POWER ELECTRONICS IN THE 9 MEGAJOULE EM RANGE GUN SYSTEM

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Abstract: The Center for Electromechanics at the University of Texas at Austin (CEM-UT) is developing an open range demonstrator electromagnetic (EM) gun system with specific size and mass constraints. The design being pursued includes a single phase full bridge rectifier and inverter to accomplish a self generated field excitation and regenerative field energy recovery. The peak power of the excitation system is over 600 MW, performing for single second operations at a repetition rate of once every 20 s over 3 min. The design also includes a solid-state thyristor switch for firing the railgun. This switch closes for one half cycle of ac current, reaching over 3,000,000 A and lasting up to 6 ms. The open circuit rms voltage is 4.2 kV at 125 Hz. These power electronics subsystems have been designed to be compact and lightweight. This paper presents the design parameters, packaging, and control strategies employed.

Introduction

The Center for Electromechanics had previously disclosed work with two other thyristor switches for railgun applications [1]. These were, respectively, 150 and 400 kA switches with 2 ms pulse-widths and involved 8 and 16 junctions. In both cases a compulsator is the power supply. The first switch operates an injector railgun to launch the projectile into a directly connected "hot rail" main gun. The second switch was used to directly fire a "cold rail" loaded gun. Successful operation of those switches has preceded the current effort involving large scale application of thyristors in an EM launcher.

The open range demonstrator EM gun system will use a gas turbine as the prime mover for an air-core compulsator [2] to power both its own field excitation and a 7 m railgun accelerator. The compensated-pulsed-alternator (compulsator) is a rotating energy-compression machine which provides a fairly high voltage and a variable, low source impedance. The output current is shaped to match the driving requirements of the load (e.g., a railgun). The air-core design allows an excitation field exceeding 2 T and takes advantage of the higher hoop stress capabilities of glass and graphite composite tubes. The very significant power requirements for the field excitation are derived by a self-excitation power circuit including a second, higher-voltage armature.

Figure 1 shows the power schematic for the EM range gun system. The (lower) field excitation circuit is a fully controlled rectifier/inverter bridge. Each of the four quadrants of the single phase bridge is comprised of six parallel modules containing eight thyristors in series. The upper circuit powers the 90 mm bore railgun. A 6 ms current pulse propels the projectiles (1 to 5 kg mass) to 9 MJ kinetic energy (2 to 4 km/s)). Table 1 summarizes some of the numbers associated with the two applications.

The Gun Switch

Vitins, et. al. [3], has described the use of phase control thyristors in railgun applications, defining requirements for an assumed capacitor bank power supply. The compulsator, as an alternating voltage machine, offers an improved opportunity to apply solid-state switching to larger railgun applications. In this project, the di/dt

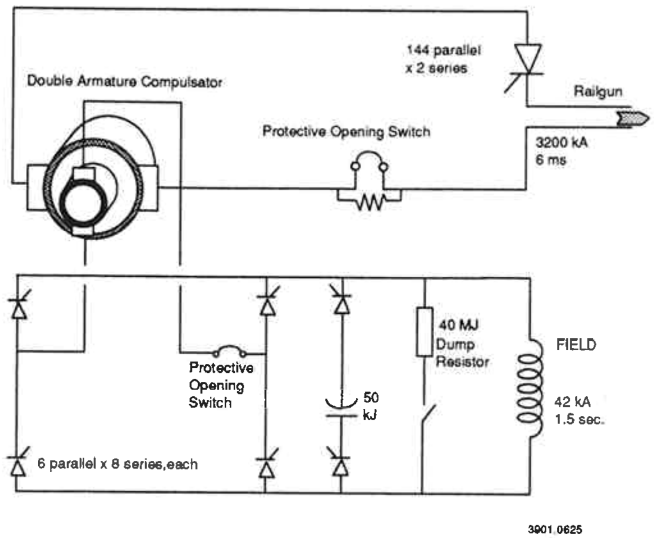

Figure 1. 9-MJ EM range gun power schematic showing railgun discharge circuit and field excitation circuit, fed from a two-winding armature

imposed on the thyristor switch is controlled by gating at low instantaneous voltage. The higher circuit di/dt occurs several hundred microseconds after initial conduction. By this time, the current and its rate of change are well distributed among the 144 parallel thyristor paths, and across the conduction area within each device. The rated gun discharge reaches its maximum di/dt of about 3,900 A/μs at 960 μs into the shot. The device di/dt is only 27 A/μs; well below the rated 100 A/μs. Since the compulsator does not discharge its full energy store, as would be the case for a capacitor or homopolar power supply, the gun switch must recover its voltage hold-off after conduction.

