DESIGN AND TESTING OF A COAXIAL OPENING AND SOLID STATE CLOSING SWITCH FOR THE CANNON CALIBER ELECTROMAGNETIC LAUNCHER SYSTEM (CCEMG)

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ABSTRACT

The Center for Electromechanics at The University of Texas (CEM-UT) is in the final fabrication and testing phase of the cannon caliber electromagnetic launcher system (CCEML). The objective of the CCEML program is to develop an electromagnetic cannon caliber launcher (30 mm) and power supply capable of firing three, five round salvos at a rate of 5 Hz. The scope of this paper is design and testing of the CCEML gun discharge subsystem, which consists of an explosive opening switch (EOS) and a thyristor gun closing switch module (GSM). The first part of the paper covers component development. In the second part, performance data of both switches is presented including high current EOS performance and GSM turn-on, turn-off, and parallel thyristor sharing data.

INTRODUCTION

The Center for Electromechanics at The University of Texas (CEM-UT) is developing an air core compulsator, pulse power electronics and EM launcher system capable of firing three, five-round salvos at a rate of 5 Hz. An additional requirement for the CCEML system is that it be compact, lightweight, and fully compatible with the Amphibious Assault Vehicle (AAV). Figure 1 shows an electrical schematic for the overall system design.

Operation of the CCEML system is described as follows. With the rotor at speed, field coil charging is initiated by a capacitive discharge and sustained by rectification of the compulsator ac output. Upon reaching full open circuit voltage, the main closing switch closes in the railgun load to initiate a gun shot. Between shots, residual field coil energy is reclaimed using full wave inversion to electrically motor the compulsator armature [1]. The CCEML system can be broken into several subsystems including: a self excited air core compulsator (CPA) [2], a field coil charging subsystem [1], and gun discharge subsystem. The focus of this paper is on design and testing of the explosive opening switch (EOS) and thyristor gun closing switch (GSM), which are integrated on a common coaxial bus (fig. 2).

The first part of the paper covers component development and general specification for the opening and closing switches. In the second part, development test data of both switches is presented including high current EOS interrupt performance data and GSM turn-on, turn-off and parallel thyristor sharing characteristics. In addition, a GSM impedance of 1.1 nH and 16.5 μΩ is empirically demonstrated.

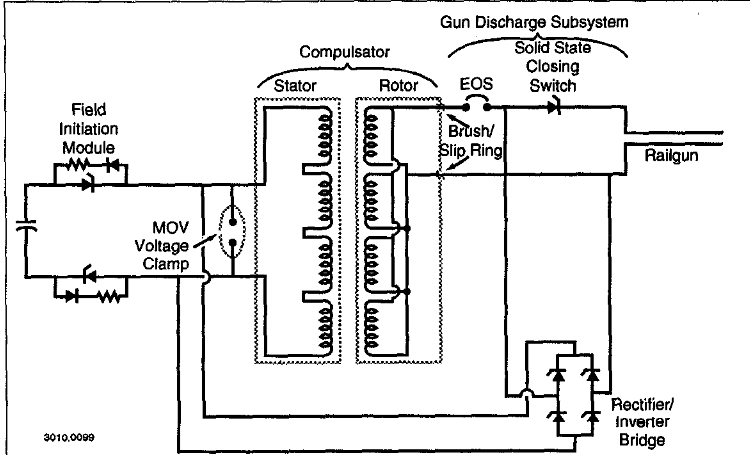

Figure 1. Overall system design

COMPONENT DEVELOPMENT

Opening Switch

The primary function of the opening switch is to electrically isolate the compulsator from the load and power electronic systems in the event of a critical fault. Since the opening switch response time (approximately 1 ms) and reliability are the crucial design requirements, an explosively actuated opening switch was developed. In addition, the explosive opening switch must be self contained to protect the rest of the system in the event of a high energy interrupt. Since the opening and closing switches were developed concurrently, it was quickly revealed that considerable volume and mass reductions could be realized if both switches could be integrated on a common coaxial bus. Successful integration of the EOS on a coaxial bus required development of cylindrical switch elements.

