Laboratory Testing of the Pulse Power System for the Cannon Caliber Electromagnetic Gun System (CCEMG)

J.R. Kitzmiller, S.B. Pratap, M.D. Werst, C.E Penney, T.J. Hotz, and B.T. Murphy

The University of Texas at Austin Center for Electromechanics, Austin, Texas

***Abstract*—The team of (prime contractor) United Defense LP (UDLP) and The University of Texas at Austin Center for Electromechanics (UT-CEM) has completed a significant portion of the testing phase of a trailer mounted compulsator driven 35 mm (round bore equivalent) rapid fire railgun system. The objective of the program is to develop a compact, lightweight pulse power test bed capable of launching 3, 5 round salvos of 185-g integrated launch packages to 1.85 km/s at a firing rate of 5 Hz. Per contractual requirements, the pulse power system is also size compatible with the Amphibious Assault Vehicle (AAV). The pulse power system is developed around a second generation air-core, 4-pole rotating armature, self-excited, compulsator design. The 40 MJ at 12,000 rpm composite rotor stores all 15 shots inertially and is capable of 2.5 GW performance into the 2.21 m long series augmented railgun.**

This paper describes the CCEMG pulse power supply configuration and highlights important features of the commissioning test plan. The paper then presents test results from mechanical runs, stand alone compulsator (CPA) rectifier tests, short circuit tests, and single shot live fire tests. Finally, CPA performance is compared with predictions for the single shot tests presented.

Introduction

System Configuration

CCEMG program goals are presented in Table I for reference. The pulse power system consists of the compulsator (CPA), field coil converter (FCC), and gun switch module (GSM). In addition, there is a power circuit protective explosive opening switch module (EOS). Previous as well as current publications discuss the optimization and design of the entire pulsed power system for CCEMG as well as the railgun [1],[2],[3]. In addition, three sister papers are presented in this symposium describing the present railgun test results, power electronics performance, and rotor mechanical spin testing performance [4],[5],[6].

The CPA is the heart of the pulse power system and consists of a second generation 4-pole rotating armature, self-excited, air-core configuration developed at UT-CEM. Fig. 1 shows the longitudinal cross section of the CPA. The single armature delivers both field charging and railgun currents respectively. The field winding is sandwiched between the titanium stator casing and a titanium reinforced selective-passive compensating winding which is placed at electrical quadrature with respect to the field winding in order to minimize field coil charging losses. Fig. 2 shows the electrical schematic for the pulse power system. Solid state switches comprise the full wave rectifier/inverter bridge for the field winding as well as the GSM. The FCC utilizes Powerex TD-20 (100 mm) devices in a 2 series, 3 parallel configuration per leg, and includes a snubber circuit. The GSM utilizes 40 parallel Westcode N750Ch45 devices and is presently operating without a snubber. AAV compatibility requirements have resulted in FCC and GSM switch designs which have demonstrated the highest energy and power densities to date in electric gun TD platforms. These parameters are presented at the end of the paper.

System Experimental Operations

Fig. 3 shows the CCEMG experimental set-up in the UT-CEM laboratory. The pulse power system, main controller, data acquisition and auxiliaries are all packaged in a 42 foot long trailer, which has 110 Vac, 50 A, and 460 Vac, 1,200 A service to power on-board systems and the CPA drive motor. The railgun is positioned on the south side of a large highbay door and is connected to the GSM through a ground trench which houses a 28 ft long flexible bus consisting of 6 parallel hexapolar cable runs. The extra impedance resulting from the cable extension taxes the CPA a bit, and limits performance to about 90% of design muzzle energy at reasonable field excitation levels (122%). The compulsator is protected by completely redundant auxiliaries which are powered from an externally located diesel generator set. The CPA is connected to a 400 hp, 12,000 rpm ac induction motor which is in turn

Table I. CCEML SOW requirements

Parameter	SOW Requirement	Final Design
Armor Penetration 0° and (56°) obliquity	73 mm (131 mm) RHA @ 1,500 m 37 mm (66 mm) RHA @ 3,000 m	meets spec
Caliber	20 to 40 mm	30 mm (equiv.)
Firing Rate	300 to 400 rnds per minute	300
Salvo Size	5 to 7 rounds (3 salvos total)	5
Time Between Salvos	2 to 2.5 s	2.5
Probability of Hit	0.9	0.9 (planned)
System Weight	5,000 lb maximum	6,300 lb
Weapon Mounting Platform	Compatible with AAV	meets spec

Manuscript received April 8, 1996.

