

A LONG CONDUCTION-TIME, 2-MA COMMUTATING SWITCH

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Abstract

An array of eight parallel opening switches is designed to commute the 2-MA current of an energy storage inductor into a low-inductance, low-resistance load for electromagnetic launcher research. Switch opening is achieved by interruption of the current path with a small explosive charge which, in this particular switch, is totally surrounded by the conductor. This switch, in its normally closed state, carries current during the 5-s interval required for the inductor to be energized by the Air Force Armament Laboratory (AFATL) battery power supply. Conductor cross section is determined experimentally so that Joule heating of the conductor does not cause overheating and improper detonation of the explosive. Prototypes of the switch modules were tested at AFATL with 168-kA, 5-s current pulses.

Introduction

A battery bank power supply¹ located at the Air Force Armament Laboratory (AFATL) will deliver a 5-s power pulse with a 2-MA current to energize energy storage inductors with up to 120 MJ. Application of this energy to EM launcher research requires subsequent commutation of the current into a low-inductance, low-resistance load. This commutation is achieved most simply by a circuit breaker in parallel with the load impedance. In its normally closed state, this circuit breaker carries the full bank and inductor current during the 5-s, energizing interval. This paper describes the development of a circuit breaker suitable for this commutating function.

Explosively actuated circuit breakers have been used in inductive-energy storage circuits where they proved capable of conducting currents for a number of seconds during which the inductor was being energized from a low-voltage current source, not unlike the application addressed here. Those circuit breakers² employed an aluminum conductor in the form of a hollow tube filled with paraffin and having a length of explosive detonating cord situated along the axis. The outside of the tube was surrounded by a series of strong, close-fitting steel rings separated by insulating gaps. Current flow is interrupted when the internal pressure from detonation of the explosive cuts and bends the aluminum conductor and forces paraffin into the gaps between the steel rings. A circuit breaker using a 6.35-cm diameter tube with 1.6-mm wall thickness was able to carry a current pulse rising to a 50-kA peak during the five-second interval required to energize the inductor.³ The maximum conduction time appeared to be limited only by the onset of melting of the conductor due to Joule heating by the current.⁴

If the aluminum tube circuit breakers were to be applied to the AFATL system, clearly a number on the order of forty of them in parallel would be required. On the other hand, the high voltage capability of the many series gaps of the tube switch is not needed for the AFATL application. Consequently, a single-gap switch with larger conductor cross section was developed to reduce the number of parallel switch modules needed. This approach also avoids some of the complexity associated with the tube-and-paraffin switch construction.

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Commutating Switch Concept

The approach taken in development of this commutating switch is suggested by experience with an earlier, single-gap switch⁵ which used an explosive detonating cord adjacent to the current-carrying conductor. In that switch a sheet of conductor, typically 1-mm thick, was wrapped around the length of detonating cord. This provided confinement of the explosion sufficient to permit rupture of the uniform cross section conductor. By having the explosive in direct contact with the conductor, the opening time was very fast and the recovery voltage high. The reader desiring fuller details is referred to the figure and switch description given in reference 5.

Having the explosive imbedded within the conductor should facilitate breaking of a much more massive conductor; so the present switch is designed with a significantly larger conductor cross section. This will achieve an increase in conduction time, although it may be at the expense of rapid opening. The proposed switch conductor is fabricated from thick plates with a central hole drilled through the entire width to accommodate placement of a detonating cord. This construction is illustrated in the sketch of an experimental switch shown in Fig. 1. Having the conductor surround the explosive this way effectively doubles the conductor cross section for a given amount of explosive.