Initial development of the cylindrical opening switch elements was conducted using a series of "explosive only" tests. Leveraging previous opening switch work, Primacord® was selected as the explosive of choice for this effort[3]. Primacord® or det-cord is an explosive powder (PETN) encased in polypropylene yarn and is widely used for safety and ease of handling. Various element geometries and det-cord weights were tested until the desired element deformation was observed. Figure 3 shows the resultant element design consisting of a two piece cartridge assembly. Each element half is riveted to a disposable polyethylene backing piece, which functions to hold the 15 gr./ft Primacord® and protect the primary coax insulation. Figure 4 shows an actual switch after a current interrupt test. Note, the axial slits seen in figure 3 allow the petal shaped deformation seen in figure 4.

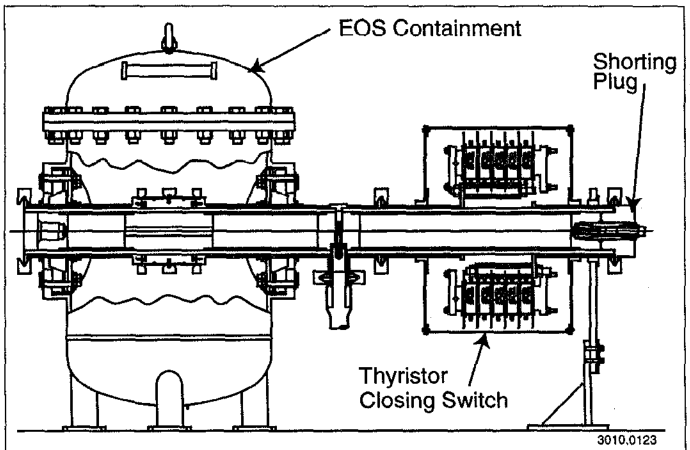

Figure 2. EOS/GSM section view

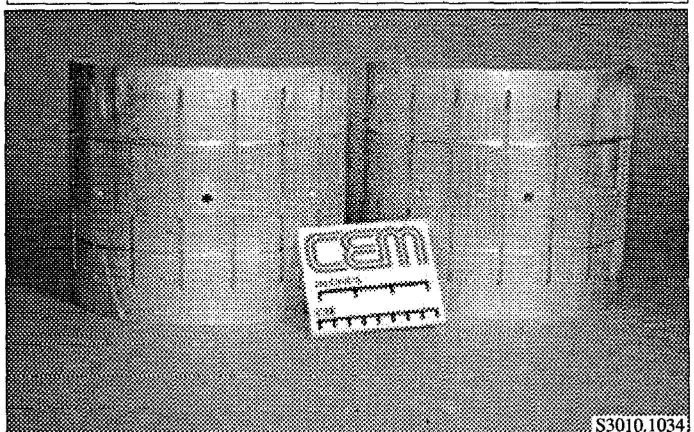

Figure 3. EOS element design

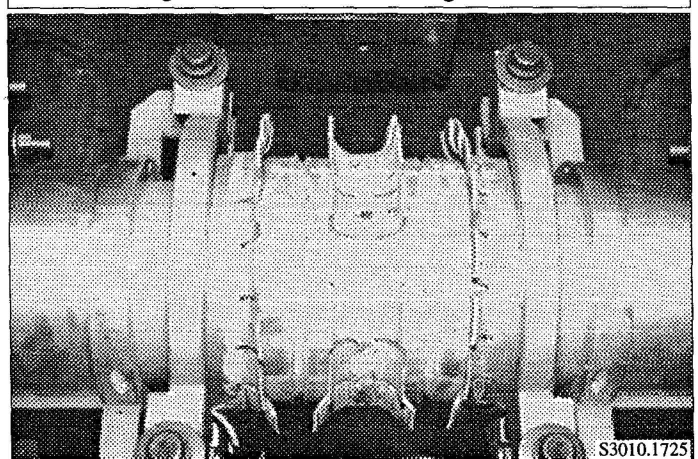

Figure 4. Blown EOS switch element

To insure reliable operation and meet the voltage stand-off requirements, two series gaps were incorporated into the EOS design. Each gap is fired at two common points 180° apart by two independently controlled fire-sets. That is a total of four exploding bridge wire initiators (EBWs) and two fire sets. Since the det-cord circuit (fig. 5) has all branches in intimate contact, initiation of a single EBW will result in a complete opening of both EOS gaps.