Table 1. 9 MJ EM gun system power electronics

	Gun Switch	Bridge	Units
Size Junctions	77	77	mm
No. in parallel	144	6	
No. in series	2	8	
Total junctions	288	192	
No. of modules	48	24	
$\int i^2 \cdot dt$ --total	30,000	390	$MA^2 \cdot s$
--per junction	1.45	2.71	$MA^2 \cdot s$
di/dt --total	3900	72	A/μs
--per junction	27	12	A/μs
peak current total	3200	42	kA
--per junction	24	7.7	kA
peak voltage total	6	15	kV
--per junction	3	2	kV

The inductive railgun load causes the current to return to zero when compulsator voltage is nearly at negative peak voltage. Forward voltage occurs about 3 ms later, adequate time for full turn off recovery if the device has not been excessively heated.

The pulse-width requirement of 6 ms dictates that the silicon wafer must accept all the heat of conduction during the shot. For this project, 20 s is allowed between shots. Thermal analysis, using the model described by Piccone, et. al. [4], shows that the silicon and copper bus have reached virtual equilibrium within 2 s after the shot, and assure that the junction temperature will not exceed 75°C above ambient. The bus mass has been designed to accommodate the entire heat loading of the 9-shot salvo within a 30°C rise.

The circuit topology is designed to minimize overall size and mass of the switch. The switch is organized into 48 modules with sufficiently matched series impedance to allow free paralleling. The number of modules are kept to a minimum by match-selecting the internal thyristors for intimate paralleling in threes and then matching the trios in groups of two for series operation. The selected thyristors are rated for a maximum hold-off voltage of 4,500 volts (V), while the expected maximum operating voltage is 5,800 V-peak. The two-stage series configuration provides a margin of only 1.5, instead of the more conventional factor of two. To accommodate that level, close attention was paid to the snubber design. Snubber circuits can easily require much more space than the devices they protect. It was decided to build one snubber for each group of three paralleled thyristors. The result is a combination of metal-oxide varistor (MOV) in parallel with a resistor-capacitor (R-C) series, with a diode added for anti-dumping during initial turn-on. The MOV effectively reduces the size of the snubber capacitor by a factor of four. The narrow overvoltage tolerance, however, does require that the MOV devices be selected from less than half of the manufacturer's normal V-I (voltage-current) curve selection tolerance: a 200 V vs. a 530 V band.

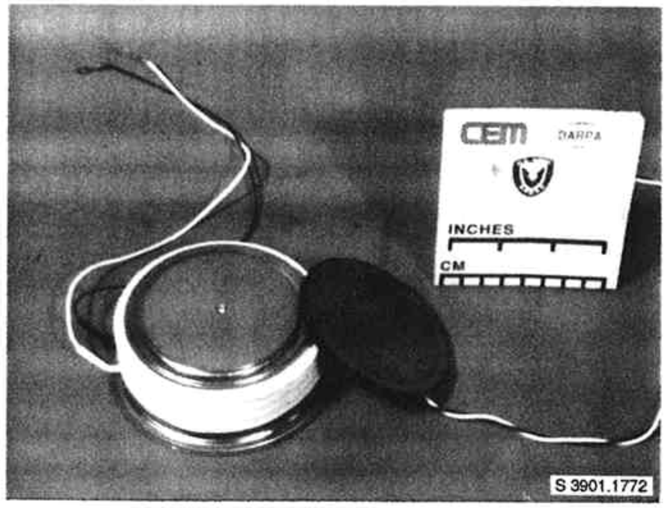

Figure 2. 77 mm thyristor junction in developmental "thin-pak" next to conventional ceramic press pack of same size silicon

Thyristor Selection

In selecting a thyristor product, inquiries were presented to vendors regarding a developmental package with minimal size and mass as compared to commercially available ceramic press-pack designs. The result is an epoxy sealed package of molybdenum and silicon on tungsten, with the copper pole pieces provided by the connective bus (fig. 2). The thyristor product selected for this application is a 77-mm device, commonly used in high voltage DC transmission systems, provided by General Electric Static Power Components Operations (GE-SPCO, Malvern PA). The doping preparation provides an especially low forward voltage drop during conduction (1.5 V at 2,000 A). GE-SPCO and CEM-UT worked together to define the "thin-pak" design, reducing the package volume by 90% and its mass 80% as compared to the "press-pak" design. The basic junction product line is of sufficient production level that yield consistency and quantity keep the match-selection process from unduly driving the thyristor cost up.

