**SOLID-STATE SWITCH DEVELOPMENT FOR HIGH POWER
PULSE DISCHARGE CONTROL**

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Abstract

High power electronics are being applied at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) to control the launching of compulsator-driven railgun loads. The design, fabrication, and testing of a 200 kA, 1.5 kV (150 Hz) switch are presented, followed by design considerations for two other projects under construction. The latter will have operating ranges of 400 kA at 2.3 kV (400 Hz), and 3.2 MA at 6 kV (138 Hz), respectively. In all cases, the switches are designed for a limited number of half-cycle current pulses (3 to 9) followed by a prolonged cooling period.

Introduction

Compulsator

The compulsator [1] is an impedance compensated alternator designed by engineers at CEM-UT and first introduced in 1978.[2] The impedance canceling action can be designed to match the desired driving needs of the system load. In the applications of railgun electromagnetic (EM) launchers, compulsators allow controlled current rise, pulse shaping to match gun characteristics, and a current turn-off to coincide with payload exit of the accelerator.[3] Because the compulsator expends only part of the total rotor-stored energy, repeat firing of the railgun is possible as soon as it can be reloaded. A thyristor switch between the compulsator and railgun allows the loading of an electrically-cold gun. This greatly alleviates the loader mechanism design. Hot-rail loading requires a fast loading cycle as compared to the alternating voltage cycle. Cold-rail loading permits a projectile loading cycle of any reasonable duration, restricted only by the firing rate desired.

Rapid-Fire EM Gun System (RFEMG)

Fabrication of the RFEMG system [4,5] at CEM-UT was completed in September 1987. It is designed to fire ten projectiles from three railguns at 20 Hz each, for a 60 Hz overall firing rate. The compulsator-railgun system is comprised of six key elements. Figure 1 shows two railguns mounted and a space for a third gun is provided. The system was designed with a switched injector to insert projectiles into the main railgun which is directly connected to the compulsator output circuit. This approach was taken because, at the time, it was not considered practical to switch the main gun current of 940-kA peak (6 ms pulsewidth).

The injector operates in the 150- to 250-kA regime (2 ms pulsewidth). Originally, ignitrons were used as the injector switching device, but they performed poorly due to the relatively low voltage of the compulsator (about 1 kV) and the negative dv/dt at the time of gating.

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1. DC FIELD SUPPLY	4. INJECTOR SWITCH
2. COMPULSATOR	5. INJECTOR
3. PROTECTIVE OPENING SWITCH	6. RAILGUN

Figure 1. Layout of RFEMG system showing major components

Ignitrons were quickly replaced with explosively-driven closing switches which served well through the testing program for single shots per railgun. To pursue the goal of multifiring through a single gun, a rep-rated switch was needed. This need, along with more recent projects requiring rapid firing railguns, motivated the development of a solid state, pulse-delivery switch.

Design Considerations

The time rate of plasma spread across the junction from the gate vs. the time rate of current rise in the junction must be considered in order to avoid point melting in the device. A good discussion and illustration of this effect is given in a paper by Vitins, et al.[6] Either a distributed gate or smaller individual junctions can be used where very high di/dt values during turn-on are required. A worst case consideration for a switch in an ac circuit is the first several microseconds after a peak voltage closure of a single thyristor junction in the array.

During conduction, the forward resistive voltage drop can affect the current distribution. The resistive effect helps to spread the conducting plasma across the junction from the gate, but random variations from junction-to-junction can affect balance from branch-to-branch in the parallel arrayed switch. Either a series impedance to make variations less significant or selecting junctions with matched forward voltage drops can compensate for this effect.

