THE CEM-UT RAPID-FIRE COMPULSATOR RAILGUN SYSTEM--RECENT PERFORMANCE AND DEVELOPMENT MILESTONES

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Abstract: A test program for the rapid fire compensated pulsed alternator (compulsator) railgun system at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) commenced in April 1986. Two years later, performance data generated in the period from the start of testing to December 1987 was presented at the 4th Symposium on Electromagnetic Launch Technology in Austin, TX.[1] Since that time, 27 compulsator powered railgun experiments have been performed including a 1.0-MJ discharge at 3,510 rpm. In this test, a 724 kA current pulse accelerated an 80 g, aluminum armature to 2.05 km/s, thus exceeding the projectile velocity goal at 73% rated machine speed. Furthermore, operation with a single gun barrel has been achieved using a parallel path, solid-state closing switch to deliver 132 kA to the railgun injector.

This paper presents the latest data from the rapid fire compulsator railgun facility. Included is a discussion of the energy transfer, power output, and system efficiency during a 1.0 MJ discharge. Also shown are the injector current, voltage, and di/dt curves for this test which were used in the design of the solid-state closing switch. Results of railgun experiments using the solid-state switch are analyzed.

Introduction

Figure 1 shows the CEM-UT compulsator driven, rapid fire Electromagnetic (EM) gun system having the design specifications listed in table 1. The compulsator is a six pole rotating field alternator with passive armature compensation to reduce machine inductance and allow high current pulses. A 68 turn-per-pole field winding is assembled on a horizontal shaft, AISI 4340 steel rotor.

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Figure 1. 1 MJ per pulse rapid fire compulsator railgun system

Armature compensation is provided by a thin, 7050 aluminum sleeve which is shrunk onto the rotor and thus rotates in the machine air gap. Armature windings are composed of six lap-wound coils of fully transposed litz wire and are bonded to a laminated steel stator. The coils are connected in parallel at three output terminals. Other design and fabrication details may be found in references [2,3,and 4].

Table 1. Compulsator system parameters

Parameter	Value	Units
Length of machine	1.52	m
Total mass	11,000	kg
Rotor speed (max)	4,700	rpm
Inertial energy (@ 4,700 rpm)	38	MJ
Projectile mass (max)	80	g
Projectile velocity	2	km/s
Projectile kinetic energy	160	kJ
Repetition rate	60	Hz
Barrel length	3.0	m
Peak current	940	kA
Peak open circuit voltage	2.0	kV
Machine Inductance (@ 4,700 rpm)	0.69	μ H
Machine resistance	0.34	m Ω

A schematic of the compulsator and gun circuit is shown in figure 2. Machine output is directed through an explosive opening switch which serves as a circuit breaker in the event of a short or other fault condition. Switch operation is described in reference 5. A coaxial busbar delivers current to the railgun and injector and a closing switch is located between the bus and one injector terminal. An armature is inserted in the injector bore and, at a predetermined angle on the machine voltage

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Figure 2. Schematic of compulsator railgun system

cycle, a signal is sent to the closing switch to initiate an injector current pulse. Injector current causes the armature to accelerate and be driven into the 3-m gun at approximately 200 m/s.

Exit of the armature from the injector is timed to correspond to zero current on the approximately sinusoidal current pulse. Upon entering the 3-m gun, a second current pulse is initiated and the armature is accelerated to full velocity. As with the injector, exit of the armature is timed to coincide with zero current. At this time, a second projectile may be loaded into the injector and the cycle is repeated for rapid-fire operation.

Testing of the compulsator driven railgun system began in April 1986. Fourteen railgun experiments at compulsator speeds of nominally 2,400 and 3,000 rpm (including several rapid-fire discharges using two railguns in parallel) were performed during the period from April 1986 to December 1987. Since that time, continued testing has resulted in the attainment of machine discharge energy and projectile velocity goals at 73% of rated machine speed. Compulsator and railgun performance data is presented for this test. The effects of solid armature requirements on injector and autoloader performance are also discussed.

In addition to realizing full energy goals, experiments have been performed on a multiple pulse rated injector closing switch. The design and performance results are given.

