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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. A single switch module is rated at 30 kA and 5000 V. 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 to a railgun load. The first of ten switch modules for a 250 kA switch has been built and successfully tested on a battery test stand. 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 IEEE Power Modulator Conference in Myrtle Beach SC on 23 June 1992.

This work was funded by WL/MNSH of the Armament Directorate at Eglin AFB FL under the Kinetic Energy Weapons Program of the Strategic Defense Initiative. Mr. Mark W. Heyse, Mr. James B. Cornette, and Mr. Nolan E. Taconi from WL/MNSH and personnel from General Atomics, Inc. (GA) in San Diego CA performed the work during the period of April 1990 to November 1992 at General Atomics in San Diego CA.

30 kA, 5000 V SOLID STATE OPENING SWITCH FOR INDUCTIVE ENERGY STORES

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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. A single switch module is rated at 30 kA and 5000 V. 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 to a railgun load. The first of ten switch modules for a 250 kA switch has been built and successfully tested on a battery test stand at General Atomics. The theory of operation, circuit topology and test results are given in this paper.

Introduction

The limited capacity of switches to interrupt DC current has impeded the development of technologies such as high voltage DC power transmission, inductive energy storage, and medium voltage (i.e. 270 V) DC power distribution in vehicles such as aircraft. It is interesting to note that while Thomas Edison intended to electrify the country with DC power, Nikoli Tesla's AC system eventually won out in part due to the lack of adequate DC opening switches.

With the advent transistors an effective means of opening DC current was realized for low and medium power applications. While increases in the power handling capability of transistors and the introduction of new devices, such as GTOs [1], has improved the situation, very high power applications are typically relegated to province of the closing switch.

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 [2]. 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, and transistors are available for this opening switch duty but all have much lower power densities than closing switches.

Mechanical switches can efficiently close and conduct to charge an inductive energy store but have limited utility and lifetime in the opening phase of their duty. In contrast solid state opening switches have exceptional utility and lifetime, but suffer conduction losses and have relatively low single device current rating.

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 which 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 which 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.

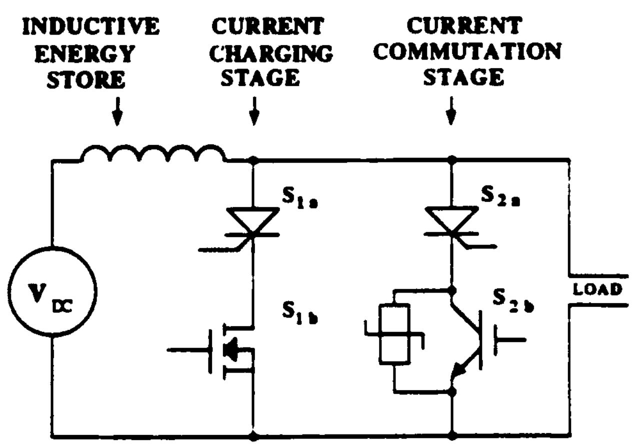

Fig. 1. Opening switch circuit schematic.

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. 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. 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. Requires high blocking voltage in the off state.

4) Reclosure

Reclose and recover current from the load upon command. 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 innovative arrangement of semiconductor devices allows the transistors to accomplish the lower voltage commutation functions while the SCR accomplishes the 5000 V blocking function in a single high power device. By separating the functions of charging, commutating, and voltage blocking we have been able to provide a switch which 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 which 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 switch S_{1a} and S_{1b} are triggered into conduction to initiate the charge cycle.

When the desired current is reached (ten parallel modules are designed to carry 250 kA) 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.

