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100kA, 5000 V Solid State Opening Switch for Inductive Energy Stores

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Inductive energy stores have demonstrated higher energy storage densities than capacitive energy stores. A limitation in the use of inductive energy stores has been the availability of adequately rated opening switches. A self commutated solid-state switch has been developed for use as an opening device for an inductive energy store. The switch is rated at 100kA and 5000V and is composed of four identical 25kA switch modules. The charging pulse lengths for the intended application vary from 0.1 to 5 seconds. Efficiency and volumetric power density were optimized. The switch topology is a two stage hybrid consisting of an SCR-FET/SCR-IGBT combination. The switch is designed to charge an inductive energy store and repetitively commutate the current into a railgun load. A 100kA switch module has been built and successfully tested. The theory of operation, circuit topology and test results are given in this paper.

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PREFACE

This paper documents research conducted on a solid-state opening switch for inductive energy store and was presented at the 9th IEEE Pulse Power Conference in Albuquerque NM on 21 Jun 93.

This work was funded by WL/MNAA of the Armament Directorate at Eglin AFB FL under the Kinetic Energy Weapons Program of the Strategic Defense Initiative. Mr. Mark W. Heyse from WL/MNAA, Dr. Joshua Kowawole from SAIC, and Mr. Ed Bowles from General Atomics, Inc. in San Diego CA performed the work during the period of Apr 90 to Dec 93 at Eglin AFB FL.

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A 100 kA, 5000 V SOLID STATE OPENING SWITCH FOR RAILGUN APPLICATIONS

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Abstract

Abstract - Inductive energy stores have demonstrated higher energy storage densities than capacitive energy stores. A limitation in the use of inductive energy stores has been the availability of adequately rated opening switches. A self commutated solid state switch has been developed for use as an opening device for an inductive energy store. The switch is rated at 100 kA and 5000 V and is composed of four identical 25 kA switch modules. The opening repetition rate for the intended application varies from single pulse to 10 Hz. Efficiency and volumetric power density are optimized. The switch topology is a two stage hybrid consisting of an SCR-FET / SCR-IGBT combination. The switch is designed to charge an inductive energy store and repetitively commutate the current into a railgun load. A 100 kA switch module has been built and successfully tested. The theory of operation, circuit topology and test results are given in this paper.

Introduction

Railgun research requires current pulses in the hundreds of kiloamps delivered at thousands of volts. Typically a capacitive energy store and a closing switch are used to deliver this power to the load. High power closing switches are available in the form of sparkgaps, ignitrons, and SCRs [1]. Each of these devices can momentarily conduct currents in excess of 100 kA, but once turned on they cannot interrupt current flow.

Another method to energize a railgun is with an inductive energy store and an opening switch. Opening switches for inductive energy stores must close and conduct current to charge the energy store and then momentarily open (interrupt the current flow) and commutate (transfer) the current to the load. Mechanical switches, GTO thyristors[2], and transistors are available for this opening switch duty but all have much lower power densities than closing switches.

Solid state devices are generally preferred over other switch types if a performance match is available for the intended duty. The purpose of this program is to build and demonstrate a solid state opening switch that has sufficiently low conduction losses and sufficiently high power ratings to be practical in inductive energy store railgun application. This paper describes the design and testing of a solid state opening switch that meets those goals.

Theory of operation

Figure 1 shows a circuit schematic for the demonstration switch. It can be seen that the switch is of a hybrid design with two conduction paths and four active switching elements.

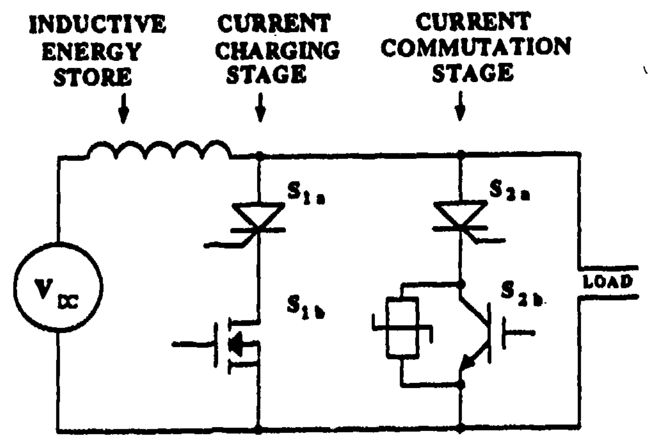

Fig. 1. Opening switch circuit schematic.

