IRON CORE COMPULSATORS FOR RAILGUN POWER SUPPLIES

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***Abstract*--Recent development efforts on compulsator based railgun power supplies have been focused on lightweight, composite, self-excited machines. However, operating experience with the iron-core (ferromagnetic) compulsator at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) has shown it to be extremely reliable and much more versatile than originally envisioned. Furthermore, recent experiments with high current solid state switches and studies of staged multiple compulsator discharges have made multiple compulsator installations attractive.**

For railgun installations where generator weight and volume are not primary concerns, multiple iron-core compulsators can provide a low cost, extremely versatile power supply. The design of such a system is presented, incorporating many of the most attractive features of advanced compulsator concepts. These include: direct connection to mechanical prime power, inherent power averaging, low jerk flat top current pulses producing high acceleration ratios, reclamation of the railgun magnetic energy with attendant elimination of muzzle arc, and rapid fire operation.

INTRODUCTION

When viewed from the perspective of power requirements, the simple railgun is demanding, but fairly straight-forward. Since the goal is generally to reach a desired velocity in a minimum barrel length, it is desirable to operate the accelerator at as high an acceleration as allowable and to maintain this acceleration as constant as possible. This maximum acceleration is generally determined by the design of the launch package as is the jerk or rate at which the acceleration can be varied. Given an acceleration profile determined by the tolerance of the launch package and the simple relationship between force, gun inductance gradient, and current;

$$F = 1/2L'I^2$$

the requirement for an ideal power supply is obvious (Fig. 1a). For a constant mass launch package, the current supplied to the railgun over the launch time must produce the maximum allowable acceleration at each point in time. In turn, the voltage required at the breech of the railgun to achieve this ideal acceleration profile is determined by the instantaneous impedance of the railgun circuit.

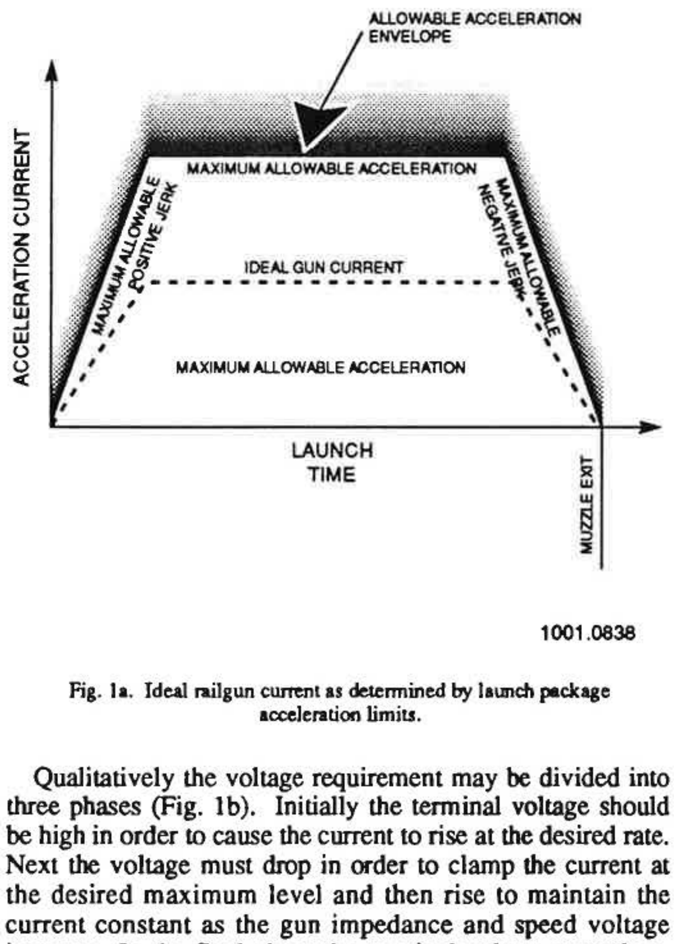

Fig. 1a. Ideal railgun current as determined by launch package acceleration limits.