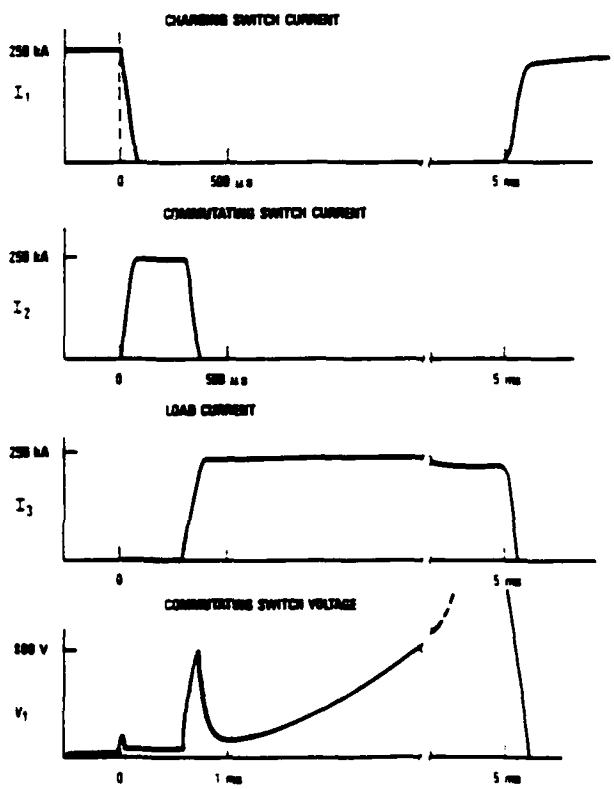

Fig. 2. Switching timeline for opening switch.

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. Current in excess of five times the continuous rating of switch S_2 is allowed for these short pulses.

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 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 which is produced by the railgun load. For applications requiring higher commutation voltages series IGBTs can be used.

The switch can be triggered back into conduction at any time during the open phase and it is self protected to trigger back into conduction if 5000 V across the load is exceeded.

Circuit description

A photograph of the first 30 kA, 5000 V switch module is shown in Fig. 3. Four of these modules composing a 120 kA switch is shown in Fig. 4. This 120 kA switch will be tested at Eglin AFB in July, 1992.

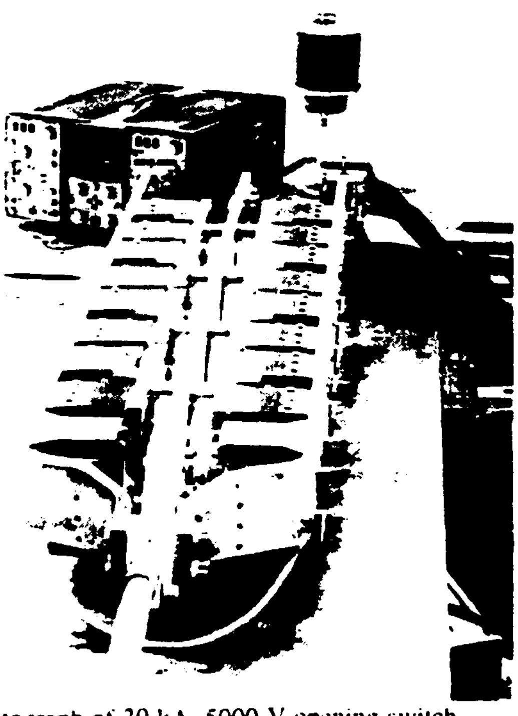

Fig. 3. Photograph of 30 kA, 5000 V opening switch.

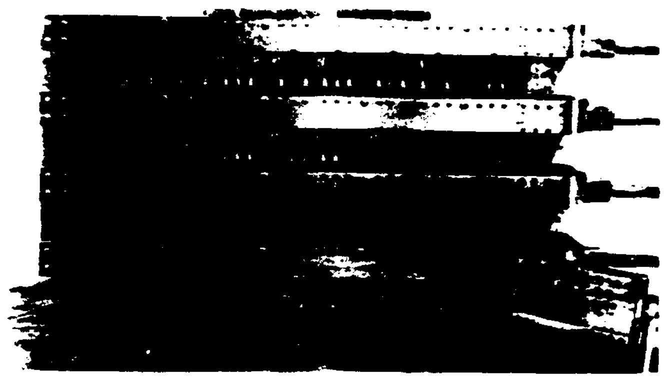

Fig. 4. Photograph of 120 kA, 5000 V opening switch.

In order to achieve a 30 kA module rating several submodules were placed in parallel. A charging switch submodule consists of an ABB CS-2104 [4], 5000 V, SCR in cascode connection with two FET modules. A photograph of a single switch submodule is shown in Fig. 5.

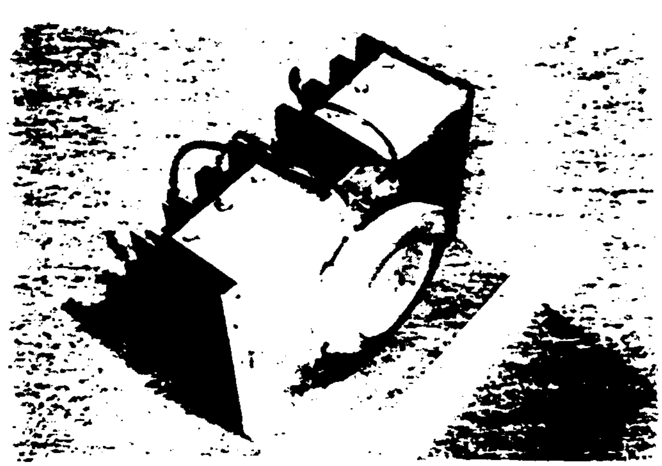

Fig. 5 Single switch submodule showing SCR, heat sink, and transistors.