Full Energy Testing

One of the goals of the rapid fire compulsator program was to accelerate an 80-g armature to 2 km/s for a kinetic energy of 160 kJ. To produce this performance, a 1.0-MJ discharge was required to overcome inductive and resistive losses. Additionally, the simulation predicted that at a rotational speed of 3,600 rpm and field excitation of 90% (1,060 A), the compulsator would develop an open circuit voltage of $\pm 1,360$ V and closing the gun circuit would result in a peak current of 760 kA.

Machine Performance

Figure 3 shows the machine terminal voltage and total current for this experiment (run #122). Since the machine voltage is negative at $t=0$ ms, a negative current pulse is produced in the injector when the switch is closed. At $t=1.0$ ms, a small perturbation is noticed on the terminal voltage indicating transition of the armature from the injector to the 3-m railgun. A positive pulse is then developed in the 3-m gun as the machine voltage swings positive. Noise at peak terminal voltage is indicative of contact loss between the solid armature and the gun rails and the large spike at $t = 4.5$ ms is due to early exit of the armature at a current of 282 kA resulting in a muzzle arc and subsequent di/dt voltage generation.

Prior to closure of the switch, the open circuit voltage measures $\pm 1,300$ V which is less than anticipated. However, examination of the open circuit voltage cycle prior to switch closure revealed an electrical frequency of 175.4 Hz, which translates to 3,510 rpm for the six-pole rotor. Accounting for the reduced speed results in an expected voltage of $\pm 1,323$ V, which is less than a 2% deviation from observed data. This reduced speed and

Figure 3. Compulsator 1 MJ discharge (run #122), machine current and voltage data

resulting voltage was then applied to the compulsator simulation resulting in a reduction of expected current to 756 kA, which differs from the actual current of 724 kA by only 4%.

Before looking at the machine energy output, it is first more convenient to determine the machine power. Using a digital data analysis program, the current and voltage of figure 3 were multiplied to produce the electric power output of the machine as shown in figure 4. Peak output power was 370 MW. Calculation of the theoretical power generation is accomplished similarly, but the machine open circuit voltage is substituted for the short-circuit voltage by performing a 360° phase shift on the voltage data. The result shows a peak power generation of 803 MW for a power efficiency of 46.1%.

Given the machine power, compulsator electrical energy was derived by integration with respect to time. A peak energy of 1.01 MJ was obtained from the theoretical power. The electrical energy delivered to the load was 536 kJ which yields a machine efficiency of 53.2%. Additionally, the theoretical energy may be confirmed by calculating the change in inertial energy of the rotor where the speed was reduced from 3,510 to 3,413 rpm. Given a rotor inertia of $318 \text{ J}\cdot\text{s}^2$, a rotor energy loss of 1.17 MJ was obtained for a mechanical to theoretical electrical energy transfer efficiency of 86.3%.

Railgun Performance

Measurements of armature velocity were obtained from break screens, B-dot probes, and high-speed photography. The break screen and photograph data is consistent with velocity predictions indicating 2,125 and 2,050 m/s, respectively. Data from two B-dot probes spaced 10 cm apart at the muzzle gave a velocity of between 2,800 and 3,300 m/s, but this value is unreasonably high. Since

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Figure 4. Compulsator 1 MJ discharge (run #122), machine current, actual power output, theoretical (zero electrical loss) power, and electrical energy

transition of the armature from solid-contact to a plasma interface is known to have occurred prior to exit from the gun, it is likely that an arc had formed in front of the armature at a location between the two probes making this velocity data invalid. Given that high speed camera velocity measurements are more reliable than either of the other methods, a velocity of 2.05 km/s was accepted.

An indication of armature contact performance in the railgun is given by examining the voltage drop across the gun rails at the muzzle. Figure 5 shows the gun muzzle voltage for run #122 indicating that good armature-to-rail contact was maintained until just prior to peak current ($t=2.5$ ms). After this time, the armature voltage drop exhibits random spikes and begins to increase exponentially, indicating a loss of metal-to-metal contact and transition to a plasma interface.

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Figure 5. Compulsator 1 MJ discharge (run #122), railgun current and muzzle voltage (armature voltage drop)

Armature Development

Table 2 summarizes all railgun tests from January 1988 to December 1989. The majority of these tests were performed to gain information on the interaction between armature performance and railgun timing. In most cases, transition from solid contact to a plasma interface resulted in a reduction of armature mass and friction. Consequently, higher than anticipated exit velocities were obtained and were accompanied by early exit of the armature and substantial muzzle arcs.

