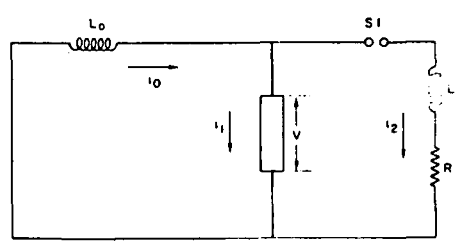


Fig. 6. Inductive storage circuit with two-stage opening switch showing circuit elements considered in determining current commutation characteristics.

Current transfer is illustrated in Fig. 7. Oscillograph traces of the exploding switch current using the Suzy II capacitor bank[15] as a source and the transfer of the current into foil fuse are shown in Fig. 7 together with the voltage appearing across the inductor and the switches. These traces, obtained in tests summarized in Fig. 4 using single section switch, demonstrate two important characteristics of the switch. The first is the transfer of commutation time, t_T , of about 20 μsec. The second point is the low resistance of the switch arc at the time (t = 90 μsec) when inductive voltage is generated by the fuse vaporization. This voltage is determined by the resistive drop across the arcs, rather than by the much higher inductive pulse.

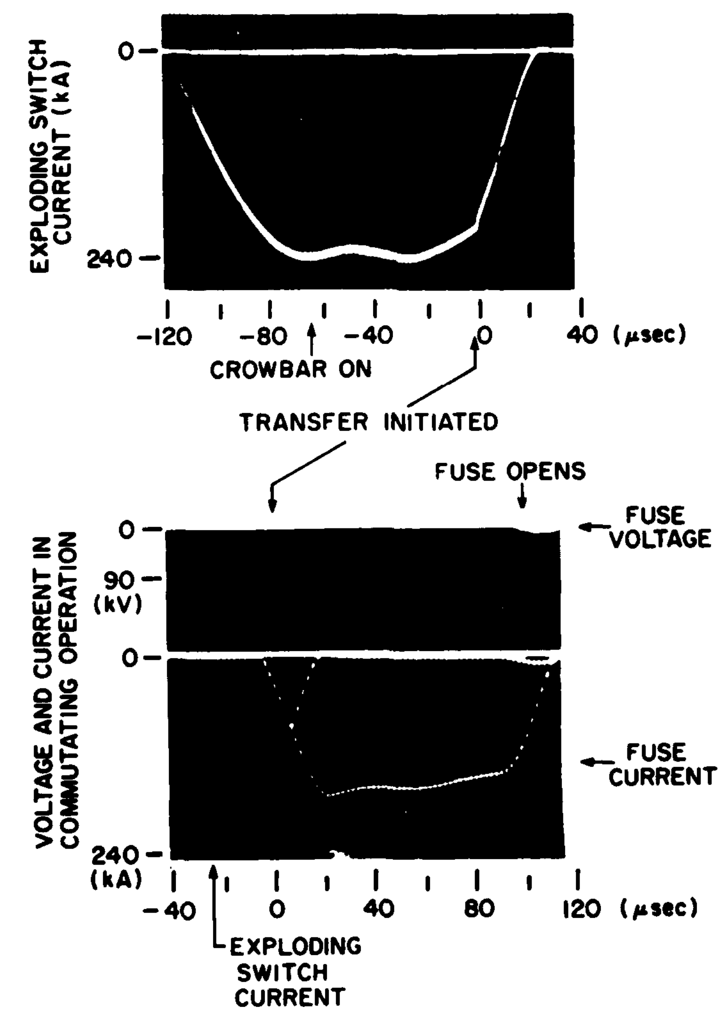


Fig. 7. Oscillograph traces of the exploding switch current transfer to the foil fuse is shown together with inductive voltage generated by the fuse.

The transfer time, t_T , for arbitrary R and L values of the fuse, are derived as follows. After the series switch (S1) closes, applying the arc voltage across the fuse circuit, the fuse current is determined by the equation

$$\frac{di_2}{dt} + \frac{R}{L} i_2 = \begin{cases} \left\{V_{max}/L\right\} \cdot \left\{t/t_e\right\}^2 & 0 < t < t_e \\ \left\{V_{max}/L\right\} & t > t_e \end{cases} \quad (2)$$

This equation can be solved for the time dependent fuse current $i_2(t)$. Commutation of the current from the explosive switch will be achieved if $i_2(t)$ increases to a point where it equals the storage coil current, i.e., the condition for commutation at a time t_T is $i_2(t_T) = i_o$. Here i_o represents the initial value of the storage coil current. If L_o is very large, i_o is essentially a constant. If L_o is smaller, so that its current is variable, then i_o is the (experimentally determined) value of coil current at commutation.