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 5,000 A at a 2.3 V conduction drop. The relative distribution of the charging switch conduction drop is shown in Fig. 6a. Six conduction switch submodules are placed in parallel to achieve the 30 kA rating.

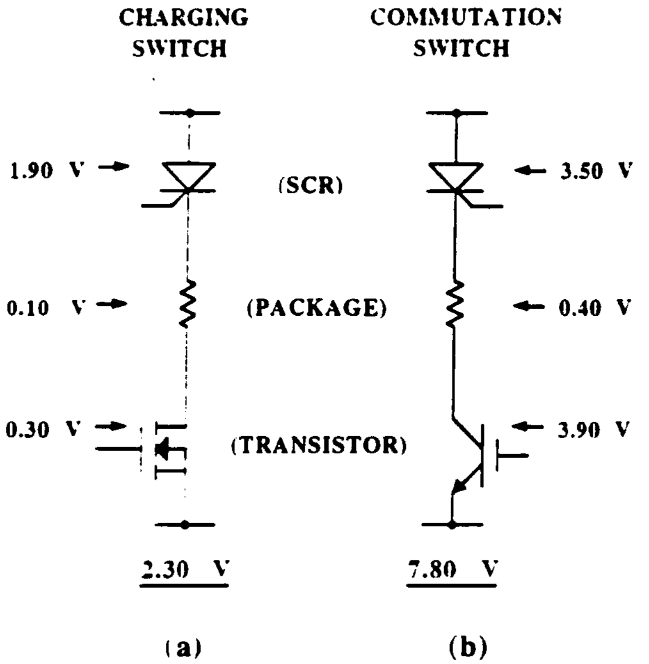

Fig. 6 (a) The relative conduction voltage drops of the charging switch components. (b) The relative conduction voltage drop of the pulse commutation switch components.

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. A photograph of the prototype IGBT array is shown in Fig 7. The full transistor module and its associated control circuitry is shown in Fig. 8.

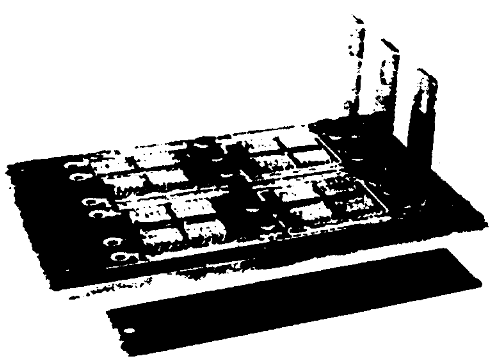

Fig. 7 Prototype IGBT array using large format IGBTs. Each IGBT measures 0.75" X 0.54"

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

The nominal current rating for each commutation switch submodule is 15,000 A at a 7.8 V drop for operation $\leq$ 3 ms for each opening cycle. The relative distribution of conduction drop is shown in Fig. 6b. Two commutation switch submodules are placed in parallel to achieve the 30 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 dependant voltage clamping action of these MOVs can be seen in Fig. 10.

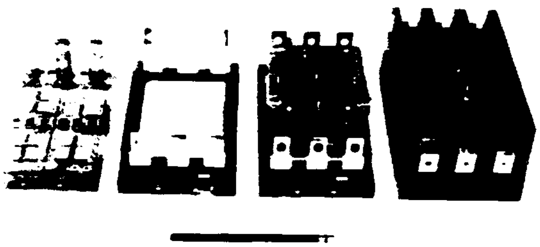

Fig. 8 A full transistor module and its associated control circuitry.

Parallel Operation and Current Sharing

SCRs have nonlinear resistivity (voltage drop) and a negative temperature coefficient of resistivity. This will cause the warm SCR in a parallel array to draw more current, which drives its temperature up even more. This positive feedback effect could raise the SCR junction temperature to the point where it cannot recover and hold voltage after conduction. If an SCR in a parallel array does not recover, it will take all the current intended for the full array. SCR destruction is likely if protective action is not taken. Circuit designers typically mitigate this situation by adding series resistance and allowing for a 20-30% current mismatch. In the approach we have taken, the cascode connected FET not only forces current commutation but it forces current sharing among the SCRs. It does so by acting as a bulk resistor with a strongly positive temperature coefficient of resistivity. This SCR-FET arrangement in a submodule has a net positive temperature coefficient of resistivity at any current above 1,200 A. This factor eliminates the major concern with the parallel connection of SCRs (current sharing) and opens the way for arbitrarily large SCR arrays.

