LOW LOSS CURRENT INTERRUPTER
FOR MEGAMPERE CHARGING OF INDUCTIVE STORAGE

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Summary

A high current, explosively operated slow (2 ms) opening switch has been developed for use as a first stage switch in multi stage switching of inductive storage systems. This switch eliminates the need to use large numbers (20-25 switches/megampere) of more expensive switches in inductive storage pulsed power systems where tens to hundreds of kilovolts are developed during switching of the inductive store. Switch operating parameters include current density to 20 kA/cm^2, opening time after explosive detonation of 100 μsec, clear time of 2 msec to produce a 6 cm gap, and voltage holdoff to 100 kV/gap (8-10 kV/cm). System innovations, including the use of a fiber optic coupled detonator firing set, simplify switch use in pulse power systems.

Introduction

Energy requirements for large pulsed power experiments have led to the development of compact (1-3 m^3) multi-megajoule homopolar generators capable of delivering current pulses with seconds duration of up to several megamperes into low resistance loads.[1] Typically these generators have output voltages of no more than a few hundred volts and therefore require an intermediate power forming stage comprised of a large inductor and appropriate current interrupter (opening) switches, for most pulsed power applications. Because of the low voltage and high current, low resistance in the power forming stage, including inductor and opening switch, is critical. Additionally, the opening switch must hold off the inductively generated load voltages, often hundreds of kilovolts, for the load pulse duration.[2]

A multi-gap explosively driven circuit breaker using paraffin to transmit explosive pressure and provide late time insulation has been used for this application, where long pulse currents are less than 100 kiloamperes.[3] This breaker has been tested with short (150 μs) current pulses to 0.4 MA with recovery in 50 μsec to 800 kV holdoff, at field strength of 10 kV/cm. Conductor cross section for this switch is such that 20 to 25 switch modules would be required for one second duration megampere currents. Even though current carrying capacity can be increased to some extent by use of copper buss, without severe deterioration of the opening

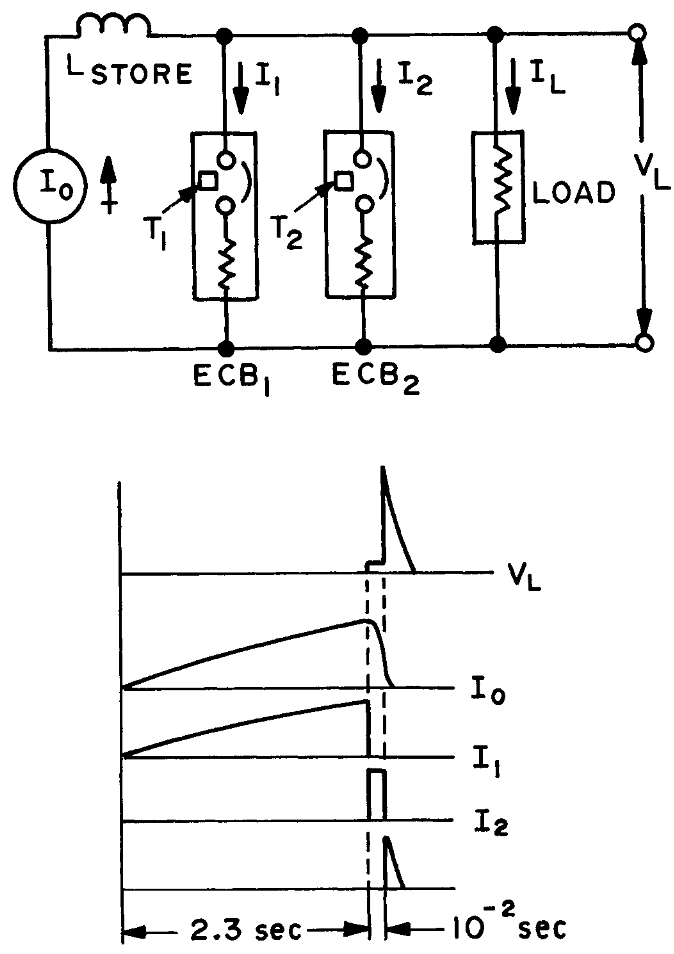

Fig. 1 Staged opening switch schematic for inductive pulsed power systems. Explosive circuit breakers (ECBs) are normally closed and are opened in sequence to produce current and voltages shown.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1983	**N/A**	**-**

4. TITLE AND SUBTITLE
Low Loss Current Interrupter For Megampere Charging Of Inductive Storage

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory Washington, DC 20375

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**3**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

action, this approach to megampere switching is prohibitive due to both cost and physical space limitations.