As will be explained, the different switching elements of the circuit schematic pertain to the different switching phases that an inductive energy store opening switch must support.

These phases are:

1) Charge

Close and conduct inductor current from zero to maximum with minimum losses. This requires low conduction voltage drop.

2) Commutation

Upon command, commutate current out of the switch and into the railgun load by forcing a large voltage drop across the switch. This requires high commutation voltage and fast turn-off speed.

3) Voltage Blocking

Block any voltage produced by the dynamic railgun load and maintain zero current in the switch. This requires high blocking voltage in the off state.

4) Reclosure

Reclose and recover current from the load upon command. This requires fast turn-on speed.

These requirements have spawned the dual stage hybrid switch design shown in figure 1. The two conduction paths, S_1 and S_2 in Fig. 1, provide for two separate switching stages. Stage 1 (switch S_1) provides for the low loss charging function of the switch while stage 2 (switch S_2) provides for the forced current commutation out of the switch. Providing these two stages has allowed the switch to meet the conflicting design requirements of low conduction loss during charging and a fast, high voltage current commutation to the load.

The topology also provides for a cascode (series) connection of an SCR and a transistor in each switch stage. The charging switch stage has a 5000 V. SCR in cascode with a 50 V. FET transistor while the commutation switch stage has a 5000 V. SCR in cascode with a 1000 V IGBT transistor. This arrangement of semiconductor devices allows the transistors to accomplish the lower voltage commutation functions while the SCR accomplishes the 5000 V blocking function with a single series device. By separating the functions of charging, commutating, and voltage blocking we have been able to provide a switch that compromises few performance attributes and has a power density approaching that of a closing switch (SCR).

Since two MOS devices (FET, IGBT) control an SCR thyristor, we call the switch a Bi-MOS Thyristor (BMT).

Operational Description

To see how this concept works, refer to the circuit schematic in Fig. 1 and the switching timeline that depicts the intended current and voltage waveforms in Fig. 2. Switches S_{1a} and S_{1b} are the charging switches. Initially, the combined switch must hold off the relatively low source voltage. Both switches S_{1a} and S_{1b} are triggered into conduction to initiate the charge cycle.

When the desired current is reached and one wishes to begin the commutation process, switch S_{2a} and S_{2b} are triggered into conduction while the FET switch S_{1b} is given a gate command to increase its resistance until a 40 V drop is obtained across its terminals. This 40 V drop will commutate current out of switch S_1 and into switch S_2 at a rate determined by the self inductance of the switch S_1-S_2 circuit. After current falls to zero in switch S_1 the SCR (S_{1a}) will begin to recover its voltage holding capabilities. The recovery time, t_q, is 275 µs for the 5000 V SCR we have chosen. After $\geq$ 275 µs of full current conduction the commutation switch, switch S_{1b}, is given a gate command to turn off. This command initiates the commutation of current from the switch to the load. The time for this commutation is determined by the inductance of switch S_2 and the load circuit and the voltage produced across switch S_2.

