A RAPID FIRE, COMPULSATOR-DRIVEN RAILGUN SYSTEM

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Abstract - It is becoming clear that compensated pulsed alternators (compulsators) are the preferred power supply for rapid-fire railgun systems. High efficiencies, inherently high repetition rates, and the elimination of high current opening switches are the primary advantages of compulsator-driven systems. The benefits and capabilities of these systems will be demonstrated in a project which is currently in the final stages of fabrication. The goals of this project are to accelerate a burst of ten, 80-g projectiles to 2 km/s at a 60 Hz rate of fire. Details of the compulsator design, the design, fabrication, and testing of system components, and proposed operation are presented.

INTRODUCTION

In the simplest configuration, compulsators are low-impedance, single-phase alternators which are designed for high currents. The compulsator combines the functions of inertial energy storage, voltage generation, and power conditioning in one machine. Compulsators can supply high current pulses at high frequencies. Pulse widths from 500 µs to several ms are readily obtainable. Since the voltage is sinusoidal in nature, proper selection of the firing angle will result in a current zero as, or just after the projectile exits the railgun. This feature extends the life of the gun, minimizes the noisy EM fields generated by a muzzle flash, and leads to high efficiency since very little energy is trapped in magnetic fields.

The compulsator concept was conceived at the Center for Electromechanics of The University of Texas at Austin (CEM-UT) and patented in 1978. Also in 1978, CEM-UT designed, fabricated, and tested an engineering prototype compulsator which successfully proved the theory of operation. The prototype compulsator delivered 130-kJ per pulse to a xenon flashlamp load at a peak power of 145 MW. This machine incorporated active compensation, which implies a variable armature inductance, and is well suited for supplying 500 µs to 1 ms pulse widths.

For many railgun applications, including the project currently being fabricated, a longer pulse is required. Passive compensation in the form of a high conductivity shield will result in a fixed armature inductance which is small. The passive machine has a pulse width which is almost equal to the half time period of the open circuit voltage. This configuration is suitable for pulse widths in the 1-ms to 5-ms range. Several other advantages are gained if passive compensation is incorporated in a rotating field configuration. Since the armature winding is stationary, it is not subjected to rotating stresses, vibration, and growth, and a high current brush mechanism is not required. The rotor of the machine need not be laminated, and can therefore operate at a higher tip speed. Also, the ferromagnetic material is more fully utilized, resulting in a much smaller machine.

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SYSTEM DESIGN

The rapid-fire railgun system is shown in Fig. 1. The compulsator is a horizontal shaft, six pole, rotating field machine. A 68 turn-per-pole field winding is assembled on the solid 4340 alloy steel rotor. A unique winding technique allows all 406 turns of the winding to be connected in series, reducing the variation of flux density among the six poles. Passive compensation is provided by a 7050 alloy aluminum shield. The shield is attached to the rotor by a combination of a thermal shrink fit and epoxy bonding. The armature winding is composed of six lap wound coils of 7 x 7 x 16 x #24 AWG copper Litz wire which are epoxy bonded to the laminated steel stator. The six coils are connected in parallel. Three pairs of armature terminals penetrate the stainless steel endplates and are joined in the coaxial bus which feeds the railguns. Operating parameters of the system are shown 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	940.0
Acceleration time	ms	2.0

The compulsator-driven railgun system consists of several components. An operational schematic of the system is shown in Fig. 2.

The compulsator is connected directly to the 3-m railguns. Therefore, the projectile acts as the making switch, initiating the discharge pulse. Due to thermal considerations, three railguns will be used. During normal operation, the compulsator will be hydraulically motored to the design speed of 4700 rpm, requiring approximately 5 minutes. Hydraulic motors are used because of their ability to withstand the high decelerations encountered during a discharge.

Once at speed, the field coil brush mechanism is pneumatically actuated and the 750 kW dc field supply is energized. The excitation flux requires approximately 1 s to build to its full value due to eddy currents in the solid rotor and shield. At this time, the compulsator is generating a 2 kV, 235 Hz open circuit voltage which the open bore of the railgun must stand off.