J.R. Kitzmiller, phone (512) 471-4496,fax (512) 471-0781, e-mail kitzmiller@crovax.cem.utexas.edu.

This effort is funded by the U.S. Army Armament Research Development and Engineering Center and the U.S. Marine Corps.

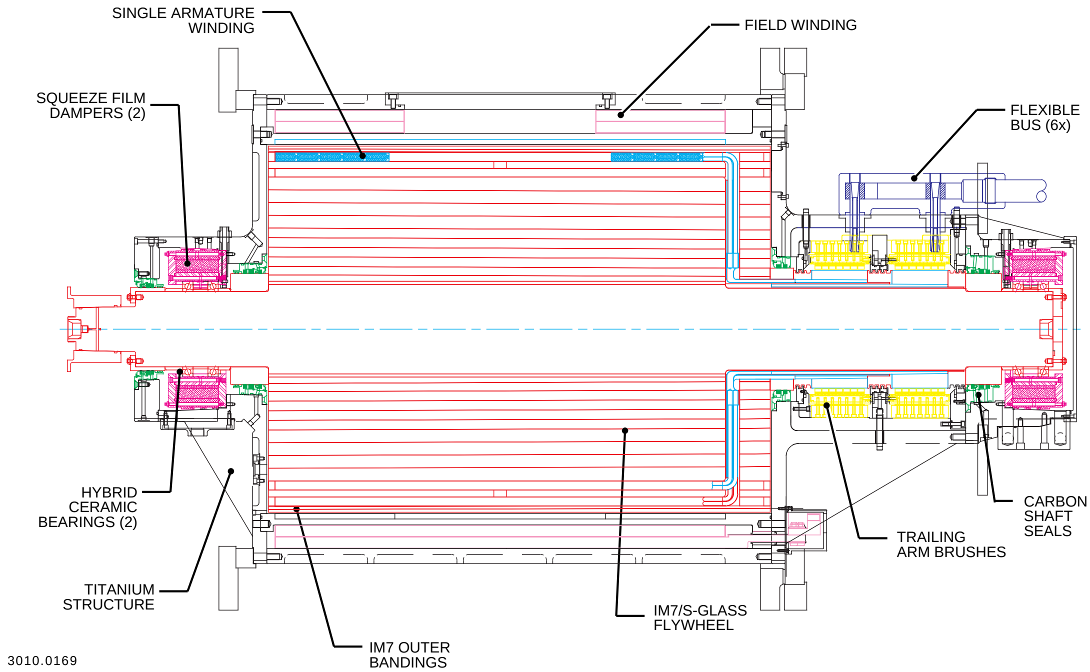

Fig. 1. Cross section layout of compulsator

protected from discharge speed transients via a high speed wet disk clutch. The motor also provides dynamic braking capability, and a redundant wet disk brake located with the clutch will brake the CPA rotor if site power is lost for any reason. Operation of the system takes place at the remote control unit (RCU) which is tethered to the main controller in the trailer. System software allows for both fully automatic mode operation (more than a single discharge) or semi-manual mode operation, which has been utilized extensively in testing so far.

For a routine shot, first a simulation is run to predict performance and timing for the experiment. Generator setup parameters are then typed into the RCU and downloaded to both the main controller and the firing and fault control monitor (FFCM). The FFCM is responsible for real time control of the pulse power systems. After bringing up auxiliaries, charging the field initiation module, and entering rotor speed, the prime mover is initiated and spins the CPA rotor up to the input speed. At this time, the RCU operator initiates a command which charges and arms all of the pulse power system SCR drives as well as the fail-safe EOS module. When completed, the system is then ready to perform its discharge.