Qualitatively the voltage requirement may be divided into three phases (Fig. 1b). Initially the terminal voltage should be high in order to cause the current to rise at the desired rate. Next the voltage must drop in order to clamp the current at the desired maximum level and then rise to maintain the current constant as the gun impedance and speed voltage increase. In the final phase the terminal voltage must drop, typically well below zero, in order to drive the current down at the desired rate and reach zero current as the launch package exits the muzzle. The current level at armature exit has been shown to have significant influence upon efficiency, rail damage, and dispersion as well as jerk. Of course this terminal voltage requirement can be complicated by

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electromagnetic diffusion in conductors and by time varying armature impedance, but the basic trends remain as indicated in Fig. 1.

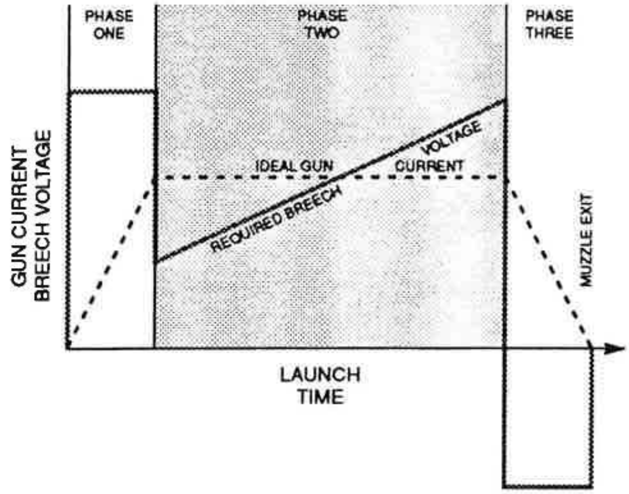

Fig. 1b. Power supply terminal voltage required to produce ideal railgun current.

COMPULSATOR OPERATIONAL MODES

The operational principles of the compulsator (CPA) have been described in detail previously [1]. Briefly, the actively compensated CPA produces sharply peaked current pulses of a millisecond or less in duration and its internal resistance is typically too high to drive a simple railgun because of the active compensating winding. It is well suited for more resistive loads such as electrothermal cartridges and flash lamps. The passively compensated CPA produces an essentially sinusoidal pulse and has been used successfully to drive railguns. The selective passively compensated CPA was developed specifically to meet the requirements of railguns [2] and comes very close to producing the ideal railgun current pulse shape (Fig. 2). It is important to recognize that since the CPA is an AC device, it inherently provides the voltage reversal required during phase three to shut the railgun current off without the need for counterpulse or commutation circuits.

All CPA's are capable of repetitive operation and although switching is not required as a part of the pulse shaping operation as it is with staged PFN's or inductors, some manner of switch may be required dependent upon the mode of operation chosen. Before discussing these operational modes it is necessary to review the CPA control variables affecting railgun performance. These are outlined in Table 1.

If the CPA is to be operated in the single shot mode, two options are available. In the "hot rail" mode the CPA output is permanently connected to the gun rails and no switch is required. The AC nature of the CPA means that a few hundred firing opportunities are available each second. To fire the gun, the launch package must be inserted into the gun breech so that the armature completes the connection between the rails between CPA pulses. Sensitivity of railgun performance to CPA "firing angle" means that the window for armature insertion is typically around 100 μs which is quite demanding. Alternatively a switch may be used to disconnect the rails from the CPA. This switch is only required to make the circuit at zero voltage and current, and to interrupt the circuit at zero current. Solid state switches have been used for this application at CEM. With the addition of a switch, the launch package can be loaded into the gun over an arbitrarily long period of time (with the switch open), then the switch is closed at a precise point in the CPA cycle to achieve the desired performance.