The high-speed digital control system, which has been monitoring rotor position and open circuit voltage, signals the autoloading mechanism to load a projectile into the injector. After the loading is accomplished, the controller initiates the injector discharge pulse by triggering the ignitron. Current rises in the injector railgun, driving the projectile with its sliding contact armature to approximately 200 m/s in 0.9 ms. The injector pulse will have a peak current of 260 kA, drawing 40 kJ from the rotor. The projectile leaves the injector, breaking contact with

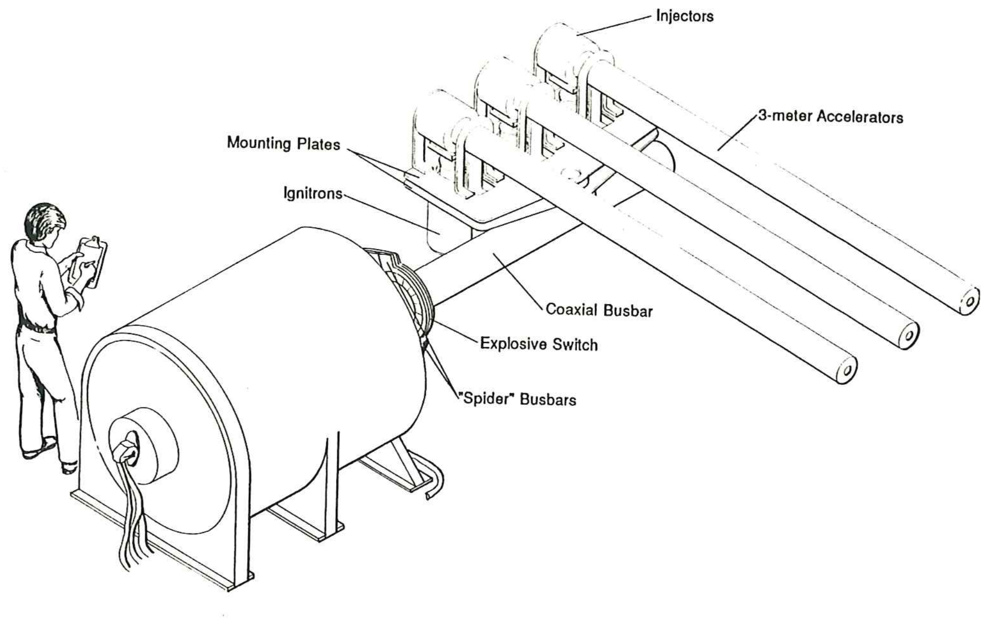

Fig. 1. Rapid-fire railgun system.

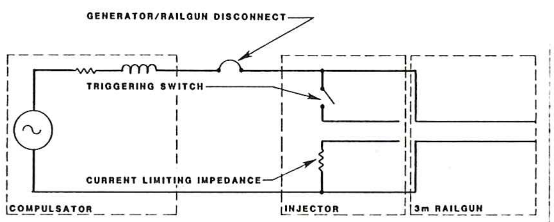

Fig. 2. Schematic of the compulsator-driven railgun system.

the rails at a naturally occurring current zero, and travels 1.6 cm (0.6 in.) through an insulated bore connecting the injector to the 3-m gun. As the armature makes contact with the rails the main current pulse will be initiated. It was originally proposed that a light armature, which will vaporize at this point, be used. However, for the velocities proposed, a sliding contact armature may be beneficial and will be investigated. The projectile is accelerated to 2 km/s by the 940 kA peak, 2.2 ms pulse and leaves the railgun at a natural current zero.

During the entire process, the controller monitors terminal voltage, injector current, and current in the main pulse. If the parameters appear normal and the timing sequence correct, the controller will continue the process by loading another projectile into the injector barrel. Small deviations in timing due to variation in injector performance or changes in rotor speed can be corrected by the controller by adjusting the time at which the ignitron is triggered with respect to the open circuit voltage. When the tenth shot is completed, the controller will shut off the field supply and signal the motoring system to dynamically brake the rotor, concluding the experiment.

Disconnect Switch

In the course of railgun operation, the possibility of a short circuit exists both in the gun itself due to a jammed projectile, or in any part of the busbars due to a breakdown in insulation. The result of a short circuit would be a continuous 235 Hz, 1.0-MA machine output which would result in overheating and failure of the compulsator armature windings. To protect the compulsator from thermal failure in the event of a short, an automatic circuit opening switch has been built into the busbar system.

The requirements of the opening switch are as follows:

- rapid operation to minimize the number of sequential current pulses
- location as close to the output terminals as possible
- low electrical resistance and inductance
- operation must be positive

Taking these parameters into account, it was decided that an explosive opening switch would offer the best results.