The continued conduction after turn-on and the ability to turn off and hold off voltage are dependent upon the junction temperature. The manufacturer's I^2t rating of the device under consideration is indicative of the limits in this regard. Usually, the circuit I^2t is more available, but the $\int (v_t \cdot i_t) dt$ of the junction is more directly the factor of interest in heating the junction. Some manufacturers offer a more conservative $I^2\sqrt{t}$ rating for their devices. When operating outside the 8- to 10-ms range, this can be used with the I^2t rating to bracket a peak current conduction rating. Alternatively, the instantaneous V_t vs. I_t data for an elevated temperature can be used to calculate a forward drop for the circuit current pulse. The integration of the VI product over the pulse-width yields the joule heating of the silicon disk when applied to the volume of the junction silicon and its specific heat. The silicon diameter is generally given and the thickness can be estimated at 0.5 mm (0.020 in.), unless specific device thickness is known. For pulses of a few milliseconds, adiabatic heating in the junction is a good assumption.

The overall circuit must be examined for the types of transient voltages to be encountered by the junctions. Transients may be generated by the junction turn-off or by other switching in the circuit, or by faults in the circuit. A protective shunt circuit about the SCR switch must absorb any transient energy without exceeding the junction hold-off maximum rating. For the compulsator-railgun system, the applied voltage to the system is generally of short duration, as controlled by the application of field excitation current in the compulsator. This fact allows the shunting circuit to be of low impedance and short duration power rating.

The RFEMG system injector requirements are 150- to 250-kA peak, and a single discharge I^2t of 39.8 MA²s (as obtained from previous shots using explosively driven closing switches). This duty is repeated every 50 ms for up to four shots. The max di/dt of these previous shots was, typically, about 750 A/ μ s. In order for SCR's to work effectively, several units would be required to share current in parallel. An eight-path design was chosen in order to lower the critical parameters for individual junctions to under 36-kA peak and 0.8 MA²s, while still allowing for some imbalance in current. The initial di/dt of 750 A/ μ s is assumed to affect whichever junction turns on first; therefore, this rating is applicable to the individual junction ratings.

A bus-geometry design was sought which would provide equal transient inductance paths to all SCR junctions. In addition, the total switch impedance must be low compared to the overall circuit while the branch impedance must be high enough to inhibit an unbalanced turn on. The expected di/dt of 400 to 750 A/ μ s should generate a branch voltage drop of at least 5 V to assure adequate voltage to nonconducting branches. This indicates a desired minimum branch inductance of $5[V] + 400[A/\mu s] = 12.5[nH]$.

A quasi-coaxial (fig. 2) design was selected, such that when all branches of the switch conduct, the magnetic field would be largely contained within the switch interior and the current would distribute evenly. The large degree of geometric symmetry assures good matching of transient inductance during turn on and through conduction. In addition, the junctions were oriented circumferentially flat to avoid any "pinching" of current within the junction cross-section (fig. 3). The SCR's were staggered axially, four each, in two positions

Figure 2. Quasi-coaxial SCR switch assembly design, general concept

on the switch in order to provide adequate room around each device for clamping.

The RFEMG system circuit was examined for transient protection (fig. 4). The series inductance at turn-off is about 1.94 μ H and, with an estimated turn-off current of 1 kA and t_f of about 2 μ s, the expected voltage generated would be about 500 V. It was decided to check the voltage generated across the switch empirically, using low initial current test. In fact, very little voltage was generated. The SCR's rapidly turned off in succession, commutating the current around the switch and the actual snap-off current was about 230 A in the test shown in figure 5. To soften the recovery charge distribution, a 500- Ω resistor was placed across the switch. It was assumed that the switch would be inductively isolated from the transient muzzle voltage generated as the projectile exited the injector and the main railgun. This, in fact, was the case.

Fabrication

The switch was fabricated at the CEM-UT machine shop. Provision was made for Rogowski coils to be included, one on each branch circuit, and to measure the voltage drop across each junction package (from the immediate bus on either side of the junction "puck" package).

The center conductor is aluminum and the strap conductors to the junctions are copper. The insulating material is G-10 glass epoxy. The clamps are steel, use two bolts, and apply pressure to the junction via a center pivot point. Proper clamping pressure is assured by the spring ratings of belleville washers, brought into partial compression, on the center clamping pile.