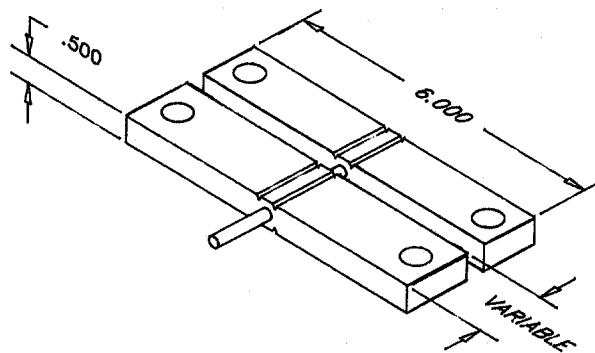


Fig. 1 - Assembly of pairs of aluminum conductor pieces with a common detonating cord for thermal tests of the conductor.

The above-mentioned, single-gap switch⁵ was used at a current density approximately that used in the earlier tube switches. However measurements made were not sufficient to establish the limit to current and conduction time. In a configuration where the explosive is adjacent to the heated conductor, a longer conduction time will permit a greater fraction of the heat to diffuse into the explosive charge. In this case, the conduction time may be limited by the allowable temperature of the explosive rather than by melting of the conductor.

Thermal Effects

The maximum switch conduction time is determined by the allowable temperature rise due to Joule heating by the current carried within the solid, metallic conductor. The local heating rate per unit volume in the conductor is $j^2\rho$, where ρ is the electrical

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resistivity of the metal and j is the current density (ratio of current to conductor cross-section area). In the simplest case, where conduction time is so very short that virtually no heat is lost by thermal conduction, the rate of temperature rise is

$$j^2 \rho = c_v dT/dt \quad (1)$$

where c_v is the volumetric heat capacity and T is the temperature within the conductor. This equation is easily integrated to give the following action-integral expression.

$$\int_0^t j^2 dt = \int_{T_0}^T (c_v/\rho) dT \quad (2)$$

The integration is over time on the left-hand side and over temperature on the right-hand side, with T_0 being the initial (room) temperature. The variables on the right-hand side are material parameters and are functions of temperature alone. Hence, there is a one-to-one correspondence between conductor temperature and value of the action integral. Now, the conductor will clearly fail if it reaches the melting temperature. Consequently, in this simplest case, the value of the action integral corresponding to the melting temperature of the metal can be used to characterize the maximum current pulse which can be permitted through the circuit breaker.

With longer conduction times, the determination of temperature rise within the circuit-breaker conductor is complicated by the effect of thermal conduction. It was found that departures from the predicted action were small for radial thermal conduction in the tube switch. In the type of explosive circuit breaker proposed here, current density and rate of temperature rise is greatest at the break points where conductor cross section is thinnest. A longer conduction time allows some of the heat generated at the thinnest points to be conducted away to the thicker (cooler) conductor nearby. Analytically, this could be represented by additional, thermal-conduction terms on the right-hand side of Eq. (1). The effect of this cooling from thermal conduction is to permit a larger action-integral (evaluated at the thinnest point) to accumulate prior to the melting point.

The long-time thermal effect of most concern with the proposed new type of circuit breaker is the heating of the explosive. Because the detonating cord used to break the circuit is in intimate contact with the heated conductor, the explosive can be heated by thermal conduction through the insulating jacket of the cord. A long current conduction time clearly permits a greater temperature rise in the explosive. This may, in turn, require a reduction in the maximum permitted temperature. The major reason for concern is that the temperature at which the explosive fails to detonate properly is not known with certainty. The explosive used in the detonating cord (PETN) has a melting point of 104°C, and its explosive performance may be altered if it liquefies. At higher temperatures, PETN will burn without exploding. It has been reported that this deflagration may occur at 225°C. If this deflagration should begin prior to the triggered firing of the detonator, the likely result is insufficient pressure to break the conductor resulting in a misfire of the circuit breaker.

Conduction Time Experiments

In view of the uncertainties present, it seems advisable to experimentally determine the current density at which the circuit-breaker contacts can be operated without impairment of the explosive switch opening. This was first done with current pulses of

300-ms duration. To put the data in a form suitable for switch design, the measured current density and conduction time are expressed in the form of the specific action experienced by the conductor.