Loss of solid armature contact with gun rails is related to railgun bore growth and surface melting due to excessive action integral ($\int I^2 dt$). It is difficult to control the current density and action integral in a railgun due to pulse frequency and velocity skin effects [6]. Therefore, armatures were designed to compensate for rail separation during a current pulse and to provide a contact area greater than the area calculated from skin effect equations.

A typical armature is shown in figure 6. To track bore growth, the fins are machined to a diameter larger than the gun bore. This interference also results in a high rail contact pressure that is a function of armature stiffness and reduces contact resistance. Unfortunately, the high contact force also creates a high drag force which must be less than the accelerating force of an injector current pulse.

Figure 7 shows the effects of armature interference. While the contacts are melted and quite worn on the run #185 armature, the run #183 armature still shows evidence of machine marks on the contact surface, thus illustrating the benefits of contact pressure. Muzzle voltage exceeded 160 V for run #185 and was less than 40 V for run #183.

Table 2. Summary of compulsator powered injector, 3 m railgun shots (January 88 to December 89)

Parameter /Run#	Date of Test	CPA Speed (rpm)	Excitation (A) (%)	Open Circuit Voltage (V)	Firing Angle (°)	Peak Injector Current (kA)	Peak Railgun Current (kA)	Railgun Muzzle Current (kA)	Projectile Mass (g)	Projectile /Bore Intf. (mm)	Projectile Insertion Force (N)	Projectile Velocity (m/s)
Run #110 (1)	2/2/88	1,747	750 (77.5)	n/a	141.0	-174	328	201	65.9	0.20	3,915	1,109
Run #110 (2)	2/2/88	1,645	750 (77.5)	n/a	141.8	-194	258	191	66.3	0.20	6,850	838
Run #112	2/9/88	2,920	851 (81.1)	969	142.7	-155	623	210	70.8	0.20	4,980	1,602
Run #114	2/19/88	2,976	851 (81.1)	1,012	142.3	-150	625	276	70.5	0.38	980	1,926
Run #115	2/26/88	2,994	851 (81.1)	1,060	142.2	-173	636	279	74.9	0.51	2,065	1,753
Run #116	3/2/88	3,000	851 (81.1)	1,017	342.0	247	-564	-334	74.6	0.76	3,425	1,286
Run #118	3/29/88	2,347	750 (77.5)	758	140.6	-122	95	0	70.3	0.76	3,380	n/a
Run #119	3/31/88	2,976	851 (81.1)	1,014	141.8	-149	626	253	70.0	0.76	3,380	2,040
Run #122	4/5/88	3,509	1,060 (90)	1,314	143.4	-203	720	282	80.3	0.76	3,580	2,050
Run #150	10/20/88	2,326	710 (75)	700	142.7	-386	-465	-193	64.9	1.02	15,262	1,607
Run #174	12/1/88	2,375	550 (65)	633	142.0	-111	448	126	63.7	0.76	2,090	1,480
Run #176	12/14/88	2,350	710 (75)	730	141.1	-127	501	207	69.2	0.76	2,090	1,615
Run #177	12/21/88	2,353	550 (65)	634	142.9	-119	460	113	69.6	0.89	3,345	1,236
Run #180	1/6/89	2,958	710 (75)	910	143.2	-141	576	173	69.6	0.89	4,285	1,600
Run #183	1/24/89	2,393	550 (65)	632	144.0	370	421	-83	72.9	1.02	7,842	1,260
Run #184	1/27/89	2,395	550 (65)	632	146.2	-126	467	79	75.3	0.69	5,227	1,032
Run #185	2/8/89	2,382	550 (65)	630	145.9	-121	456	97	74.7	0.76	5,018	1,399
Run #187	3/2/89	2,400	620 (70)	691	143.7	-132	488	138	79.8	0.83	4,390	1,518
Run #188	3/22/89	2,375	620 (70)	679	145.1	-132	485	153	79.7	0.70	4,390	1,390
Run #189	3/28/89	2,387	620 (70)	679	144.9	-132	473	129	79.5	0.76	4,809	1,510
Run #190	4/12/89	2,969	710 (75)	908	143.3	-144	594	71	80.1	0.74	5,018	1,695
Run #192	5/12/89	2,967	710 (75)	918	144.8	155	-589	-175	80.0	0.91	5,436	1,581
Run #195	5/26/89	2,990	710 (75)	921	145.2	-159	594	121	79.4	0.76	6,272	1,700
Run #196	6/2/89	2,983	710 (75)	915	145.2	-159	588	118	80.0	0.76	8,572	1,610
Run #213	9/18/89	2,400	550 (65)	615	146.2	-118	n/a	n/a	65.1	0.33	4,181	<200
Run #214	9/26/89	2,400	550 (65)	625	148.0	-132	453	61	74.0	0.76	10,871	1,417