At this time, the controller then discharges the field initiation module (FIM) into the compulsator field coil to initiate the self-excitation process. From this point forward until the compulsator is again fully de-energized, the FFCM assumes real-time control of the pulse power systems. The FFCM locks onto an optical encoder signal which rotates synchronously with the armature winding and triggers the field coil converter (FCC) until it senses that programmed ac voltage has been achieved. At this instant, the FFCM gives freewheel command pulses to the bridge and simultaneously triggers the GSM at the programmed firing angle, which initiates the flow of current into the railgun. The remaining field energy is then allowed to freewheel down to zero via the freewheel diode module (FWD). The FFCM and associated hardware is also capable of reclaiming the field coil magnetic energy into the rotor, however, at this time schedule and funding restraints will not permit this function to be realized. Throughout the discharge event, the FFCM is continuously monitoring CPA, GSM, and gun breech currents and will interrupt the cycle by initiating the EOS in case of a fault. As redundant protection,

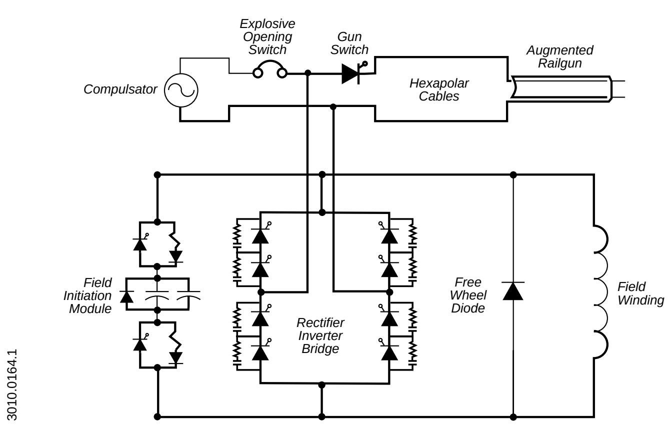

Fig. 2. Electrical schematic

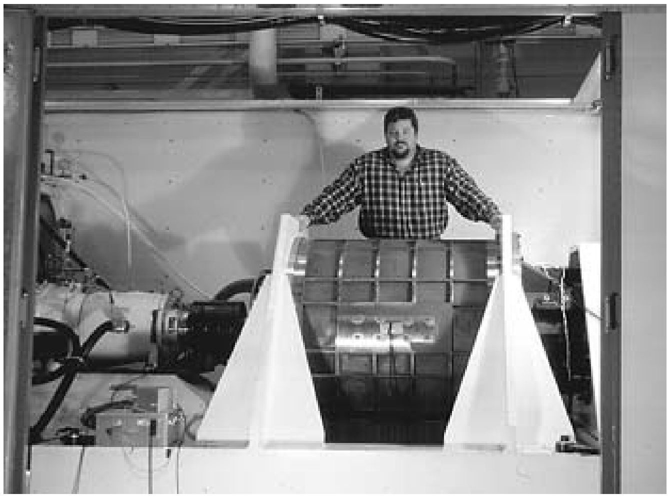

Fig. 3. Experimental set-up at UT-CEM

the main control system will also activate the EOS should the FFCM detect a fault, and the main control system has a timed EOS event as well which has proved itself most beneficial during commissioning.

PULSE POWER TESTING

Extreme caution must be used in developing test plan strategies for prototype CPA driven electric gun hardware. Since the CPA is designed to provide maximum current to what is essentially a short circuit load, special attention must be paid to software and hardware components to make certain all are working as expected. Regardless of the power supply, it is common knowledge that in this business surprises generally manifest themselves as spectacular faults and/or destruction of hardware.