The simplest case for calculation of the fuse current from Eq. (2) is when the series switch closes after the explosive switch arc voltage has reached V_{max} . If the series switch closes at t_1 (measured from the start of explosive switch opening) and $t_1 > t_e$, then the right-hand side of Eq. (2) is a constant, and for $t < t_1$

$$i_2 (t) = \frac{V_{max}}{R} \left[1 - e^{-\frac{R}{L}(t-t_1)} \right] \quad (3)$$

This equation shows that $i_2(t) < V_{max}/R$ so that full commutation of the current can be achieved only if

$$R < \frac{V_{max}}{i_o} \quad (4)$$

This condition must be satisfied in all cases, since V_{max} is the greatest possible voltage and the fuse current can never exceed V_{max}/R .

Commutation will be achieved at some time if the above condition on fuse resistance is satisfied. For the case being considered, the commutation condition $i_2 = i_o$ is satisfied at a time given by

$$t_T - t_1 = \frac{L}{R} \ln \left(\frac{V_{max}}{V_{max} - Ri_o} \right) \quad . \tag{5}$$

The commutation time interval becomes shorter as the circuit resistance is reduced. In the limit as $R \rightarrow o$, the build up of fuse current is limited solely by the inductance of the fuse circuit:

$$\frac{di_2}{dt} = \frac{V_{max}}{L} \quad \text{for } t_1 > t_e \tag{6}$$

and

$$i_2(t) = \frac{V_{max}}{L} (t-t_1) \tag{7}$$

So the commutation time is

$$t_T - t_1 = \frac{Li_o}{V_{max}} \quad . \tag{8}$$

This is the shortest possible transfer time interval for a given circuit inductance. If the resistance is greater than zero, t_T increases as illustrated in Fig. 8. The graph of Fig. 8 is a plot of time, t_T, in units of Li_o/V_{max} as calculated by Eq. (5) as a function of fuse resistance expressed by the variable Ri_o/V_{max}. The graph shows that for resistance values just slightly less than the critical value required for commutation, V_{max}/i_o, there is commutation, but it takes a long time. As resistance is reduced, the commutation time decreases rapidly toward commutation time for $R = 0$. When the resistance is half of the critical value, the commutation time is only 37% greater than the value for $R = 0$ case.

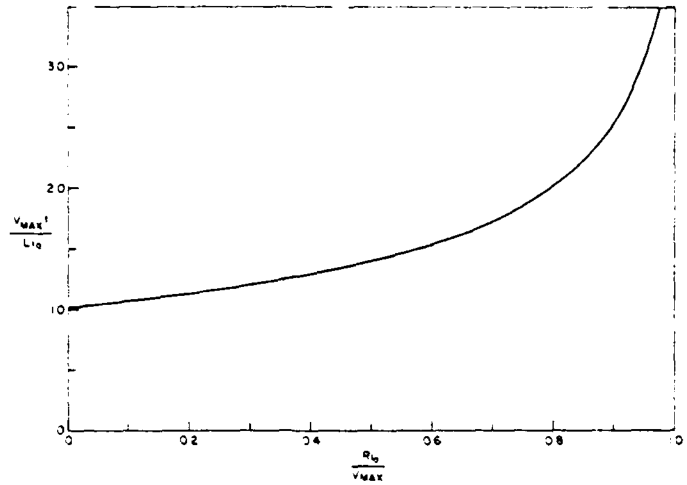


Fig. 8. Effect of loop resistance in the circuit shown in Fig. 6 on the rate of current transfer from the exploding switch to the foil fuse.

Transfer time shown in Fig. 7 agrees with that calculated from Eq. (8) for V_{max} = 13 kV , i_o = 250 kA and with the measured circuit inductance of 1 μH. The critical resistance required for commutation is V_{max}/i_o = 0.5 mΩ . Typical foil used in switches such as those associated with Fig. 7 has room temperature resistance of 1.7 mΩ , so that t_T is virtually independent of fuse resistance, as indicated by Fig. 8 graph.

Because of the critical role of V_{max} in establishing transfer time, the study of arc voltage on current in ref. 12 was extended to higher currents. The results, shown in Fig. 9, indicate an over 50% decrease in V_{max} as the current being interrupted by the switch increases to 400 kA.