Figure 6 shows the eight-path SCR switch developed for use with the RFEMG system. The individual SCR's comprising the switch are Westcode

Figure 3. Partial cross-section of SCR switch assembly for the rapid-fire EM gun system

Figure 4. Equivalent circuit for the RFEMG system

Semiconductor Converter Grade Capsule Thyristor Type N540CH18. These were purchased from vendor stock without selection for parameter matching. The 1 kA/ μ s critical rating for di/dt was considered the primary selection criterion for assuring good performance in this application.

Inductance measurements of about 400 nH were obtained for the single path tests, whereas the multipath tests shows a switch inductance of 190 nH due to the coaxial geometry. These readings were somewhat higher than expected, but satisfactory for the circuit requirements. The explosive closing switch, by contrast, had an inductance of only 90 nH. The SCR switch had

Figure 5. Plot of total current and 8 branch currents at turn-off

been designed with extra length so that more series inductance could be added, if necessary. More inductance has not been needed and this contingency could have been eliminated for a somewhat more compact switch design.

A trigger circuit was constructed to provide a strong pulse simultaneously to each of the eight junctions, as well as providing isolation between the control circuit and the pulse power circuit. Figure 7 shows the resultant schematic. The electrolytic storage capacitor holds enough charge for multiple discharges; the field-effect transistor (FET) is on only about 500 μ s for each shot. The 1:1 pulse transformer (EG & G #TR-181) is the main point of voltage isolation and to a lesser degree, the multisecondary transformer. The multisecondary transformer was wound empirically to provide a 250% gate level to each junction, as determined by the manufacturer's highest minimum required trigger.

Test Results

Short-circuit testing of the switch was performed at low energy levels with the compulsator at 2,400 rpm and field excitation at 10% to obtain an open circuit voltage of 100 V. By varying the switch trigger point with respect to the compulsator voltage cycle, a range of currents from 13.2 to 39.7 kA was obtained for single device tests. Figure 8 shows the calculated junction resistance during the conduction time. A switching time of about 500 μ s is indicated, consistent with manufacturer's data. A single junction was then tested to destruction. The failure occurred during a multishot planned at the 40-kA level. After the second discharge, the manufacturer's specified maximum I^2t was exceeded. The junction succeeded in turning off at zero current and while the device was reverse biased, but failed as expected when forward voltage was reapplied by the compulsator.

Figure 6. Photograph showing 8-junction railgun switch and gate trigger box for RFEMG system

Figure 7. Schematic drawing of gate trigger for 8-junction SCR switch

A 45.0 kA, multijunction, short-circuit discharge was performed to confirmed the current sharing ability of the whole assembly. A 15% maximum imbalance was observed. After this test, the injector railgun was fired with increasing current pulses while the switch performance was observed. A 65-g armature was accelerated to 138 m/s and the timing characteristics of the injector were consistent with previous injector tests using an explosively-driven closing switch. Peak current through the switch was 118 kA and an I^2t of 16.2 MA²s was developed. A 3-m railgun was then added to the circuit, a 74-g armature was accelerated from the injector into the gun, and a final velocity of 1,417 m/s was obtained. Switch current for this test was 132 kA and the I^2t was 21.4 MA²s.

The turn-on timing of the eight junctions was indistinguishable (resolution = 1 µs/sample), but a

sequential turning off of the devices was observed. The junctions easily commutated the low current of turn off around the switch structure, generating a small voltage spike only on the last branch to turn off (fig. 9). In these high current experiments, variation of current between individual SCR's was less than 15%.

Figure 8. Plot showing junction resistance and periods of turn-on, conduction, and turn-off.

400-kA Project

The small caliber EM-launch system is intended to launch three, 60 caliber (0.6-in. diameter) projectiles at a firing rate of 10 Hz.[7,8] Electrically, the compulsator generates 1,625 V_{rms} at 400 Hz. A 1.86 ms current pulse, peaking near 400 kA will be used to launch the 32-g projectiles at 2 km/s. This project will make use of a solid-state switch to fire the railgun directly, thus eliminating the injector preaccelerator used in the RFEMG project.