Staged Switching

One solution to the switching problem seeking to reduce drastically the number of switch modules, involves a staging concept used effectively in previous experiments. Figure 1 shows an example of switch staging whereby the storage inductor, L_{store} is charged through closed ECB1 over a 2.3 second period. The sequence of events shown in Fig. 1 illustrates the time history of currents and voltages resulting from use of staging. At time T_1, charging current has reached a maximum level and ECB1 is opened, diverting the inductor current to ECB2. ECB2 carries current only long enough to allow ECB1 to reach full open position, then at T_2, ECB2 is opened to transfer stored current to the load circuit. Inductively generated load voltage, V_L, appears across all switches as well as across the storage inductor. Using this technique, only a single relatively massive and slow operating first stage switch is required for inductor charging, while a single fast second stage switch permits rapid opening required to develop inductive voltages for driving the load. For some

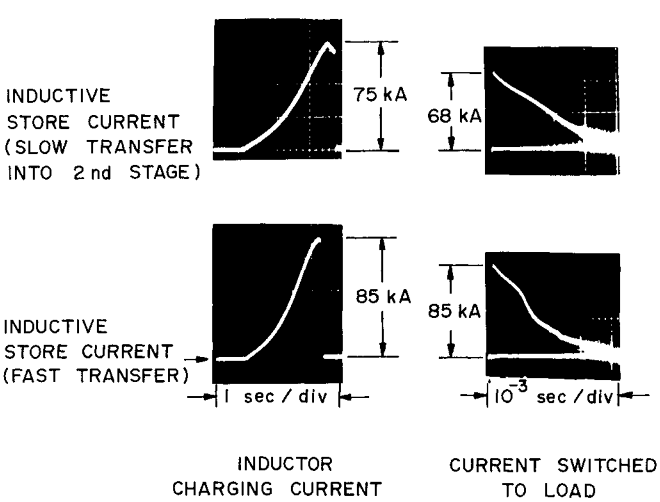

Fig. 2 Waveforms from inductive pulsed power switching using 2 stage explosive circuit breakers. Note that charging current is displayed on a 1 sec/div. scale, load current on 1 msec scale.

applications where load requirements include sub-microsecond, hundred kilovolt pulses, this concept can be extended to 3 or more switching stages similar to those described in Ref. 3.

Circuit Breaker Operation

Although the first stage circuit breaker, ECB1, may open slowly as compared to following stages, current traces in Fig. 2 show that optimizing the switching speed for a given application is essential for efficient energy transfer. Current traces in the left hand of Fig. 2 show slow currents charging the inductor. At right on the figure, current transferred rapidly (with 10^3 times faster time scale) into the load is shown. In the upper trace, a developmental model circuit breaker requiring 200 msec clearing time was used, with the result