To establish the upper limit on the amount of energy that can be transported through the exploding switch, Gould Inc. facility[6] was used as a source of 60 Hz oscillatory current for a duration of four cycles, in addition to the 0.5 MJ tests using Suzy II pulsed current source. Electrical energy transferred from the rotational storage (generator) through the switch (with and without auxiliary fuse) to a resistive load was about 7 MJ. Circuits shown in Fig. 10 were used, resulting in switch and load currents I_{SW} and I_L and in load voltage V_L , indicated in the figure. In both instances, arc resistance of the switch is greater than 2 Ohms for the entire

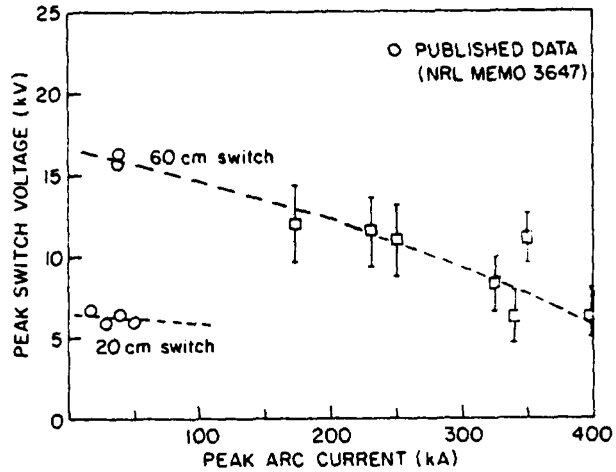


Fig. 9. Arc voltage of the exploding switch shown as a function of arc current.

period of current flow. At the end of the test, the switch remained confined within its cardboard jacket.

Although other configurations of the exploding switch were used,[12] the cylindrical geometry of the switch shown in Fig. 4, which allows convenient confinement of the explosive forces, appears to be the most practical. The amount of the explosive, typically 4g per 0.5m represents only 5-10% of the electrical energy transported by one switch module.

IV. INERTIAL CURRENT SOURCE SWITCHING

Inductive storage using inertial current sources imposes special requirements on the circuit design when these systems are utilized for high power applications. The long current rise times can now be handled efficiently by the exploding switch described in the preceding section. However, such current sources, in practice, can not support high power pulsed voltage which appears across the output, as well as across the generator and the inductor.*

*Modification of the homopolar generator (including the storage inductor) for operation with output voltage at up to 2MV is discussed in ref. 25.

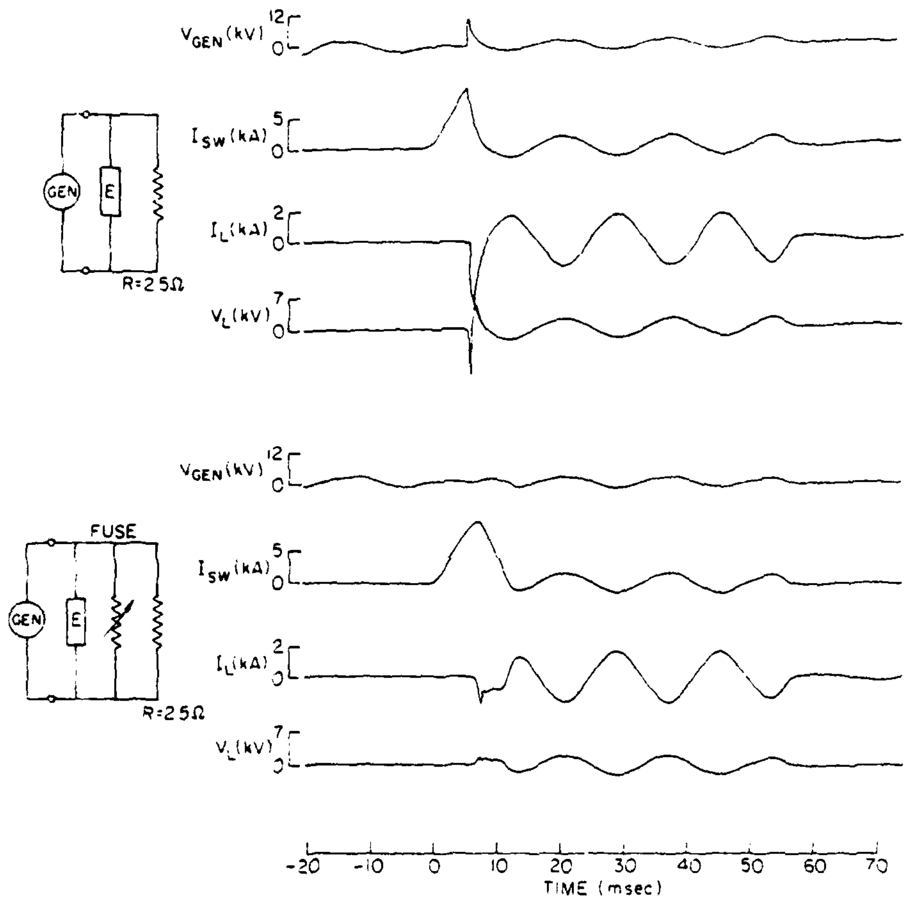


Fig. 10. Two test modes of the exploding switch using an output of 1000 MVA short circuit generator.