Containment of the EOS is achieved using a traditional pressure vessel design incorporating two feed-throughs to allow the coaxial bus to pass (fig. 2). The containment vessel is sized to contain the worst case fault, approximately 2.5 MJ. Using an iterative code, which compares the dynamic spring mass response of the vessel to a plastic deformation criteria, a minimum containment geometry was identified. The containment vessel is designed and built to ASME pressure vessel code section VIII, division 1. The containment is built with elliptical heads and from A354 (60 ksi min. yield) alloy steel with all circumferential welds fully X-rayed. Sealing around the coax feed through is accomplished using a self aligning three piece compression bushing made of polyethylene with stainless steel backing plates. In addition, the containment vessel features a way cool, spring loaded, swivel top, which allows unprecedented ease of access during switch installation.

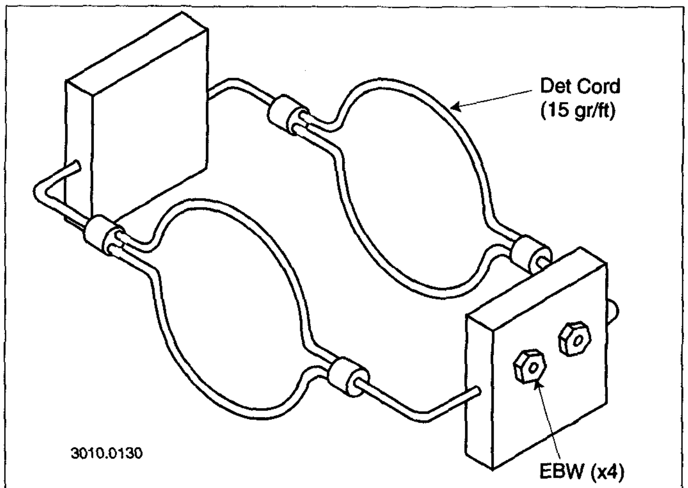

Figure 5. Det-cord circuit

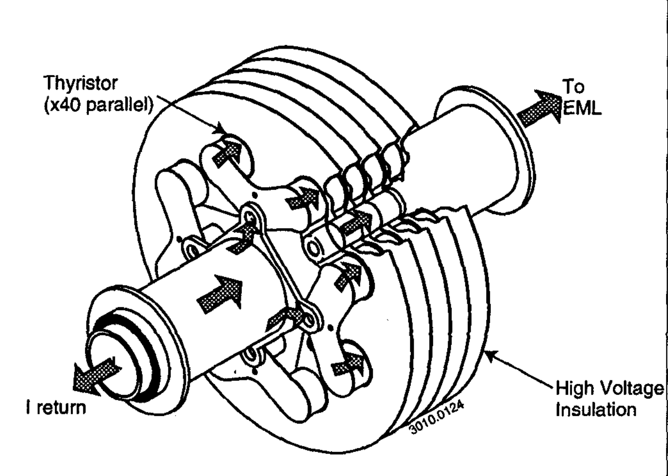

Figure 6. GSM parallel current flow

Closing Switch

A complete description of the design and development for the solid state gun switch closing module (GSM) is reported reference [1]. A summary is reported here to set the performance data presented below in context. To meet the CCEML system requirements the GSM is required to repetitively switch a 825 kA, 2.5 ms, half-sinusoidal pulse from a 200 Hz, 3.8 kV source. The required rep-rate for the switch is three consecutive five shot salvos at 5 Hz with 2.5 s between salvos.