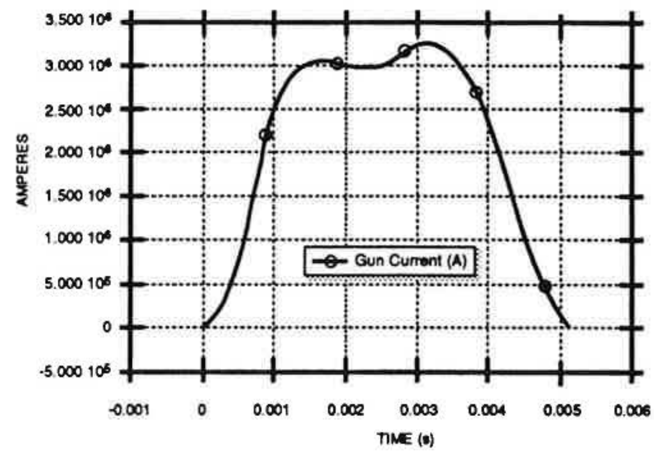

Fig. 2. Typical current pulse from a selective passive compulsator driving a railgun load.

TABLE 1. COMPULSATOR CONTROL VARIABLES EFFECTING RAILGUN PERFORMANCE

CPA Variable	Primary Effect on Performance
•Rotor speed	Pulse width
•Excitation level	Terminal voltage, delivered energy
•Firing angle	Delivered energy, pulse width

Either of the above options; hot rail or switched, can be used in repetitive fire operation as well, the desired rate of fire determining which is preferable. A hybrid mode of operation involves switched operation of a high L' electromagnetic injector with a hot rail railgun. This reduces the duty on the switch. Two new modes of operation are made possible by development of solid state switches. The first, involving rectification of a polyphase CPA output, is most relevant to lightweight composite CPA's. The second involving staged operation of multiple compulsators is discussed in the example below.

FERROMAGNETIC CPA OPTIONS

Recent emphasis on field mobile power supplies for railguns has led to the development of lightweight composite CPA's. However, many of the developments can be applied to ferromagnetic CPA's as well. The Iron Core Compulsator [3] was the first CPA built specifically to drive railguns. During the past six years it has been used to drive a variety of railguns, ranging from 15 to 30 mm bore size, in both single shot and repetitive fire modes and has demonstrated the CPA virtues of passive pulse shaping, flexibility of operation, inherent repetitive firing and zero muzzle arc. A modular ferromagnetic compulsator based on a modest extrapolation of the Iron Core CPA has been designed as a fixed (non mobile) railgun power supply. Such technology is thought to have application for laboratory and range testing of railguns as well as for fixed installations including naval and air defense. The proposed modular ferromagnetic CPA is compared to the existing Iron Core CPA in Table 2.

TABLE 2. COMPARISON OF EXISTING IRON CORE COMPULSATOR WITH PROPOSED MODULAR COMPULSATOR

	Iron core compulsator	Proposed modular compulsator
Outside diameter (m)	1.18	1.36
Overall length (m)	1.50	1.50
Rotor diameter (m)	0.80	0.94
Number of poles	6	6
Conductors/pole	8	20
Operating speed (rpm)	4,800	4,064
Open circuit voltage (kV)	2	7
Peak current (kA)	950	1,700
Pulse width (ms)	2.0	2.4
Compensation	passive	passive
Pulse shape	sinusoidal	flat-top
Stored energy (MJ)	38	72
Energy/pulse (MJ)	1.3	8.9
Pulses stored	10	4
Machine mass (tonne)	12	17

A single modular compulsator offers useful railgun performance as shown in figure 3 for 10, 8, and 5 m barrel lengths. However, it is the growth potential represented by the ability to couple multiple modular CPA's using solid state switches that makes the concept so attractive. Fig. 4 shows the performance for four machines coupled together while Fig. 5 compares the resulting pulse discharge for a single modular CPA discharge and a staged discharge of four modules. Table 3 lists the projectile energy available from multiple CPA installations.