Gun Switch Packaging

Each of the gun switch's 48 modules contain six "thin-pak" thyristors, snubber components and firing electronics. The modules are divided into two banks of 24 which are assembled onto a rigid interconnect plate. This innerconnect plate provides electrical buswork and mechanical mounting interfaces for the 24 modules and such auxiliary components as an explosively operated circuit interruption switch, a circuit dump resistor and receptacles for the array of flexible cables that connect the compulsator, gun switch and railgun (fig. 1). The output terminals for the cables consist of compact, high current, single-bolt expanding copper studs (this terminal design and parallel circuit operational performance is described by Price, et. al., [5]). The interconnect plate serves as a convenient interface allowing easy disconnection of circuit elements for routine service and maintenance.

Figure 3 shows the circuit schematic for the switch module and figure 4 is a photograph of the prototype component assembly. Module components are assembled onto a G-10 base plate that provides for positive location and structural support of the components. The six thyristors are assembled in two stacks of three and include one MOV each. The thyristor/MOV stacks are connected in their series/parallel configuration with 1 mm thick copper sheet sandwiched between the thyristors and G-10 insulating barriers. Each thyristor stack is clamped with a triangular clamping plate transmitting its force through a central ball-bearing pivot point. Electrical taps are taken from the copper sheet common points to the two sets of snubber circuit components mounted above the thyristor stacks. Once assembled onto the G-10 base plate, the module components are inserted into a rectangular aluminum enclosure to provide electrical shielding, and back-filled with FC-84 Flouroinert® (3M Corp.) liquid dielectric