The GSM consists of 40 parallel Westcode® N750CH45 thyristors, which are packaged without the use of a traditional RC snubber network. Thyristor selection followed an extensive test program to evaluate the turn-off characteristics of devices from different manufactures[1]. The selected Westcode® device demonstrated a soft turn off characteristic, which allowed snubberless operation during initial device testing[1].

In order to maximize power density and force current sharing, a coaxial geometry is used with the thyristors arrayed in five layers of eight. This design allowed additional mass and volume reductions by gang clamping five devices at a time. Current sharing between parallel devices is accomplished by the unique packaging of the GSM (fig. 6). The input to output current path for each device is equal length and encloses the same area. This yields an equivalent resistance and inductance for each parallel thyristor path[1]. Thyristor sharing data is presented in more detail later.

PERFORMANCE DATA

Iron Core Compulsator Testing

Testing of the gun discharge subsystem was performed on the lab based iron core compulsator (ICC) at CEM-UT. The ICC has a 2 kV sinusoidal output and is rated to produce a 1.0 MA pulse with pulse widths ranging between 3 ms to 10 ms. Figure 7 is a photograph of the test setup. An adapter was fabricated to interface the gun discharge subsystem and the coaxial output from the ICC bus. A shorting plug was installed across the GMS output bus to complete the discharge circuit (fig. 2).

The goals of this test sequence were to demonstrate operation of the GSM and EOS to CCEML performance levels, demonstrate operation of the GSM gate drive enclosure, and provide a low stress environment for first pass setup of the GSM current sharing monitor. Of particular interest were the EOS opening time and verification of current sharing within the GSM. In addition, testing allowed characterization of the GSM impedance. This is important because the complex current paths within the GSM make an actuate inductance value difficult to calculate.

Preliminary tests (1 to 20) of the GSM looked at the intra-layer current sharing of parallel thyristors in common gating groups. These tests indicated adequate current sharing to proceed safely to higher levels. Table IA is a summary of the high current EOS interrupt tests while table IB shows the GSM turn of tests.

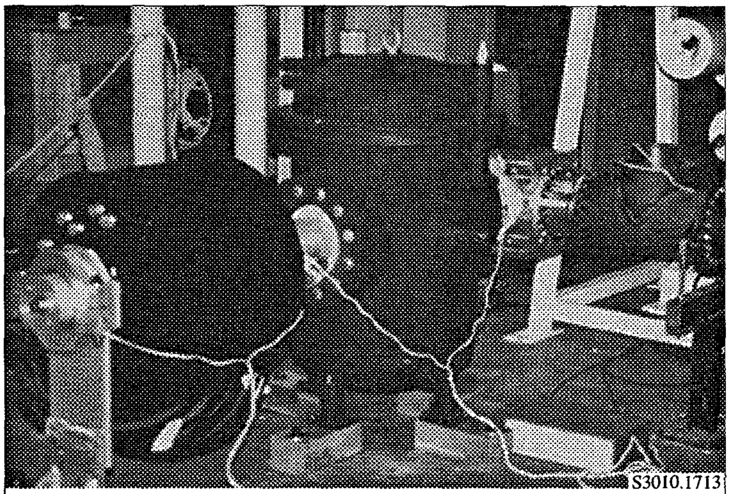

Figure 7. ICC installation

Table 1. ICC Summary

a. Non EOS tests on ICC

Test #	CPA Speed (rpm)	Peak Current (kA)	Rec. Current (kA)	Turnoff Di/Dt (A/μs)	Overshoot (V)
26	1,000	446	*	*	*
28	1,000	350	3.75	55.7	91
29	1,000	434	**	**	**
31	1,000	440	4.39	89	120
32	1,500	556	8.77	184	205
33	2,000	646	13.16	276	291
34	2,000	717	14.41	304	317
36	2,500	833	16.55	457	392
37	2,500	847	16.92	444	347