With all of this in mind, the CCEMG test plan was designed to bring the software and hardware on line incrementally, thus minimizing risk exposure of critical components wherever possible. In addition, the test plan had to be designed to accommodate an assembly flaw in one of the four existing rotor armature outer bandings which essentially limited the rotor speed to 8,500 rpm. There is a plan to replace this damaged banding and allow the rotor to be spun to rated speeds. The test plan called for the following incremental tasks to be carried out in order:

I) Mechanical spin-up
II) Stand alone rectifier testing
III) Single shot testing - dry fire
IV) Single shot testing - live fire
V) Stand-alone rectifier/inverter testing
VI) Multi-shot dry fire testing
VII) Multi-shot live fire testing

Above the term 'dry fire' refers to short circuit discharging of the CPA without an armature or launch package loaded in the gun. In practice the gun was used as the load and a calibrated current viewing resistor (CVR) was attached across the muzzle and used to calibrate system Rogowski coils. As of this writing, the team had completed task IV, and the remainder of this paper presents data and observations from those four tasks.

Mechanical Spin-Up

Mechanical spin-up was performed in order to validate the operation of the prototype composite rotor to useful test speeds. As mentioned previously in this paper, the rotor did have a compromised outer banding installed. From rotordynamic analyses, there was a strong bearing natural frequency predicted at about 5,700 rpm. Operation above this speed meant that the mode had to be confirmed and traversed using the actual CPA. Fig. 4 is a plot of shaft vibration vs. speed for the CPA operating to 8,250 rpm which agrees well with rotordynamic predictions. This plot clearly defines the bearing natural frequency and based on this information the desirable rotor operating speed range was set from 0 to 4,500 rpm and 7,000 to 12,000 rpm respectively. In practice, the rotor could actually be operated anywhere within this critical speed range, which is a tribute to the bearing damper designs. Details concerning the rotor suspension system for CCEMG can be found in an accompanying paper at this conference [6].

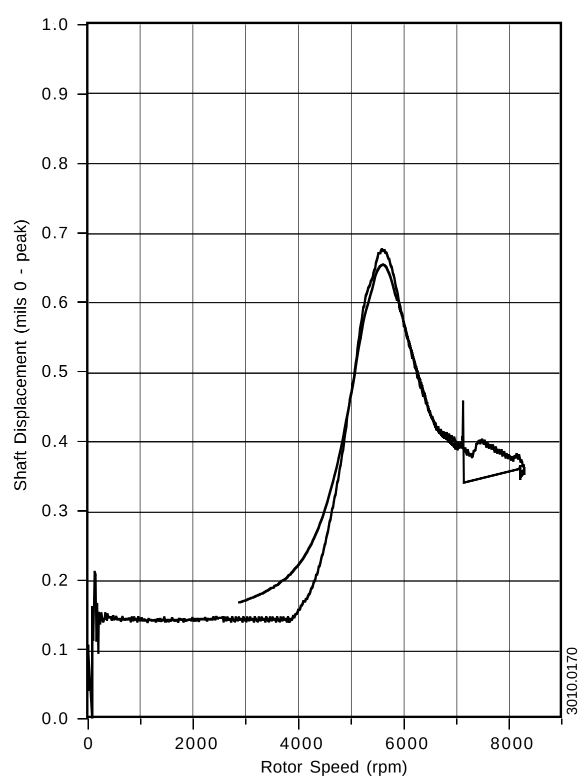

Fig. 4. Vibration plot

Stand Alone Rectifier Testing

Stand alone rectifier testing was designed to validate two critical CPA subsystems, namely, the field initiation module (FIM) and the field coil converter bridge (FCC). The FIM is responsible for initiating self-excitation by injecting a small current (2 to 5 kA) into the field winding. The magnetic flux induced by this current then 'seeds' the CPA armature winding with enough voltage to enable the FCC to rectify alternating current produced by the armature winding to direct current for the field coil. This action is controlled by the FFCM module mentioned above. For CCEMG, the rotor provides all the required energy for this operation. The resulting charging action occurs exponentially, and in order to minimize losses to the CPA, is performed at very high power levels.