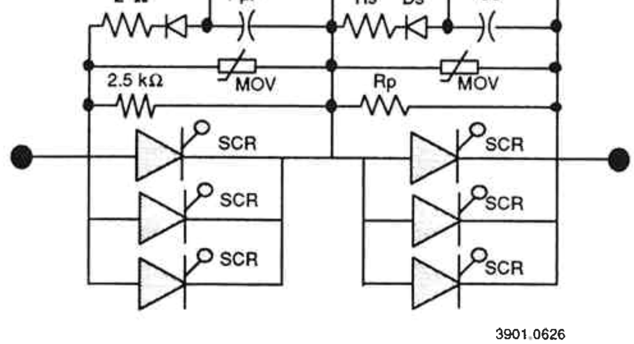

Figure 3. Schematic of gun switch module, internal

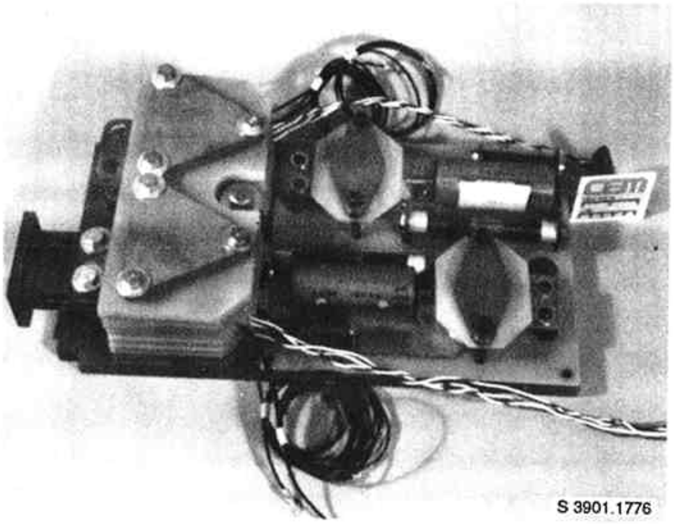

Figure 4. Prototype components for gun switch module

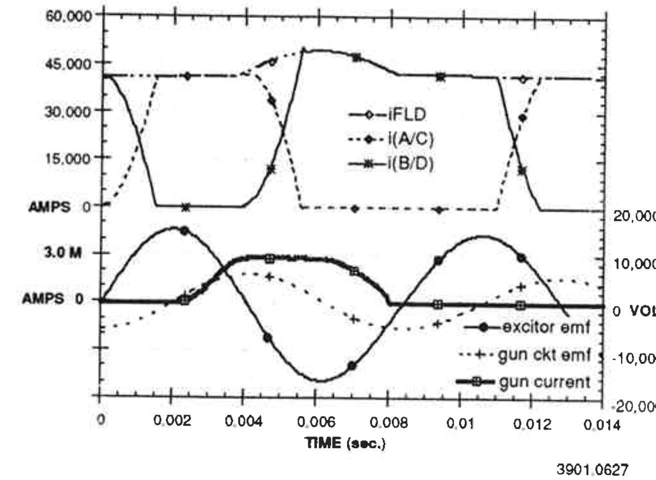

Figure 5. Bridge current commutation

as contaminant protection. On the end of the module enclosure, provisions are made for mounting the gate control and module diagnostic electronics. The fully assembled module is 48 cm (19 in.) long, 20 cm (8 in) wide, and 34 cm (13.5 in.) tall and weighs approximately 59 kg (130 lb.). The overall switch volume is 1.6 m^3 (57 ft^3) and weighs about 2,800 kg (6,200 lb).

The Bridge Switch

A single phase, full control bridge is required to serve the self excitation and regenerative field dump of the compulsator. Since the air-core design of the compulsator does not provide a residual excitation field, a capacitor discharge is used to initially excite the field winding to about 1,000 A (23-kJ inductive). The compulsator field coil has a time constant of about 1.0 s, so the field level is maintained as the armature voltage climbs (i.e., the field flux becomes established through the armature).

The charge up proceeds exponentially for about 1 s under nominal conditions, until the rated field current is reached at 41.5 kA. The field excitation armature delivers 15-kV peak at that point. Figure 5 shows field current commutation and railgun discharge on a common timebase. The 20% rise in field current at 6 ms on the plot is induced by a coupling with the gun discharge current. After discharge of the railgun, the gating of the bridge is shifted to invert the field current back to the rotor kinetic energy store. The full field stores nearly 40 MJ inductively and inversion returns 70% to rotor kinetic energy in about 700 ms. This 2 s of operation (about 250 switching cycles) exceeds the silicon thermal time constant and allows inertial cooling out to the thyristor pole-piece copper. External cooling can be used to recool the package for the next excitation period. To eliminate an active cooling requirement, the bridge was expanded to six parallel paths and extra copper mass was added to the pole-piece connections to absorb the conduction heat of the entire 9-shot salvo.

The bridge module contains 8 thyristors in series, providing a factor of 2.4 over the expected 15 kV maximum peak operating voltage. Six such modules in parallel form each quadrant of the bridge. Since the series impedance of the connecting cable was not adequate alone, a series resistive element was added at each module to help force parallel sharing. MOV's are used in parallel with the snubber R-C circuits to minimize the capacitor size. The same thyristor product was selected for the bridge application as for the gun switch. This allows an economy in purchasing because devices rejected from gun switch selection (parallel matching) may enter a pool for the bridge (series matching). The low forward voltage drop during conduction is helpful also for the bridge, which will operate at a maximum current level of 7,700 A, 50% duty.

Bridge Packaging

In the design of the bridge, a modular design approach was again pursued. Construction and assembly methodologies developed in the gun switch modules were applied and where possible, components of similar function were utilized in the bridge modules to reduce construction costs. Figure 6 illustrates the component layout within the module and includes a circuit diagram of the module.

The bridge rectifier/inverter consists of four quadrants, each composed of six modules. A bridge module consists of three major subassemblies. These are the thyristor stack, MOV stack, and snubber component array. The thyristor stack includes eight "thin-pak" thyristors stacked in series with 1.75 cm of copper between each to act as a thermal heat sink. This assembly is then clamped with triangular clamping plates to provide the desired contact pressure. Adjacent to the thyristor stack is the MOV stack. Eight MOV's are stacked and clamped in series with 1.5 mm copper sheets between each. Finally, the thyristor and MOV stacks and the snubber components are connected in their parallel configuration by copper wire. These three subassemblies are mounted to a G-10 base plate with the completed assembly enclosed in a rectangular aluminum enclosure, and back-filled with FC-84 Flouroinert® liquid dielectric for contaminant protection. An innerconnect plate provides electrical buswork and mechanical mounting interfaces for the six modules; the bus work also serves as a series impedance for the modules, forcing even current distribution. The output terminals are identical to those used in the gun switch modules. The bridge module measures 41 cm (16 in.) long, by 30 cm (12 in.) wide, and 46 cm (18 in.) tall and weighs approximately 73 kg (160 lb). The overall bridge volume (four banks) is 1.4 m^3 (47 ft^3) and weighs about 1,800 kg (3,900 lb).