The switch design is a logical extension of the assembly described above, but with 16-branch circuits and higher voltage rated 52-mm junctions. The clamping design uses aluminum hoops and socketed bolts against belleville washers on each thyristor. To keep the switch size small, the SCR's were staggered along four axial positions with four junctions each. The individual SCR's comprising the switch are International Rectifier (IR) Ring-Amplifying Gate, Phase Control Thyristor Type S52K34(88-6613). These were purchased with a 3.4 kV forward and reverse rating (higher than the vendor's normal stock offering of 2 kV).

The switch is being fabricated at this writing and is a free standing design (fig. 10). An alternate design would have the switch constructed at a larger radius

Figure 9. Plot showing turn-off timing of 8-junction switch, as seen in voltage drop across the junctions

and installed around the current collector housing of the small caliber compulsator (SCC) (fig. 11). This would provide a more compact package for the compulsator-gun system as a whole and would be more appropriate for a field-transportable demonstration system.

3.2-MA Project

The repetitive fire, 9 MJ gun system is designed to launch nine projectiles, firing once every 20 s. The projectile mass and energy are considerably higher than either of the preceding projects, requiring a 6 ms current pulse reaching as high as 3,200 kA.[9,10,11] An equivalent circuit is shown in figure 12 indicating the multiple current feeders involved. In this project also, it was decided to pursue a solid-state switch of current into the railgun. The immense currents involved have motivated an entirely different approach to packaging the large number of parallel junctions required. In addition, the repetitive fire, 9 MJ gun system has constraints on its overall size and weight and will be operated at a location remote from the laboratory. The number of junctions involved (approximately 270) and the system constraints mentioned led to a search for a smaller package than the typical "hockey puck" design. Working with General Electric Static Power Components Operation (Malvern, PA), a minimal junction package (fig. 13) was developed alongside a typical SCR package (fig. 14). Both devices pictured house 77 mm silicon junctions.

Since current must be conveyed by multiple conductors in parallel, it was decided to let the branch length extend from the compulsator current-collectors to the railgun breech and include the SCR switch and a triggerable circuit protection switch (fig. 15). In all, 45-branch circuits have been chosen. Each of these will have three SCR's in parallel and two groups in series to switch a peak of $71 \text{ kA} \pm 15\%$. The maximum voltage standoff rating will be 9 kV or 150% of the nominal peak

Figure 10. Photograph of 16-junction SCR switch for the small caliber EM-launch system

Figure 11. Concept drawing of field transportable small caliber EM-launch system

Figure 12. Schematic view of multiple current feeder concept for the repetitive fire 9-MJ gun system

Figure 13. Features of the compact SCR package for repetitive fire 9-MJ gun system

voltage. The circuits will be cabled in groups of 3 branches to form 6 conductor bundles (fig. 16). CEM-UT will be attempting to package these devices in as compact an arrangement as possible. An energetic gate trigger will be sourced from a 50 kJ high voltage capacitor, but the coupling design is not finalized.

Conclusions

Power thyristors are being successfully paralleled for use in the regime of their single pulse maximum transient ratings. They have been applied to the compulsator-driven railgun application using an 8 junction parallel structure, further enhancing the performance of this system. A 16 junction scale-up of this design is in fabrication. No obstacles to further development of highly parallel, large current pulse control scenarios have been encountered at this stage. A large-scale switch (270 to 300 junctions) has been planned and will involve new packaging and triggering approaches.

Figure 14. Comparison photograph showing conventional package for 77-mm SCR and compact design for the repetitive fire 9-MJ gun system

Figure 15. Schematic drawing of single current feeder branch for the repetitive fire 9-MJ gun system

Figure 16. Cross-section and features of a cable bundle containing 3 current feeder pairs (repetitive fire 9-MJ gun system)

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