During early testing some difficulty was encountered in getting the CCEMG system to self-excite. This turned out to be the result of attempting to perform self-excitation at voltage levels which were essentially not quite high enough. The desired test rotor speed was set at 4,500 rpm. This speed was selected because 4,500 rpm is the maximum allowable speed prior to the bearing bounce mode; and more importantly, there would not be enough rotor stored energy to either over-current or over-action the field winding in case of a bridge or controls fault. Unfortunately, at 4,500 rpm and a 1 kV FIM charge, this provided for only about 80 Vac to rectify with. The back EMF of the field winding and bus was slightly above 50% of this voltage, so the SCRs had less than 40 V forward bias across them. Apparently, this was not enough forward bias to get the SCRs turned on reliably, and the CPA would not self-excite. Interestingly, similar behavior to this was noted on both the CEM-UT small caliber CPA and iron core CPA systems in the gun switch modules; attempting to turn on multiple SCRs with less than 40 V forward bias is not recommended.

Once this behavior was identified, the FIM voltage was doubled to 2 kV, providing about 2.7 kA seed current and 160 Vac from 4,500 rpm. At this level, the bridge worked as expected as seen in the self-excitation plot in Fig. 5, which is also compared to the simulated result. At about 0.72 s, the gating ceases upon command and the dc current decays to 0 again through the freewheeling diode.

Single Shot Testing - Dry Fire

Completion of stand alone rectifier testing meant the system was ready to perform tests using the railgun switch module (GSM). The intent of this test phase was to verify that the GSM and controlling electronics were working properly, as well as to calibrate critical system Rogowski coils used throughout the main discharge circuit. In this phase of testing, generator speed ranged from a minimum of 4,500 rpm to a maximum of 7,000 rpm with currents not exceeding the 230 kA level, which was dictated by the shorting hardware affixed to the end of the railgun. Fig. 6 presents some representative data for this phase of testing.

Several things are worth note in Fig. 6. First, along with simulated and experimental CPA terminal voltage and current there is a plot called 'syn_cpa_volts'. This 'synthetic' curve was produced using a combination of experimental data and