Controls & Diagnostics

To facilitate maintenance and compact size, the gun switch and bridge are modularized. Individual modules may be removed without affecting the remaining modules aside from reducing overall capacity. Instrumentation and

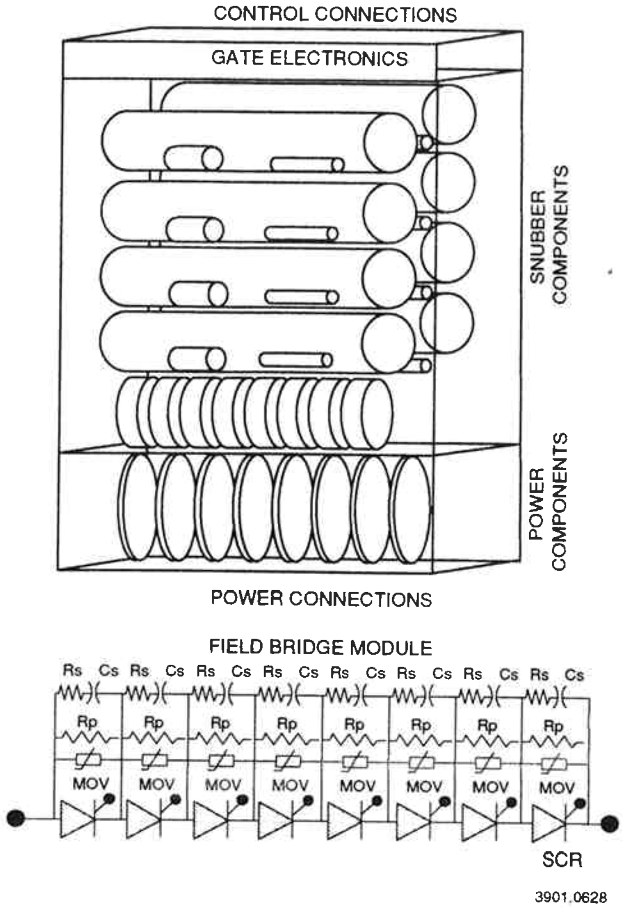

Figure 6. Internal schematic of the bridge module and bridge module package showing placement of components

control maintains that same approach. Individual circuits are located in each module and operated synchronously from a master control circuit. Short haul communications and control are transmitted over 1,000 micron plastic fibers to provide noise immunity and isolation while maintaining field serviceability.

Control functions include an ENABLE command to the module followed by a self-diagnostic check and a READY response returned to the master control. A single READY output from the master control is returned to the experiment controller. A communication line to the master control will allow an inquiry as to the specific conditions of each module. The next input is a GATE signal transmitted to each module. Ten-MHz optical receivers handle the opto-electric conversion to provide sub-microsecond synchronization of the GATE signals. A latching TROUBLE signal from the modules indicate either bad control power, shorted thyristor series levels, or over-temperature. Bench testing afterwards will differentiate the problem detected.

In the gun switch modules, the primary failure mode is a bus short circuit or a false trigger of one or a few modules. Available current from the compulsator is capable of reaching destructive levels before a single current half cycle is completed. For this reason, fault detection is based upon module di/dt (Rogowski coil sensor), with the threshold trip signals parallel-polled to trigger explosively-driven circuit interrupters. A latch feature will allow investigation after the fact into the cause of the trip. Over-temperature failures are easily handled in a slower time frame by simply impeding further operation of the experiment and annunciating the point of the over temperature trip.

The primary failure mode of the bridge circuit is a failure to gate after higher current has been established in the field coil. This circuit has much higher source inductance so that even short circuits are limited in their rate of change. Failure-to-gate causes the field current to continue in the established path with power flowing from rotor to field and vice-versa during respective half cycles of exciter armature voltage. This failure will allow at least 50 ms before the thyristors are damaged by over temperature of the junctions. An opening switch is provided on the ac side of the bridge to interrupt current at a zero-crossing and, concurrently, a dump resistor is switched in parallel to the field coil to accept the field energy store.

Conclusions

The gun switch design presented here represents an operational improvement over mechanical and single-shot switches which have preceded it. Both the gun switch and the bridge constitute a large scale application of thyristors at power levels comparable to utility transmission systems, although of course, not of the same duty. As such, they are a significant demonstration of thyristor technology in a relatively small package. Further reductions, however, in size and mass are desirable and should be expected with new switch topologies. While the design described is expected to serve the demonstration system well, an improvement factor of three or greater is needed for mobile high current systems. Hopeful areas for future size improvements include development of MOS-controlled thyristors (MCT's), gallium-arsenide devices, and improved snubber or snubberless designs.

Acknowledgments

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