The circuit breaker conductors used in this test are made of 1100 aluminum alloy. They are 6-in. long and 0.5-in. thick, and have a 0.5-in. clearance hole at each end for electrical connections. A 50 grain/ft. PETN detonating cord is located at the center of each conductor as shown in the sketch of Fig. 1. To break the circuit, the cord is detonated by an RP80 exploding bridge wire (EBW) detonator affixed to one end. Each test circuit breaker consists of one or two of these aluminum conductor pieces of various widths to permit variation of current density. When two pieces are used, they are assembled together to share a common detonating cord as shown in the figure. At the critical points, next to the explosive, the minimum conductor thickness is 0.126 in. The action integral value corresponding to each test is calculated using the current density at these points.

These tests were performed at Eglin AFB by switching a battery bank (a prototype for the large AFATL battery bank development) into the test circuit breaker connected in series with additional resistance sufficient to limit the test current to a nominal value of 100 kA. Current flow through the circuit breaker is started by closure of the gang switches internal to the battery bank and interrupted by opening of the explosive circuit breaker. The time delay between triggering of the two switches is set so the conduction interval is nominally 300 ms. This interval was maintained constant for all shots of the test series. Since the current supplied by the battery bank remains fixed for all shots, the current density (and resulting heating effects) in the circuit breaker must be changed by the use of conductors with different cross-sectional areas. The area is changed without disturbing the relationship and location of the explosive relative to the conductor by changing the width of the test pieces shown in Fig. 1.

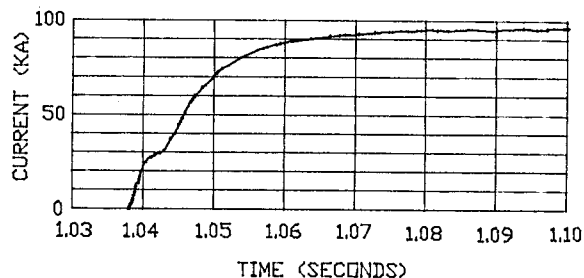


Fig. 2 - Early portion of time-dependent current through the conductor showing rise of current following closing of gang switches at 1.038 s.

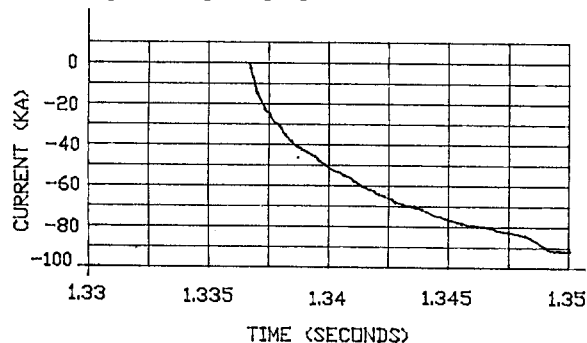


Fig. 3 - Late portion of time-dependent current through the conductor showing current drop during opening of circuit breaker.

For each shot, measurements are made of the time-dependent current and voltage across the circuit breaker. Records of the time-dependent current were obtained by integration of signals from calibrated Rogowski coils placed around the conductors. Fig. 2 shows the early portion of the current pulse, with current rising to 96 kA following closure of the gang switches at 1.038 s. Fig. 3 shows the final portion of the current pulse where the current decays accompanying the opening of the circuit breaker at 1.337 s. The measured current is subsequently used to calculate the magnitude of the action integral, $\int j^2 dt$, for each shot. The arc voltage developed across the circuit breaker as it opens is observed to ascertain if the breaker indeed opens properly. Fig. 4 shows the time-dependent arc voltage drop across the opening switch. A measurement is also made of the trigger signal used to fire the EBW detonator to verify that it is coincident with the onset of arc voltage.