* No data, setup error ** No data, ICC SW opened

b. EOS tests on ICC

Test #	CPA Speed (rpm)	Peak Current (kA)	Curr Opened (kA)	EOS Energy (kJ)	Opening Time (μs)	Peak Vltg (V)
21	1,000	241	178	17.9	500	
22	1,500	385	362	74.0	810	1,096
23	1,500	442	403	91.7	520	1,600
24	1,500	530	491	136.0	810	1,440
25	2,000	637	624	220.0	950	1,575
27	2,000	688	678	256.0	1,150	1,640
35	2,500	816	790	352.0	1,100	1,829

EOS Interrupt Data

Due to the relatively straight forward EOS design and previous "explosive only" development, the testing reported here was primarily a mechanical endurance test of the non-replaceable EOS switch components and the containment vessel. EOS testing began at approximately 200 kA and proceeded at 100 kA increments up to 790 kA. Figure 8 shows the EOS current and voltage data for test #35.

The opening time of ≈1 ms seen during this test is the longest opening time recorded during the EOS testing. Initial EOS testing at low current and energy produced opening times of approximately 500 μs with a roughly linear increase relative to total stored energy. The relatively slow opening time demonstrated by the EOS is very desirable from a system perspective. In the event of a worst case interrupt of a full current gun shot, it is possible for the CPA main armature to produce hazardous self-voltages. Since the EOS exhibits slower opening times at higher energies, the risk of rotor damage due to self voltage may be partially mitigated.

GSM Performance

Reliable turn-on of parallel thyristors within the GSM is critical to switch performance. If all the devices don't latch on initially, then as a single device begins to conduct, the voltage across the switch will drop. This can result in some devices not achieving full turn on due to inadequate voltage. This problem is further compounded by the absence of a conventional RC snubber, which can provide critical latching current during low voltage turn-on.

Since the CCEML compulsator sinusoidal output has a relatively low dv/dt, a significant development effort was undertaken to develop a reliable gate drive for this application[1]. To summarize here, a hard gate drive with back porch was selected for the CCEML system. Hard drive refers to a gate current five to six times the minimum required gate current to provide latching. Back porch implies the use of a pulse transformer for isolation between the thyristor gates and the driving circuit. When driving the transformer primary winding with a square wave capable of saturating the core, an initial spike with an exponential decay is the resulting secondary output.

Using the thyristor gating method outlined above, the GSM was able to turn on reliably at relatively low applied voltages. Acceptable, if somewhat erratic, turn-on was obtained from 20 to 50 V. Above 50 V, overall turn-on and sharing improved dramatically. All tests conducted with a turn-on voltage of 120 V or greater demonstrated superior characteristics.

Each of the 40 GSM thyristors are instrumented with a Rogowski coil. These 40 Rogowski signals are conditioned and monitored by the gun current sharing monitor (GCM). Since each layer is gated as a common group, the GCM likewise handles the 40 signals as 5 groups of 8. After integration of the Rogowski signal, the average of each eight channel group is formed. This establishes a layer average for each of the five layers. The minimum acceptable sharing threshold is then added and subtracted from each average signal. This provides a window against which each of the individual integrated Rogowski signals can be compared. Any signal falling outside of its associated window will generate an error condition.

Positive and negative current flow is indicated for each channel using a similar windowing technique with fixed conduction thresholds for the forward and reverse directions. The high, low, and negative current signals are displayed by layer on an array of LEDs. This diagnostic allows evaluation of switch performance and aids trouble shooting a bad device.

In addition, the individual thyristor current signals are available as outputs for the data acquisition system. Since only ten data acquisition channels were available, it was not possible to collect all 40 traces simultaneously, thus current traces were collected on the suspected problem devices as identified by the GCM. Figure 9 shows the data obtained from the GCM buffered outputs during test #37 with a peak current of 845 kA. Current sharing between thyristors is within approximately 15%. The droop that appears on the current traces is a function of the integrators, which were designed for a shorter active time. The ICC supply has a pulse width in this test of 6 ms compared to a CCEML gun pulse of 2.5 ms.