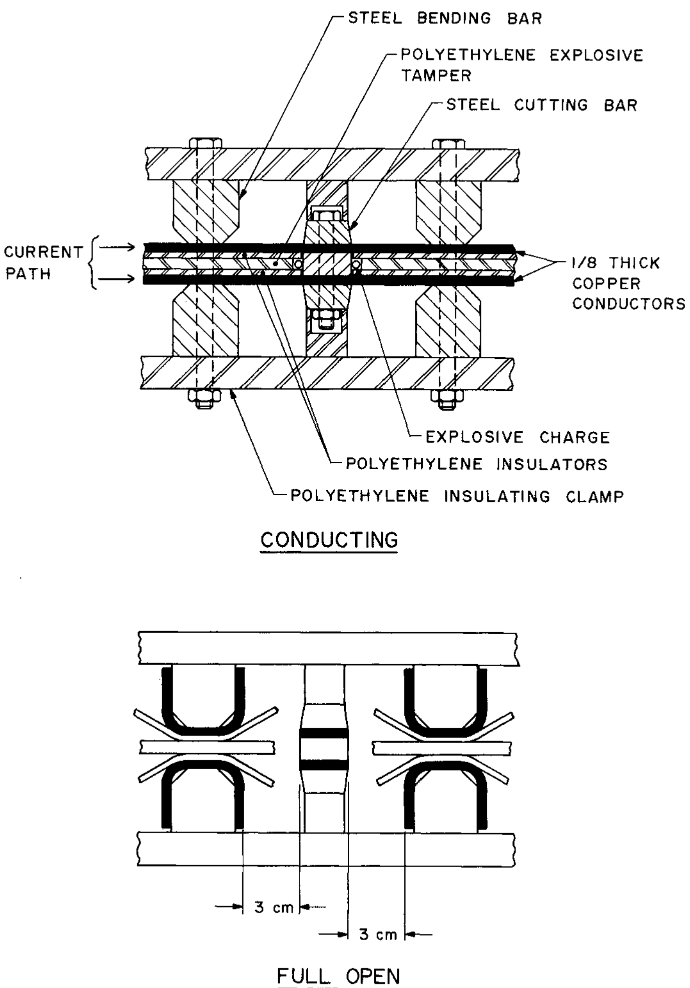

Fig. 3 Schematic representation of explosive circuit breaker operation using relatively large mass conductor.

that second stage switch resistance reduced current delivered to the load by 20%. Improved switch design reduced clearing time to 2 milliseconds, resulting in current transfer of more than 99% to the load.

Figure 3 shows a schematic representation of the high current ECB used with the NRL Homopolar generator. A careful balance between mass of conductor and explosive charge dissipates a large percentage of explosive energy in metal forming of the conductor. Thus, the switch assembly remains intact during and after explosive detonation. This configuration, operated to 100 kA for a time of 2.3 seconds, utilizes two copper sheets 3.18 mm thick by 10.2 cm wide, driven by two 50 grain (3.24 gm)/ft explosive charges. Upon detonation of the explosive charge, initial current interruption begins in approximately 100 µs. Explosive pressure drives the polyethylene insulators outward, forcing the copper conductor against hardened cutting bars. The conductor is folded against the bending bars to produce a 3 cm gap on each side of the cutter bar. The polyethylene insulators fold outward partially interrupting the arc path formed at conductor separation. Although arc voltage is 500 V to 1 kV per gap, it is sufficient to commutate stored current into a closely coupled second stage circuit breaker in less than 100 microseconds. An arc clearing time of approximately 2 miliseconds is required for high voltage holdoff. During this time the conductor is folded firmly against the bending bars, as shown in Fig. 3b. The resulting 6 cm gap has been shown to withstand inductive voltages up to 100 kV.

The basic configuration shown in Figure 3 may be increased in length at approximately 12 cm intervals to provide high voltage operation compatible with the multigap paraffin filled switch (8-10 kV/cm). It can be increased in width, as desired, to provide for high current operation.

System Operating Considerations

Emphasis in switch development has been placed on producing a low resistance modular switch sufficiently versatile to operate over a range of 10^5-10^6 A with 10^5-10^6 V holdoff.

However, system constraints such as water insulating medium, high voltage protection of equipment, and explosive safety procedures dictate certain design limits. Several innovations have been included in developing this high current breaker to make it more versatile. Explosive charges including main charge and detonator use only secondary explosives which are insensitive to thermal, radio frequency (RF) and electro-static initiation. Detonators used are exploding bridge wire (EBW) type requiring >600 A impulse having risetime of 1 µs/kA to prevent accidental firing from capacitive or inductive pickup. Detonator firing set has been specifically designed for system high voltage operation. It is battery powered providing approximately 1 joule at 2 kV for firing the detonator. A fiber optic link is used both for energizing the 2 kV power supply and firing detonators. Precision control of inductive store current is obtained since detonator and firing sets have a jitter of less than 1 microsecond.

Conclusion

The switch described here is easy to use in experiments which would otherwise require massive and expensive switching components. It is especially well-suited for charging inductors from high, long duration current sources such as homopolar generators. Switching parameters such as voltage holdoff of 8-10 kV/cm and arc voltages of 500 V to 1 kV/switch gap closely match that of other circuit breakers and fuses which would be used as second stage components for many pulsed power applications. Switch assembly and trigger control is sufficiently simple and inexpensive, and may readily be tailored to many specific circuit applications.

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