A COMPULSATOR-DRIVEN RAPID-FIRE EM GUN

S. B. Pratap, W. L. Bird, G. L. Godwin, and W. F. Weldon

Presented at the
2nd IEEE Symposium on
Electromagnetic Launch Technology
Boston, Massachusetts
October 11-14, 1983

Publication No. PR-16
Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

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Center for Electromechanics
The University of Texas at Austin
Austin, TX 78712

Summary

A compulsator-driven railgun is an attractive alternative to the homopolar generator-inductor-switch configuration, especially for repetitive duty. A conceptual design of a rapid-fire EM-gun system is presented. The generator is sized to accelerate a 0.08-kg projectile to 2 to 3 km/s at a 60 pulse-per-second repetition rate. Initial design parameters are discussed, and example current and velocity waveforms are given. The generator is discharged at the proper phase angle to provide a current zero just as the projectile exits the muzzle of the railgun.

Introduction

Although substantial progress has been made in the last few years, the electromagnetic (EM) railgun is in its infancy as a potential launch technology. A primary difficulty and the focus of a great amount of attention is the switching of the electrical current from the pulse compression inductor to the railgun. In the "conventional" single shot railgun circuit, the homopolar generator charges the inductor relatively slowly. Then at peak current the transfer switch opens to develop a high-voltage across the breech and transfers current into the railgun. In this process the transfer switch has to absorb and dissipate a part of the energy initially stored in the inductor.¹ The energy that must be absorbed by the switch is significant and makes this approach less attractive for use in a multishot burst mode.

The family of compensated pulsed alternators, or compulsators (Fig. 1), invented and under development by the Center for Electromechanics of The University of Texas at Austin,² presents an attractive alternative to dissipative arc switching for high-power, high-rate-of-fire EM guns. This type of device combines the functions of inertial energy storage, electrical voltage

generation and power conditioning into a single device. Because of the nature of the power conditioning, the need for an opening switch is eliminated.

The potential advantages of using a low impedance single-phase alternator is that by proper selection of the firing phase angle it is possible to obtain zero current just after the projectile exits the railgun. This reduces the electromagnetic signature (muzzle flash) and increases the efficiency, since the magnetic energy stored in the rails at the end of a shot is small. Alternatively, it is possible to select the firing angle to increase the projectile velocity from 2 to 3 km/s. However, the muzzle flash and EM signature is increased, since the rail current is approximately 500 kA at projectile exit.

In general, the compulsator is more massive than the homopolar generator, since it delivers a smaller fraction of the inertially-stored energy. Additional pulse compression is not required, however.

Under a contract sponsored by the Lawrence Livermore National Laboratory, a prototype compulsator was designed, fabricated, and tested at CEM-UT.³ This machine was designed to drive flashlamps for solid-state laser amplifiers, with a current pulse width between 500- μ s and 1-ms. Rapid-fire EM gun duty will require pulse widths of 2 to 3 ms, resulting in less severe mechanical stresses. Machines designed to drive EM guns will also operate at a lower voltage than flash lamp drivers. Therefore, the machine has a high probability of success. Based on more than five years experience in the design of compulsators, CEM-UT has prepared a program funded by DARPA/ARRADCOM to develop a prototype compulsator for a rapid fire EM gun test bed.

Conceptual Design of System

The rotor of this machine is fabricated using electrical sheet steel shrunk-fit onto a shaft. The armature winding made of Litz wire is wound in the air gap and bonded to the laminations using high-shear-strength epoxy resin. This design minimizes the inductance of the windings compared to a conventional approach with conductors embedded in slots. Banding is provided around the circumference to keep the interface between the epoxy and the laminations in compression at all times. Since the required pulse width is about 2 to 3 ms, passive compensation is adequate. A cylindrical copper shell is bonded in the bore of the stator to shield the solid poles from the transient armature flux. The laminated rotor is operated at tip speeds of 150 m/s.

The field coil is pulse-rated and is wound on solid poles on the stator. Conventional alternating current generators have the field coil rotating and the armature winding stationary. The advantage of the latter scheme is that slip rings and brushes are not required to tap the current in the armature and brushless excitation could be provided to the field coil. However, a rotating field coil implies a need for a rotating compensating shield. Because of the mechanical spin stresses, the shield must be made thicker. This would result in a 30- to 40-percent larger machine. In addition, the exciter would add to the length of the machine. Taking the above factors into consideration, a machine having a rotating armature and stationary field coil and shield has been selected for initial analysis. The relative performance merits of the two

Fig. 1. Cut-away view of engineering prototype compulsator pulsed alternator

Fig. 2. System schematic

schemes need to be determined before a final selection is made. A schematic of the system is shown in Fig. 2.

The system includes the prime mover, the exciter and the compensator as the power supply. The five barrels are fed with an autoloader. The autoloader would inject projectiles into the barrels at 200 to 400 m/s in order to reduce erosion on the rails and the projectile itself would act as a make-switch, eliminating the need for a separate make-switch.

The parameters for the proposed rapid fire gun test bed are as in Table 1.

Table 1. System Parameters

Parameter	Units	Nominal Value
Projectile Mass	kg	0.08
Projectile Velocity	km/s	2.0
Projectile Kinetic Energy	kJ	160.0
Repetition Rate	pps	60.0
Pulses/Burst	--	10.0
Barrel Length	m	3.0
Peak Current	kA	730.0
Acceleration Time	ms	3.0

A two-barrel gun with multiple closing switches will be fabricated for initial tests. This will provide the essential compensator performance information without requiring the high-speed autoloader. The projectiles will be fired at rest initially, and the switches will be fired sequentially over two revolutions of the generator. Figure 3 shows the circuit schematic for the system that will be made for the test bed.