A common failure mode for thyristors occurs at device turn off. The device can, without the presence of a snubber, suffer an over-voltage failure due to circuit inductance producing a voltage spike at turn-off. The conventional

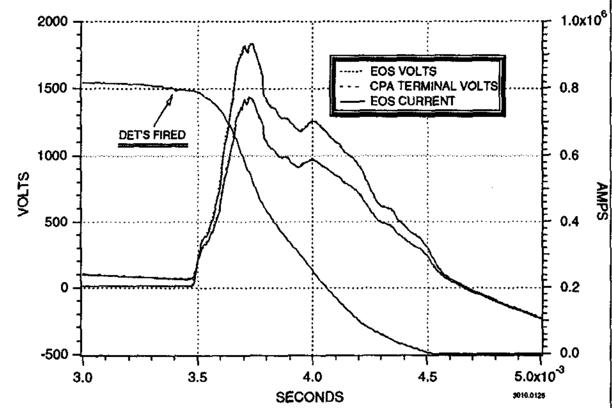

Figure 8. EOS interrupt data shot #35

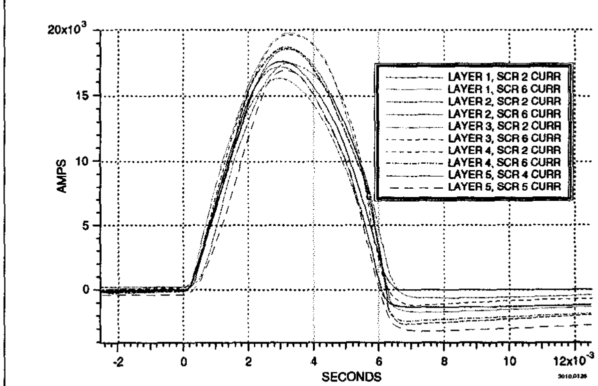

Figure 9. Parallel thyristor current traces shot #37

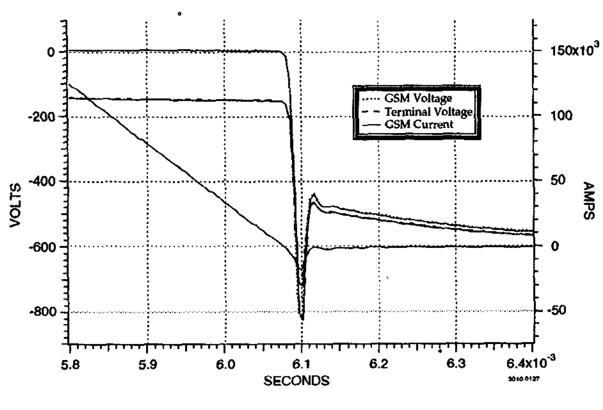

Figure 10. GSM turn-off at shot #37

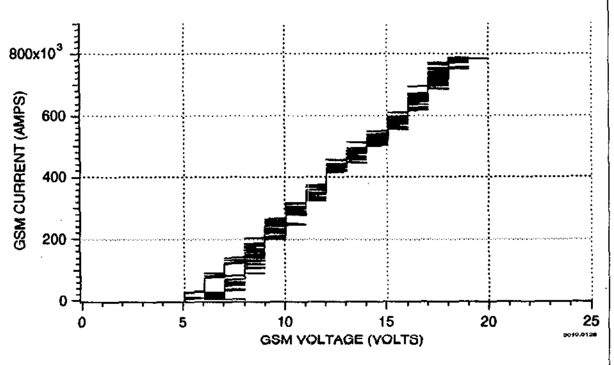

Figure 11. GSM VI curve shot #35

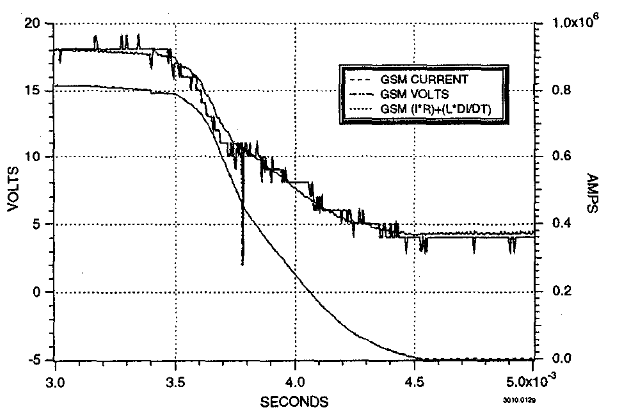

Figure 12. GSM current and voltage shot #37

Table II. Summary

Parameter	EOS Design #	EOS as Tested	GSM Design #	GSM as Tested
Resistance (μΩ)	Minimize	17.7	Minimize	16.5
Inductance (nH)	Minimize	low	Minimize	1.1
I_{peak} (kA)	825	790	825 kA	847
V_{peak} (kV)	4.5	1.83	4.5 kV	1.83 ††
$Action_{peak}$ A^2s	9.0×10^9	1.7×10^9	$*9.0 \times 10^9$	1.7×10^9
$Power_{peak}$ (GW)	5.04	1.45	5.04 GW	1.45
Energy (MJ)	2.5	352	N/A	N/A
Opening Time† (μs)	>> 100	1.1 †	N/A	N/A
Mass (kg)	<250	227	105 kg	125
Volume (m^3)	Minimize	0.266	Minimize	0.126

*Assumes adiabatic system; †At 790 kA; ††Highpotted to 4 kV

RC snubber circuit limits the magnitude of this spike by providing an alternate path for thyristor reverse recovery current after turn-off. This results in a lower di/dt and associated L*di/dt voltage. If the thyristor turn-off characteristic is slow enough, then a snubberless design is possible. As reported earlier[1] single device testing indicated that the Westcode N750CH45 exhibited an acceptably slow turn-off.

Figure 10 shows the turn-off data for the GSM during shot #37. After reaching a forward peak of 845 kA the reapplied reverse voltage for test #37 was -480 V with a voltage overshoot of 347 V. Excellent current sharing coupled with the soft turn off characteristics of the Westcode® devices validates the snubberless design approach adopted for the CCEML system.

GSM Inductance