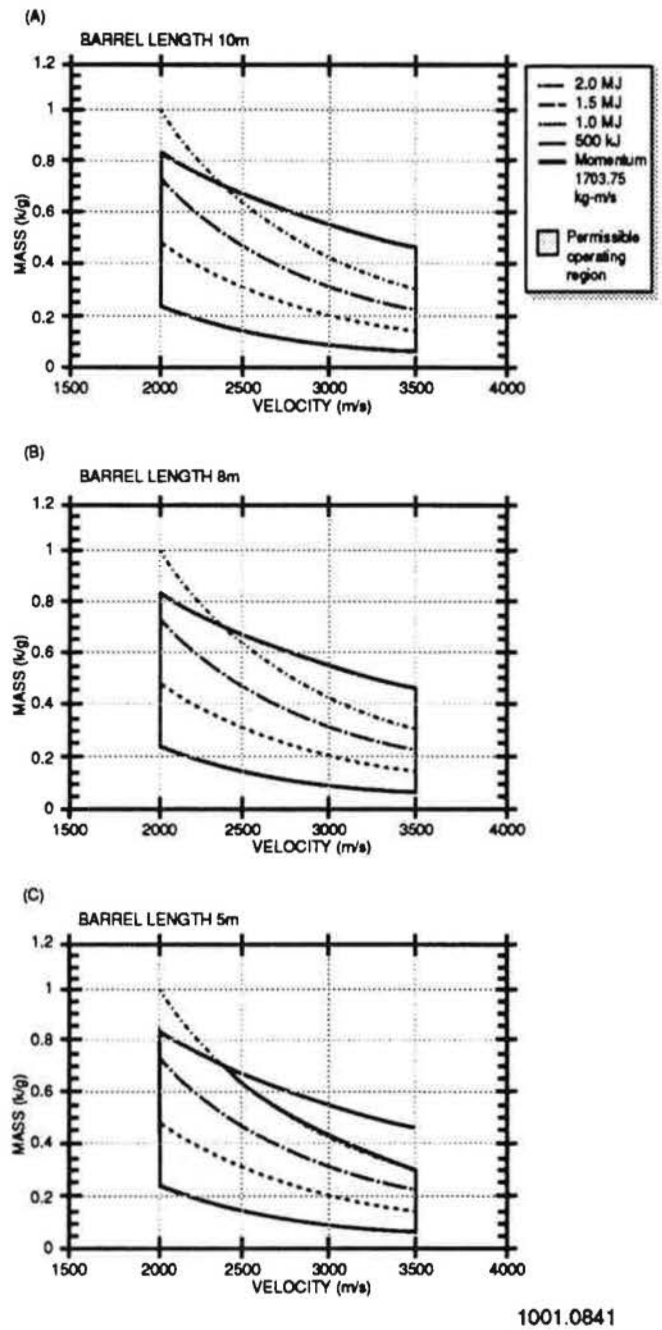

Fig. 3. Performance of a single modular compulsator with sinusoidal pulse.

The proposed modular CPA offers the advantages of simple, reliable rotating electrical machinery to railgun experimenters and to fixed weapon installations. For the first time it makes the advantages of low jerk, high acceleration ratio, zero muzzle arc, and inherently repetitive operation available at minimum cost to experimenters and integrators. Furthermore, it offers the ability to grow from a single CPA installation to multiple staged units while actually increasing the operational flexibility of the single unit.