Circuit Simulation Results

The circuit schematic of the system used for simulation studies is shown in Fig. 4. Also, the assumed parameters for the circuit simulation are listed in Table 2.

The machine has eight poles and an angular mechanical frequency of 58.8 Hz. This implies an electrical frequency of 235 Hz or a half period of 2.1 ms. The expression for internal voltage developed is $V = V_{max}$

Fig. 3. Schematic diagram - initial test configuration

Table 2. Circuit Parameters

Parameter	Units	Value
O.C. Voltage	kV	2.9
L_{gen}	μH	1.23
R_{arm}	$\mu \Omega$	262.0
R_{comp}	$\mu \Omega$	368.0
L_{gun} (useful)	$\mu H/m$	0.42
R_{gun}	$\mu \Omega/m$	267.2
Rotor Diameter	m	0.813
Rotor L/D Ratio	--	2.25
No. of Poles	--	8.0
Rotor Inertia	$kg \cdot m^2$	713.9
Rotor Speed	rpm	3,525.0

$\cos(\omega_e t + \phi)$, where ω_e is the electrical frequency and $V_{max} = N_{cp} B_{avg} l_a v$

where N_{cp} = number of conductors per pole,
 B_{avg} = average value of the magnetic field over one pole pitch,
 l_a = active length, and
 v = tip speed of the rotor.

The circuit simulation at present neglects the effect of magnetic saturation of the laminated rotor. For a single-shot operation, it is possible to adjust the armature current pulse width, so that eddy currents induced in the shield prevent the armature field from penetrating the solid poles. Other eddy currents induced in the copper shield and solid stator structure support the main field flux when the rotor iron saturates. However, armature reaction will have a greater effect for multiple-shot bursts, especially for high repetition rates. The best suitable repetition rate must therefore be arrived at experimentally. Additional electromagnetic analysis and an experimental test program will be required to determine the maximum repetition rate in the burst.

Results obtained from the circuit simulation are presented in Table 3. Two cases have been investigated: Case I, in which the armature current passes through zero as the projectile leaves the muzzle; and Case II, in which there is a residual current of about 500 kA in the circuit when the projectile exits.

Fig. 4. Circuit schematic

Current and velocity are plotted against time and position in the rail in Figs. 5 and 6. As can be seen in these plots, a higher projectile velocity can be obtained at the same efficiency if muzzle flash is acceptable.

Fig. 5. Current and velocity vs time

Fig. 6. Current and velocity vs length

Conceptual Design of the Generator

The cross-section of the machine with various

layers is shown in Fig. 7 along with the dimensions. With these dimensions, the rotor has an inertia of $713.9 \text{ kg}\cdot\text{m}^2$ and at 3,525 rpm stores 50 MJ.

Table 3. Performance Data

Parameter	Units	Case 1	Case 2
Projectile Mass	kg	0.08	0.08
Injected Velocity	m/s	200.0	200.0
Peak Current	kA	899.7	1,029.0
Time to Peak	ms	0.95	1.2
Velocity at Peak	m/s	1.173	1.172
Position at Peak	m	0.459	0.736
Time to Exit	ms	2.19	2.048
Muzzle Current	kA	7.0	504.0
Rail Friction Loss	kJ	42.62	82.37
Resistance Losses			
Armature	kJ	217.0	310.0
Shield	kJ	307.0	439.0
Bus	kJ	49.6	70.7
Rail	kJ	139.5	273.3
Arc	kJ	191.0	228.9
Residual Magnetic Energy	kJ	0.036	82.37
Change in Inertial Energy	MJ	1.15	2.23
Projectile Kinetic Energy	kJ	225.0	434.0
Discharge Efficiency	%	19.5	19.5
Armature Temperature Rise	°C	2.18	3.11
Shield Temperature Rise	°C	3.91	5.58

Fig. 7. Section of rapid fire compulsator

A developed view of the winding is shown in Fig. 8. It has eight conductors per pole which are obtained by lap-winding four complete turns around each spacer. The eight lap windings are connected in parallel at the slip rings. In order to make the end turns on edge on a tight radius, the conductors have two 90° barrel rolls, one on each side of the spacer at the beginning and end of the end turn. The conductors are made of $8 \times 19 \times 7 \times 25$ AWG Litz wire. The shield is machined to a final radial thickness of 0.95 cm.

The main field coil provides 80,000 At-per-pole excitation. The conductors of this coil may or may not be water cooled depending on the desired time interval between ten-round bursts. Engineering trade-offs will be made between field-coil power (and temperature rise) and stator mass before a final configuration is selected.

Initial stress calculations indicate that in order to ensure that the epoxy bond remains in compression at full rotor speed, the banding must provide a compressive radial pressure of at least 4 to 5 MPa (600 to 700 psi).

Fig. 8. Lap winding - 8 parallel

Future Work

(1) Shear stress on the epoxy bond due to thermal expansion of the copper shield will be calculated using the finite-element method

(2) The possibility of using 16 parallel circuits will be investigated. This configuration is more efficient (29% vs 19%), but requires an extra transposition and is therefore more difficult to manufacture.

Acknowledgments

This was supported by DARPA/ARRADCOM under Contract No. DAAK-10-82-0185.

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