Therefore, a crowbar at an appropriate point in the circuit is needed. In addition, matching of the generator current output with the required pulsed current output often requires that a transformer be inserted between the generator and switching stage. Both of these requirements reduce the maximum energy transport efficiency to less than 25%, associated with energy being transferred from one inductor to another inductor in such circuits.

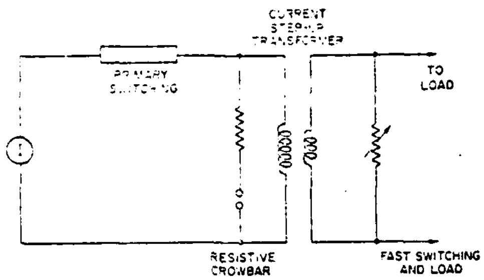


Fig. 11. Circuit for optimizing energy transport in inertial-inductive pulsers.

The transport efficiency can be increased by use of a circuit such as that in Fig. 11. Detailed discussion of this type of circuit has been provided elsewhere.[26] This analysis is summarized in Fig. 12, for the case of self-excited homopolar generator where the generator inductor coil is used as the primary of the current step-up transformer. Fig. 12 shows the energy transfer efficiency as a function of the transformer coupling constant, k, for different values of the resistance of the crowbar branch. The resistance is varied from short circuit (preventing any voltage from appearing across the current source) to a value such that 20% of the output voltage (as transformed from the secondary to the primary) appears across the source. It is seen that even 50% efficiencies can be achieved for a price of reasonable voltages across the generator.

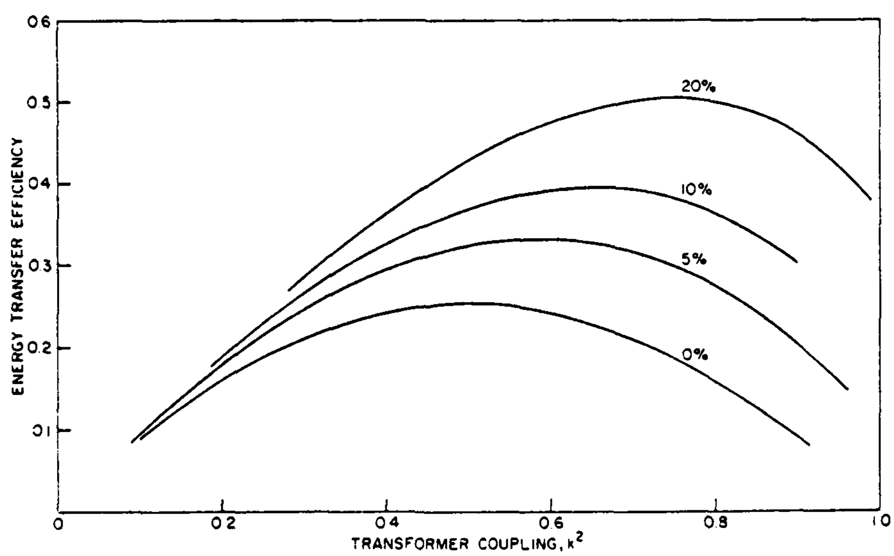


Fig. 12. Energy transfer efficiency in inductive storage circuits with resistive crowbar.

V. CONCULSION

Development of the exploding switch, described here, used in combination with fuse stages, places the inductive storage on par with capacitor banks, traditionally used in applications requiring high power output pulses. S. A. Nasar and H. H. Woodson[27] indicate in their review of methods of energy storage for pulse power applications that just such a development is necessary for full exploitation of the inductive storage. Substantial experience with operating opening switches in parallel,[3,11] indicates that many modules can be assembled into large storage systems, such as those in development by Bohdanova et al.[28] Further, projected development of opening devices that are not destroyed during the interruption of the current,[29] will make inductive storage systems even more attractive and versatile.

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