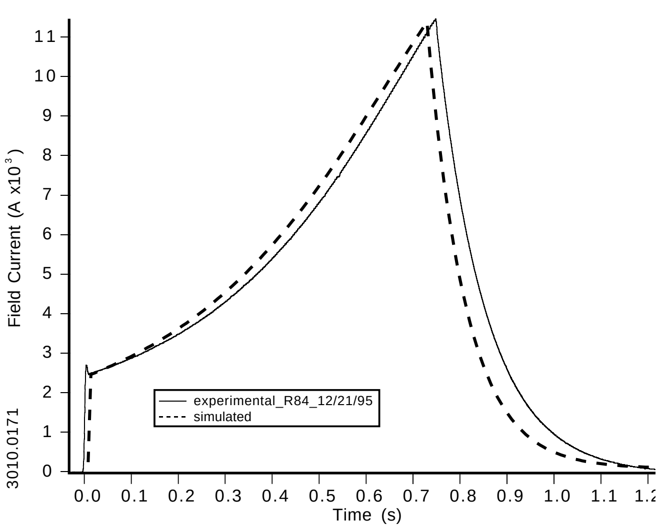

Fig. 5. Self-excitation plot

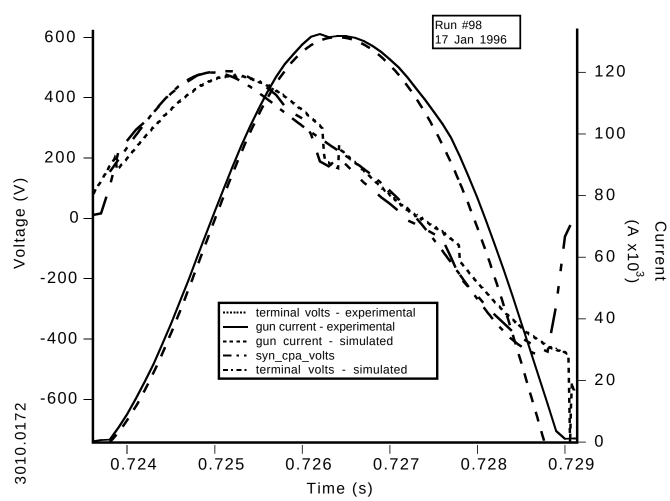

Fig. 6. Single shot dry fire

Table II. CCEMG single shot simulated and measured values

CCEMG LIVE FIRE Parameter	Shot #1 Simulated Value	Shot #1 Measured Value	Shot #2 Simulated Value	Shot #2 Measured Value	Shot #3 Simulated Value	Shot #3 Measured Value	Shot #4 Simulated Value	Shot #4 Measured Value	Shot #5 Simulated Value	Shot #5 Measured Value	Shot #6 Simulated Value	Shot #6 Measured Value
Excite Speed (rpm)	6,950	7,000	6,950	6,958	7,450	7,580	8,000	8,021	8,000	8,000	8,250	8,264
FIM Charge (kV)	2	2	2	2	2	2	2	2	2	2	3	3
Field Current (kA)	13.40	13.57	19.19	19.50	21.99	22.0	26.5	27.4	26.5	27.4	28.8	30.5
% Design Field (%)	54	54	77	78	88	88	106	110	106	110	115	122
Field Rise Time (s)	0.174	0.172	0.208	0.208	0.192	0.192	0.181	0.1946	0.181	0.195	0.150	0.160
Peak AC Voltage (V)	1,086	1,099	1,554	1,555	1,909	1910	2,471	2510	2,471	2,485	2,770	2,835
Discharge Speed (rpm)	6,855	6,858	6,745	6,753	7,214	7,251	7,697	7,607	7,697	7,653	7,912	7,772
ILP Mass (g)	183.2	183.2	183.2	183.2	135.3	135.3	148.4	148.4	165	163.3	155	155
Load Force (lbf)	3,100	3,100	3,000	n/a	3,100	3100	3,000	3,000	3,000	3,000	3,000	3,000
ILP Loaded Position (m)	0.0	0.0	1.41	1.41	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Fire Angle (°)	10	10	10	10	5	5	5	5	5	5	5	5
Volts @ Trigger (V)	193	182	320.6	299.01	166	166	213	221	213	221	238	219
Peak Gun Current (kA)	315.3	297	269	269	501	495.67	601.8	598.5	605.8	598.5	652.7	660.4
ILP Velocity (m/s)	-0-	0	410	385	1,322	1,299	1,662	1,729	1,539	1,530	1,864	1,900
Gun Pulse Width (ms)	3.4	3.4	3.448	3.4	3.35	3.3	2.9	2.97	3.02	2.97	2.7	2.78
Exit Time (ms)	no exit	n/a	3.5	3.4	3.35+	3.3	2.9	2.97	3.02	2.97	2.7	2.78
Muzzle Current (kA)	0.0	0	0.0	0	0.0	0.0	111	125	61	68	177	212

simulated or known impedances to validate the simulation code. Specifically,

$$\text{syn\_cpa\_volts} = L*di/dt + R*i(t)$$

where

L = simulated total load inductance
R = simulated total load resistance
di/dt = experimental current (derivative)
$i(t)$ = experimental current

This method is used extensively during commissioning new CPA systems to fine tune the simulator code. Secondly, this curve is also useful for verifying the calibration of the main current Rogowski coil used in the CCEMG system. Finally, Fig. 6 also indicated the presence of an unwanted bridge rectify pulse, which is indicated by the square notches in the voltage traces around 0.726 ms. The FFCM was corrected to avoid this. In all, 21 runs were completed during the dry fire test phase, ultimately preparing the system to begin live fire testing.