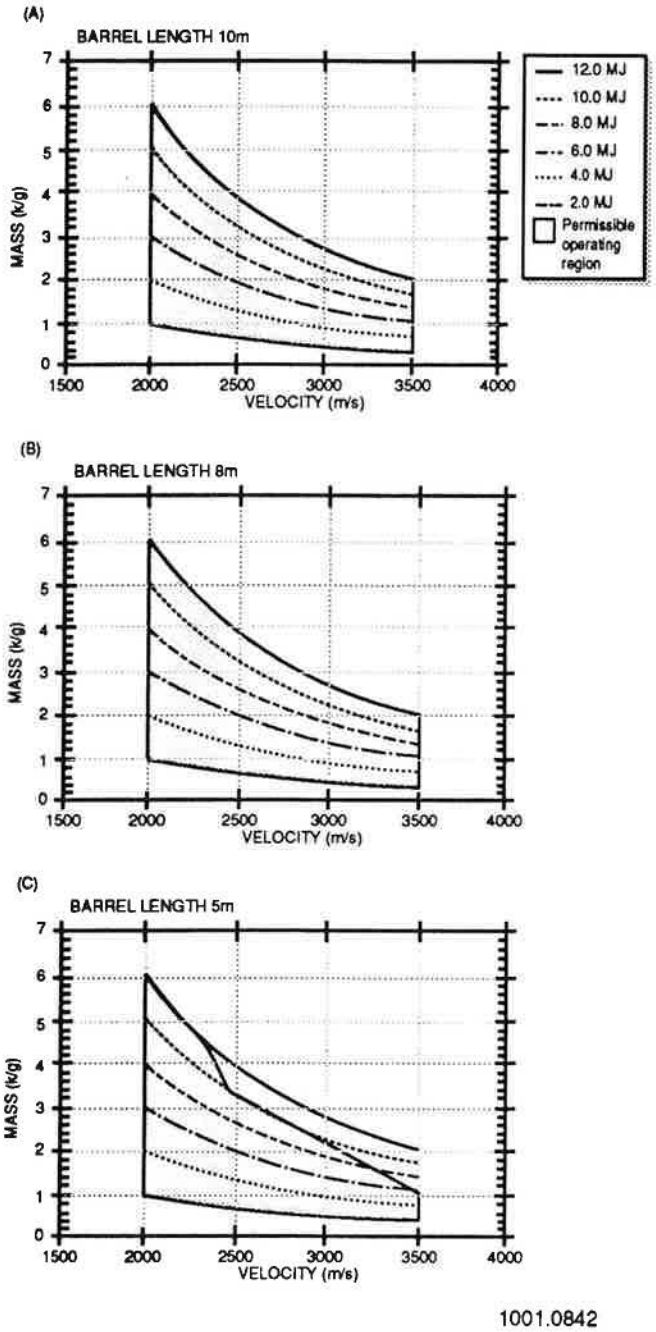

Fig. 4. Performance of system of four modular compulsators with sinusoidal pulses.

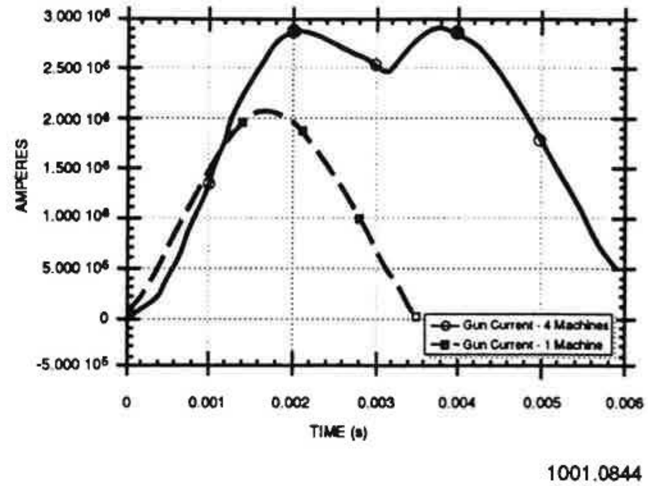

Fig. 5. Comparison of gun current with a single modular machine discharge and a four machine staged discharge.

TABLE 3. PERFORMANCE OF VARIOUS COMBINATIONS OF MODULAR MACHINES

No. of Modular Machines	Launch Package Muzzle Energy (MJ)
1	2
2	5.5
4	12
6	18

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