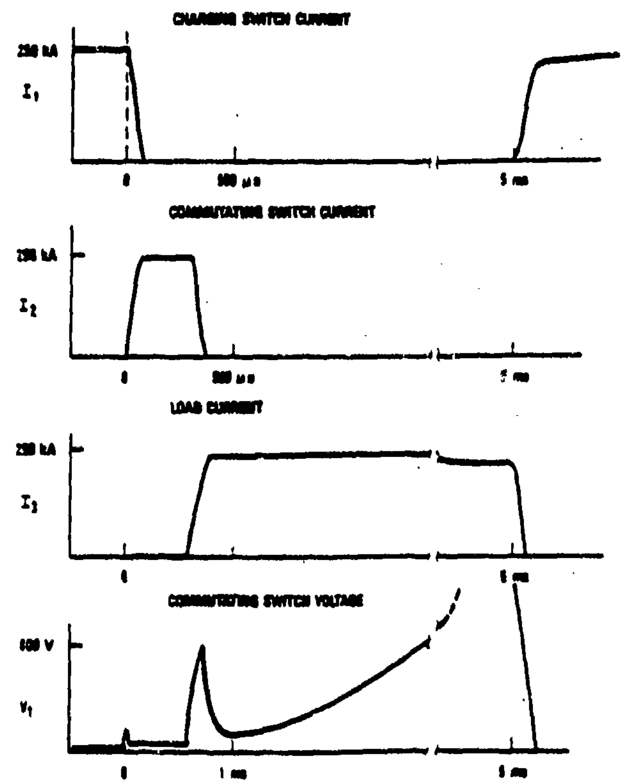

Fig. 2. Switching timeline for opening switch.

The IGBT switch S_{2b} has a 1000 V rating and an 800 V MOV clamp across it. An IGBT turn-off time of 10 µs is selected to provide a smooth current hand off to the MOV clamp, to maintain a reapplied dV/dt to the S_{1a} SCR of $\leq$ 100 V/µs, and to minimize switch S_{2b} turn-off loss.

After the IGBT of S_{2b} is fully turned off, the MOVs maintain 800 V across its terminals until current is fully commutated to the load. With nominal circuit inductances this turn off process takes ~ 75 µs. The entire process takes < 1 ms, allowing switch S_2 to be pulse rated.

After commutation is complete, the voltage across the switch will fall to a level dictated by the instantaneous voltage drop of the load (this voltage is generally about 200 V and much less than the 1000 V rating of S_{2b}). The commutation switch SCR, S_{2a}, is allowed recovery time in the interval between current commutation and the point where the dynamic voltage produced by the load exceeds 800 V (speed voltage). After this recovery time elapses, ~ 250 µs for SCR S_{2a}, the entire switch is ready to support a 5000 V back voltage that will eventually be produced by the accelerating railgun projectile.

Circuit description

A photograph of the first 25 kA, 5000 V switch module is shown in Fig. 3. Four of these modules composing a 100 kA switch is shown in Fig. 4. This 100 kA switch was first tested at Eglin AFB in July, 1992.

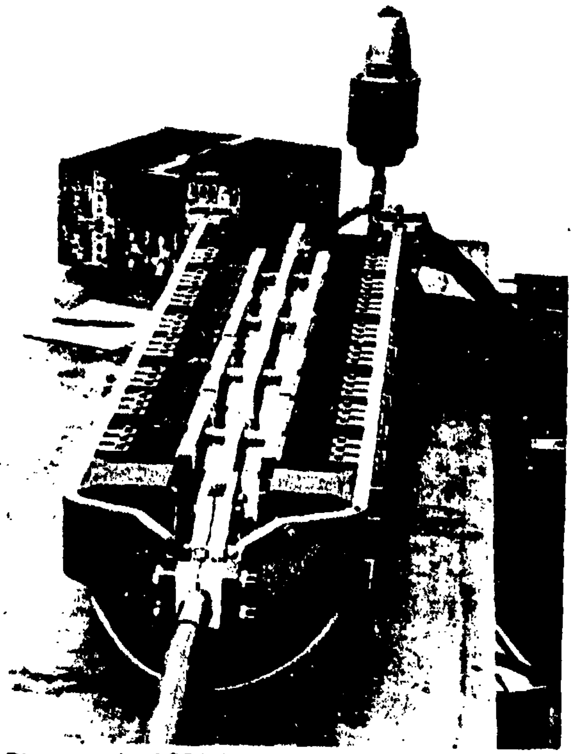

Fig. 3. Photograph of 25 kA switch module.