Single Shot Testing - Live Fire

Live fire testing was intended to bring the pulse power system incrementally up to full duty over a minimum series of shots. To realize this goal, minor changes to the performance simulation code and careful analysis of the data at each test interval was required. In all six shots were performed, which incrementally brought the compulsator up to full rated performance for an 8,250 rpm discharge, given the added impedance of the extended laboratory bus. Table II shows pertinent test results from each shot along with simulated predictions. Table III shows the incremental power level for the 6 shots performed. Tabulated is the CPA terminal power, field ac charging power and peak current, percent design field, and rotor speed. The CCEMG CPA has demonstrated well over 100% design field coil current.

Fig. 7 is a plot of gun current vs. time for the last single shot live fire test, along with simulated current. There is a

Table III. CCEMG single shot pulse power output demonstrated

Parameter	Rotor Speed (rpm)	Field Current (kA)	Percent Design Field (%)	Field AC Charging Power (MW)	CPA Terminal Power (MW)
Shot 1	7,000	13.57	54	13.5	20.8
Shot 2	7,000	19.50	78	30.6	127.3
Shot 3	7,500	22.0	88	41.9	204.4
Shot 4	8,000	27.4	110	69.6	896.3
Shot 5	8,000	27.4	110	69.6	754.2
Shot 6	8,250	30.5	122	89.0	962.2

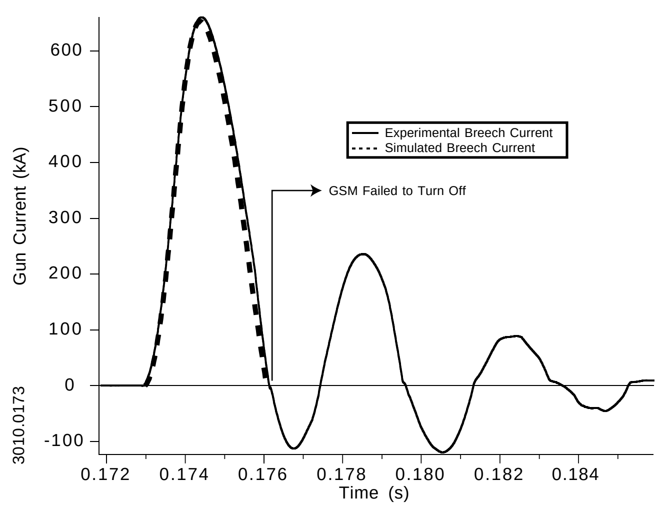

Fig. 7. Gun current experimental and simulated, shot #6

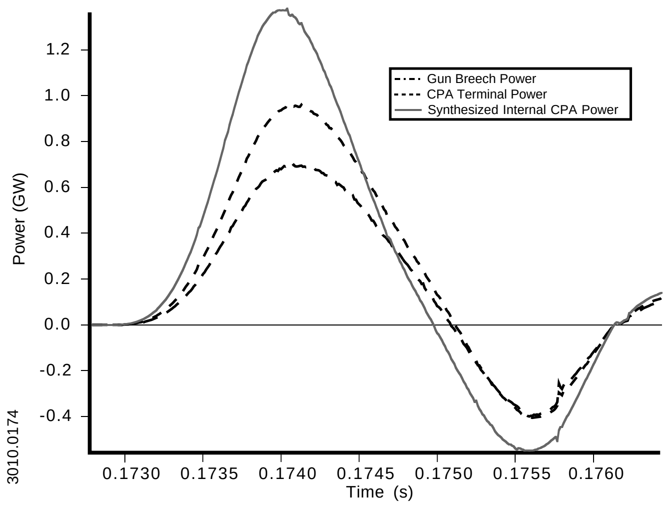

Fig. 8. Shot #6 power (breech, gun terminal)