Thermal Management

Even with a relatively low conduction drop of 2.3 V, a 30 kA switch must reject tens of kilowatts of heat. This switch, which is intended to be used for 5 seconds at a time, lends itself to thermal inertial cooling. The copper buswork serves as a heat sink to absorb the 11.5 kW dissipated in each charging switch submodule. The thermal mass of the buswork is sized such that the copper temperature rises at $1^{o}C$ per second with its nominal heat load. Several 5 second runs can be made before temperature limits are reached. The heat flux into the copper is such that water cooling could support continuous operation if required.

Test Results

The 30 kA switch module shown in Fig. 3 has been successfully operated at full current at General Atomics in San Diego, California. The design margin was such that the switch survived an intentional 100% overcurrent (200% rated submodule current) for a period of 1.5 seconds. Current and voltage waveforms during a 32 kA commutation are shown in Fig. 9 and Fig. 10.

A current reduction is seen during the 40 V switch 1 commutation in Fig. 9 because the battery test stand used for testing has no energy storage inductor. With the intended energy storage inductor the switch 1 commutation would cause a negligible reduction in the system current.

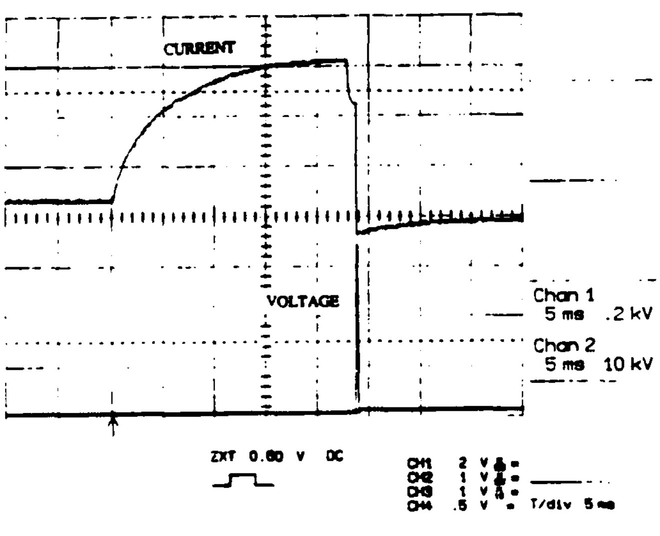

Fig. 9. Operational test results from 32 kA current charge and commutation. Top trace is switch current at 10 kA/div. Bottom trace is the load voltage at 200 V/div. The time interval per division is 5 ms.

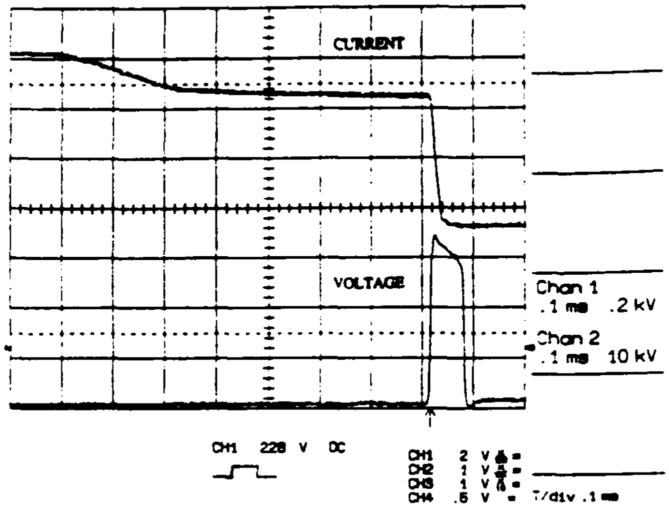

Fig. 10. Operational test results from 23 kA commutation detailing commutation voltage as produced by the IGBTs and the MOV clamp. Top trace is switch current at 10 kA/div. Bottom trace is the load voltage at 200 V/div. The time interval per division is 100 μs.

Conclusion

A hybrid arrangement of power semiconductor which 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 30 kA, 5000 V switch module using this switching topology. The switch can operate at full current at up to a 50 Hz rate. Parallel operation of ten switch modules at 250 kA is anticipated.

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