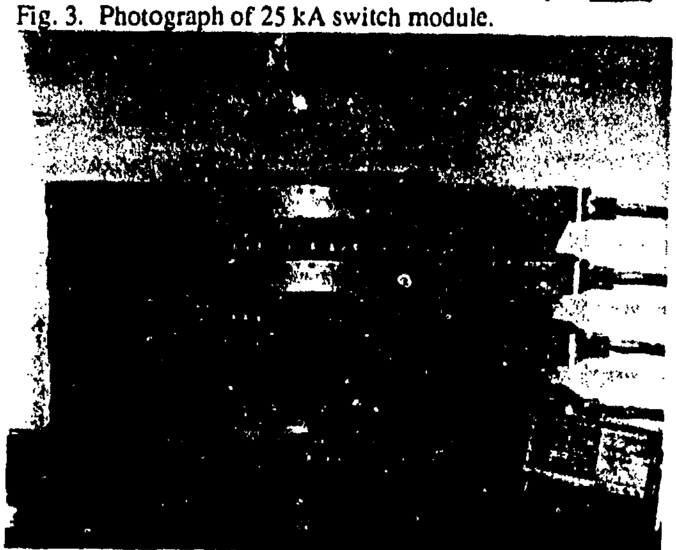

Fig. 4. Photograph of 100 kA, 5000 V opening switch.

In order to achieve a 25 kA module rating several submodules were placed in parallel. A charging switch submodule consists of an ABB CS-2104 [3], 5000 V, SCR in cascode connection with two FET modules. A photograph of a single switch submodule is shown in Fig. 5.

Each FET module (the two black boxes in Fig. 5) consists of an array 50 V FET transistors in parallel connection. The nominal 5 second current rating for each charging switch submodule is 4,166 A at a 2.2 V conduction drop. Six conduction switch submodules are placed in parallel to achieve the 25 kA rating.

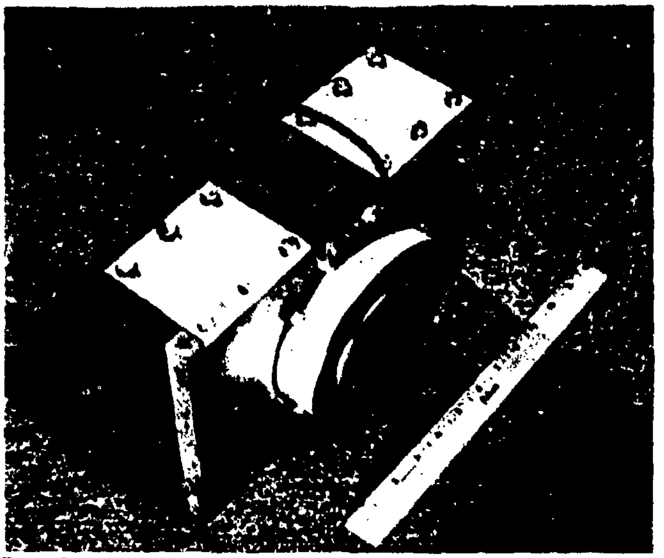

Fig. 5 Single 4,166 A switch submodule showing SCR, heat sink, and FET transistors.

A commutation switch submodule uses the same SCR as a conduction switch submodule and is identical in appearance. The only difference is the use of 1000 V IGBTs in each of the two cascode transistor modules. An IGBT transistor module and its associated control circuitry is shown in Fig. 6.

This 1000 V IGBT transistor array uses 16 large format IGBT chips manufactured by Advanced Power Technologies.

The nominal current rating for each commutation switch submodule is 12,500 A at a 7.0 V drop for operation ≤ 3 ms for each opening cycle. Two commutation switch submodules are placed in parallel to achieve the 25 kA rating.

To complete the switch, seven Siemens B80K275 100 mm, zinc-oxide varistors are placed across the IGBT transistors in the commutation switch submodule. Each MOV can absorb up to 4100 Joules of commutation energy. The current dependent voltage clamping action of these MOVs can be seen in Fig. 8.

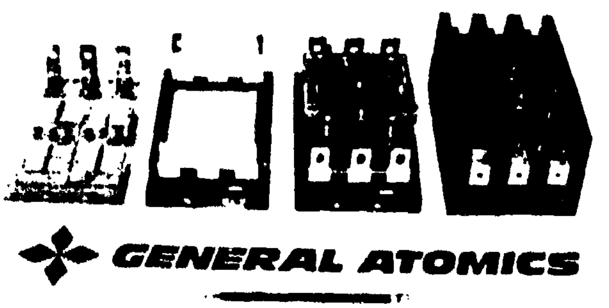

Fig. 6 A full transistor module and its associated control circuitry.