In six of these test shots, the conductor width was varied from 2.5 in. to 2.0 in., and the circuit breaker was command fired successfully. The largest action value calculated for these shots is 2.45×10^{16} [A²-s/m⁴] at a current pulse duration of 0.291 s. The precise limit for successful operation was not determined, but additional test shots were made, without explosive, to allow conductor melting. A single, 1.25-inch-wide conductor melted and opened at 0.206 s. The resulting action was calculated to be 4.0×10^{16} [A²-s/m⁴].

The action for melting observed here can be compared with the melting action at short conduction times. The melting action calculated from formula (2) above, using the temperature-dependent material constants for aluminum, is 2.67×10^{16} [A²-s/m⁴]. The action for melting measured at very short conduction times (very large current densities) by Tucker and Toth⁶ is 2.52×10^{16} [A²-s/m⁴]. The increased melting action measured here shows the effect of heat conduction during the 200-ms pulse duration.

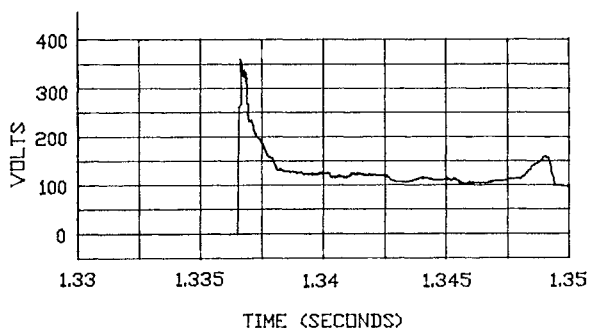


Fig. 4 - Time dependent voltage across test circuit breaker following opening command at 1.337 s.

Commutating Switch Module

The 2-MA commutating switch will consist of an array of eight, parallel, modular switch elements; one for each bus bar pair on the AFATL battery bank. This will permit the versatility of using less than the full system for smaller experiments, as well as simplifying testing for the final switch. In the design of this switch module, the action values obtained from the measurements with 0.3-s current pulses were used to estimate the allowable current density at a longer conduction time. This current density and working current of up to 250 kA were used to determine the needed conductor cross section. The greater conductor thickness is realized by fabricating it from 0.75-in. thick aluminum plate. The 250-kA switch module uses a 12 in. conductor width which results in a cross-sectional area of 3.1×10^{-3} m². The explosive charge

was increased to 150 grain/ft. to accommodate the thicker conductor. Two separate detonating cords are used in the switch to provide two series switch gaps. This is mainly for redundancy to ensure reliability. Fig. 5 shows a cross section view of the switch conductor and enclosure. A prototype of the individual switch module was tested at AFATL using a separate prototype of the battery bank capable of up to 200 kA. This battery bank was connected to the switch module in series with a current limiting resistor. The switch interrupted a current pulse of 168-kA on command after an interval of 4.97-s. From measurements of the current (168 kA) and its e-fold rise time (3 ms), we estimate that the circuit resistance was 0.6 mΩ with a series inductance of 1.9 μH. In this test, the switch dissipates significant electrical energy in addition to the explosive energy. From the above circuit values, the magnetic energy was estimated to be 26 kJ.

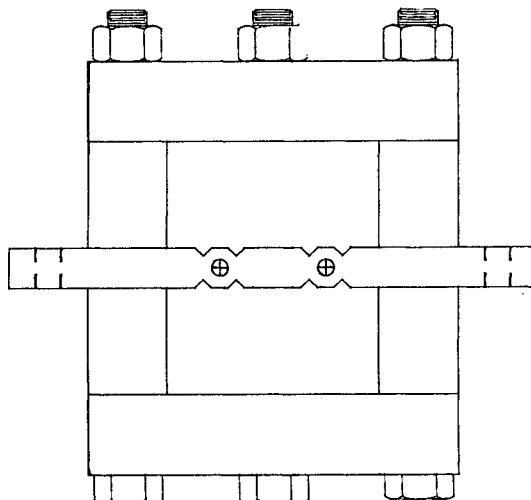


Fig. 5 - Outline of 250-kA switch module showing conductor cross section parallel to direction of current flow.

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