Table IV. CCEMG demonstrated pulse power performance

Parameter	**Units**	**Original Design Goal**	**Demonstrated Value**
CPA Weight	kg	<2,275	2,046
CPA Volume	m^3	<1	0.875
FCC Weight	kg	<225	200
FCC Volume	m^3	<.15	0.125
GSM Weight	kg	<225	215
GSM Volume	m^3	<.15	0.15
PPS Weight	kg	<2,727	2,461
PPS Volume	m^3	<1.25	1.15
Rotor Speed	rpm	12,000	8,250
Peak Field Current	kA	25.0	30.5
Peak AC Volts‡	V	2,613	2,835
CPA Terminal Power‡	GW	1.035	0.965
CPA Terminal Energy‡	MJ	1.15	1.02
Gun Breech Power‡	MW	790	698
Gun Breech Energy‡	kJ	673	572
Muzzle Energy‡	kJ	318	280

(‡ equivalent design values taken from 8,250 rpm simulations)

good match between the simulation and the experimental data for the main current pulse, but there were actually a few more current pulses following the main gun pulse. This was caused by a bad SCR in the GSM which failed to turn off following the main gun pulse. It did not appear to be a dV/dt type failure, however as of this writing, investigations were underway as to the cause. Fortunately, the explosive opening switch interrupted the current flow out of the generator and no further damage was seen in the system.

Fig. 8 shows a plot of gun breech power, CPA terminal power, and synthesized internal CPA power vs. time. Once again, the synthesized curve is derived using known internal impedances of the CPA combined with experimental current and its derivative. As the reader will notice in the plot, the power flow changes signs during the railgun event. This does in fact result in a net increase in the rotor speed as the railgun delivers its stored inductive energy back to the generator within the shot period.

And finally, Table IV summarizes the demonstrated to-date pulse power system parameters vs. what was originally specified for the CCEMG system. Clearly, the CCEMG system is on target to meet TD goals as of this writing.

CONCLUSIONS

The CCEMG system has successfully completed single shot live fire commissioning at UT-CEM. Following the writing of this paper, the system will be prepared for multi-shot operational mode. The entire pulsed power system has performed extremely well so far with the CPA developing power per original predictions. The field winding has been successfully operated to 122% design value; this in an effort to circumvent artificially high gun output bus impedance due to the laboratory setup. With still multi-shot testing to go, the system has demonstrated the viability of electric gun systems already, and we hope to accomplish a great deal more during subsequent testing.

ACKNOWLEDGMENTS

The authors would like to recognize the many CEM-UT and UDLP engineers, technicians, and students that have worked long hours to make the CCEMG program a success. This effort is funded by the U.S. Army Armament Research Development and Engineering Center and the U.S. Marine Corps.

REFERENCES

[1] J.R. Kitzmiller, S.B. Pratap, T.A. Aanstoos, K.G. Cook, R.A. Kuenast, B.T. Murphy, and D.R. Perkins, "Optimization and critical design issues of the air core compulsator for the cannon caliber electromagnetic launcher system (CCEML)," *IEEE Transactions on Magnetics*, vol 31, no. 1, January 1995.

[2] J.H. Price, H.D. Yun, K.G. Cook, J.P. Kajs, H-P Liu, and M.D. Werst, "Discarding armature and barrel optimization for a cannon caliber electromagnetic launcher system," *IEEE Transactions on Magnetics*, vol 31, no. 1, January 1995.

[3] D.J. Wehrlen, R.A. Lee, and R.F. Thelen, "Power electronics and controls for air core compulsator," *IEEE Transactions on Magnetics*, vol 31, no. 1, January 1995.

[4] M.D. Werst, T.J. Hotz, J.R. Kitzmiller, C.E. Penney, and R.M. Telander, "Testing of the cannon caliber rapid fire railgun," submitted to the 8th EML Symposium, Baltimore, MD, April 1996.

[5] C.E. Penney and T.J. Hotz, "CCEMG switch testing," submitted to the 8th EML Symposium, Baltimore, MD, April 1996.

[6] B.T. Murphy, S.M. Manifold, and J.R. Kitzmiller, "Compulsator rotordynamics and suspension design," submitted to the 8th EML Symposium, Baltimore, MD, April 1996.