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Figure 6. Solid armature design used in the rapid fire compulsator gun system

Figure 7. Effects of armature interference on insertion force and performance. Run #185, interference = 0.76 mm, insertion force = 3,425 N. Run#183, interference = 1.02 mm, insertion force = 7,840 N

Not shown is the detrimental effect on timing caused by the 7,840 N insertion force of the run #183 armature. This force exceeded the magnetic accelerating force of the injector such that armature movement did not begin until a current of 370 kA had been attained from the positive pulse that was intended for the railgun. All subsequent events occurred much later than expected. Exit of the armature from the gun occurred during rising current and machine voltage and resulted in a very high energy muzzle arc.

Solid-State Silicon-Controlled Rectifier Switch

To pursue the goal of multiple armature delivery through a single gun, a rep-rated switch was required. Previous experience with ignitrons had shown them to be unreliable and short lived when operated near peak ratings. While improvements in peak current and power ratings of SCR devices have occurred in the past several years, the single device ratings were still well below the railgun injector requirements of 200 to 250 kA and single discharge I^2t of 39.8 MA²s as obtained from the data of run #122 (fig. 8). In order for SCR's to work effectively, several units would be required to share current in parallel.

Figure 8. Run #122 injector data, injector current, I^2t , di/dt

Figure 9 shows the eight path SCR switch developed for use with the compulsator railgun system. The individual SCR's comprising the switch are Westcode Semiconductor Converter Grade Capsule Thyristor Type N540CH18. Table 3 lists the SCR specifications which were of primary concern to the switch design.

Table 3. Westcode semiconductor NC540CH18 solid-state thyristor specifications

Parameter	Value	Units
Voltage	1,800	V
Peak one cycle surge current	27.2	kA
Peak surge energy (I^2t)	4.47	MA ² s
di/dt	1,000	A/ μ s
dv/dt	200	V/ μ s
Peak on-state voltage drop	1.41	V
Forward conduction resistance	0.174	m Ω

* All parameters based on manufacturers data for 60 Hz operation.

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Figure 9. High current, parallel path, rep-rated, solid-state closing switch

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. Additionally, a 45.0 kA multiunit, short-circuit discharge was performed and confirmed the current sharing ability.

Inductance measurements of 0.4 μ H were obtained for the single path tests whereas the multipath tests

shows a switch inductance of 0.2 μH due to the coaxial geometry. It is believed that the higher inductance of the single path aids turn-on of the other devices by maintaining a voltage drop across the switch that is proportional to di/dt . Additionally, the coaxial arrangement and SCR orientation prevents current constriction within individual SCR's.

Following the short-circuit tests, the switch was connected to the railgun injector and a 65-g armature was accelerated to 138 m/s and had timing characteristics consistent with previous injector tests. Peak current through the switch was 118 kA and an I^2t of 16.2 MA^2s was developed. A 3-m railgun was then added to the circuit and 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 MA^2s . In these high current experiments, variation of current between individual SCR's was less than 15%.

Conclusions

Testing of a rapid fire, compulsator powered EM gun system has led to the following accomplishments and developments:

- (1) achieved an 80-g armature velocity exceeding 2.0 km/s from a 724 kA compulsator current pulse,
- (2) demonstrated the feasibility of using a low current injector to initiate a railgun discharge in an electrically "hot" gun,
- (3) developed high current, repetitive closing switch capabilities through the use of parallel SCR devices.

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