Test Results

The 100 kA switch module has been successfully operated at full current and repetition rate at Eglin Air Force Base. The switch , as installed in it's test setup, is shown in Fig. 7. Referring to Fig. 7, the battery power supply and 40 µH inductor are shown on the left of the switch while the railgun and dummy load are shown on the right. Current and voltage waveforms during a 103 kA commutation into a dummy load are shown in Fig. 8.

Fig. 7. Test setup at Eglin Air Force Base. Battery power supply, storage inductor, switch, and railgun can be seen.

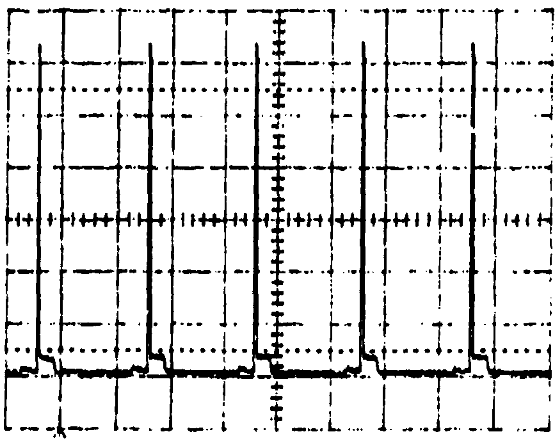

Fig. 8. Operational test results from 103 kA current commutation. into a dummy load at 5 Hz. The voltage waveform from five commutation events are windowed at a time base of 1 ms/div and an ordinate of 100 V/div (intervening 200 ms between shots is not shown). First voltage rise, ~ 10V, is switch S1 to S2 commutation. Second voltage spike, ~ 640 V, is the commutation from switch S2 to the load. Voltage plateau after the voltage spike is the resistive voltage drop of the dummy load. All 103 kA is commutated to the load when this ~ 50V plateau is reached.

Conclusion

A hybrid arrangement of power semiconductor that consists of an SCR-FET / SCR-IGBT combination has been designed and built for use as an inductive energy store opening switch. Exceptional performance has been obtained with a 100 kA, 5000 V switch module using this switching topology. The switch can operate at full current at up to a 50 Hz rate.

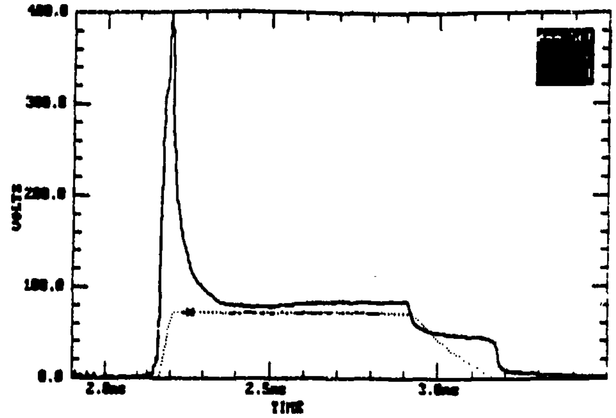

Fig. 9. Operational test results from an 83 kA, 5 Hz, 5 shot railgun burst. The waveform shows the commutation voltage and current from the first shot. Data set 1 is railgun current, data set 2 is railgun breech voltage. Switch reclosure occurs at 2.9 ms.

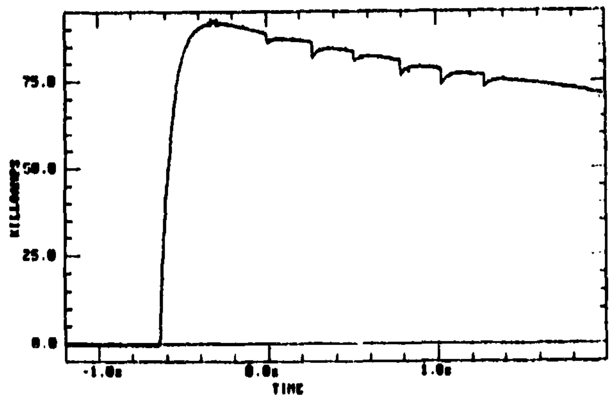

Fig. 10. Storage inductor current during 92 kA, 4 Hz, 6 shot railgun burst. Current is approximately constant, apparent droop is caused by Rogowski current monitor integrator.

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