The VI curve for the GSM during test #35 is shown in figure 11. This curve clearly indicates a forward threshold voltage of approximately 5.0 V and a very linear ohmic slope of approximately 16.8 μΩ. Both the linear nature of this curve and the very low hysteresis indicate an extremely low GSM inductance. In fact, due to the low total inductance of the GSM, initial attempts to use the phase shift as a means to measure inductance were unsuccessful. In order to obtain a more sensitive measurement, the data collected during high di/dt EOS testing was used.

During the 790 kA interrupt of test #37, a slight phase shift could be distinguished between the GSM voltage and current traces. From this data an inductance of 1.1 nH was estimated. Figure 12 shows the original GSM voltage data plotted against a numerical result for $V=(I*R)+(L*di/dt)+V_{threshold}$. The extent to which sampled and calculated data agree indicates that the estimated GSM impedance is accurate.

CONCLUSION

Table II is a summary of the design and performance data for the EOS and GSM subsystem. The EOS was tested to the CCEML design current levels with out any signs of distress. In addition, the relatively slow opening times demonstrated during testing may partially mitigate self-voltage issues during operation of the CCEML system.

The GSM demonstrated reliable turn on and current sharing at applied voltages above 50 V. In addition, the soft turn off characteristic of the GSM validates the snubberless design approach. Finally the extremely low impedance of the GSM ensures the impedance budget for the CCEML system is realized.

References

1. D.J. Wehrlen, et al, "Power Electronics and Controls for Air Core Compulsator," 7th EML Symposium on Electromagnetic Launch Technology, San Diego, CA, April 20-24, 1994.
2. S.B. Pratap, et al, "Optimization and Design of the Air Core Compulsator for the Cannon Caliber Electromagnetic Launcher System (CCEML)," Ninth IEEE Pulsed Power Conference, Albuquerque, NM, June 21-23, 1993.
3. D.J. Wehrlen, et al, "Commissioning of the Explosively Operated Switches Used at CEM-UT," 8th Pulsed Power Conference, San Diego, CA, June 17 to 19, 1991.