A test fixture was designed and fabricated to determine the conductor material and thickness and the required explosive. The resultant switch design is shown in Fig. 3. The circular geometry is easily connected to the coaxial bus. Aluminum alloy 5052 H32 was chosen as the conductive element. Twenty of the aluminum conductors, 0.16 cm (0.063 in.) thick are connected in parallel and can be opened using 15 grain primer cord. The conductors are notched over the explosive to produce a stress concentration which facilitates ease of opening. Again, it should be

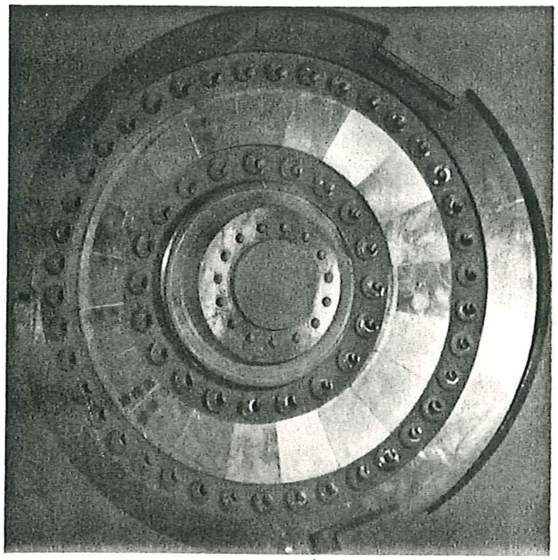

Fig. 3. Disconnect switch.

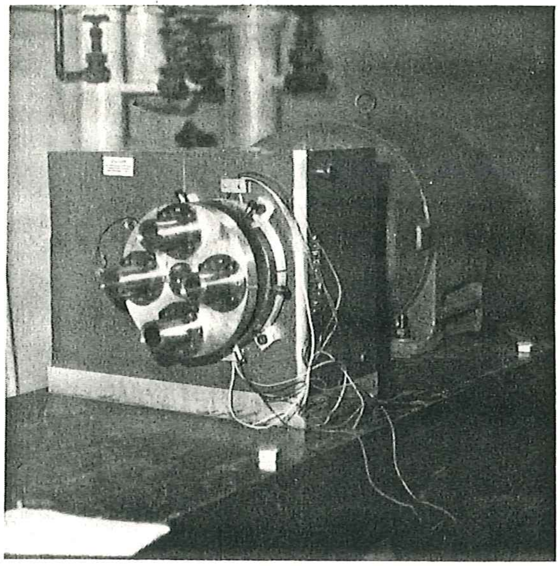

Fig. 4. Autoloading mechanism.

noted that the switch will not be used during normal operation of the system, but only in the event of a jammed projectile or a voltage flashover in the railgun.

Autoloader

The autoloading mechanism performs the same function as an autoloader in any conventional rapid-fire gun. It is a mechanism which drives a clip or belt of projectiles, and loads them into the injector at a rapid rate. The speed and reliability of this mechanism is one of the limiting factors of the system repetition rate. Since three autoloader-injector railguns are to be used sequentially to accomplish the project goals, each autoloader must operate at 20 Hz. In an EM gun system, the breech of the gun can be left open during the shot, therefore a locking bolt mechanism is not required. However, the loading mechanism will be subjected to a blast of hot gas and molten debris which is the result of the armature vaporizing.

Several attempts at an autoloading mechanism have been tried, with varying degrees of success. The first attempt incorporated a simple spring-driven clip with projectiles being driven into the injector by a solenoid. This mechanism had insufficient stiffness and mechanical integrity to withstand the pressure blast formed when the injector was energized. Also, the solenoid actuation time was longer than desired and it did not provide sufficient force to insure that the projectile was properly loaded after some rail erosion had occurred.

A later design, shown in Fig. 4., is very promising and seems to satisfy all of the requirements. The design is centered around a rotary index mechanism which converts continuous rotary input, supplied by an electric motor, to a stepped rotary output. The output shaft holds four small barrels which each contain a projectile and a very small explosive charge. The explosive is a self-contained device which is electrically triggered. These devices were originally developed as torpedo ignitors and have a very clean burning explosive. A segmented slip ring enables each ignitor to be separately triggered by the controller. The output shaft of the indexor dwells in the stopped position for 17 ms and requires 33 ms to rotate to the next position and stop, corresponding to a 20 Hz rate. A series of interlocking cams inside the indexor insure that the stopped position of the mechanism is very repeatable.

In a typical firing sequence, the ignitor is triggered several ms after it has come to a stop. The explosion accelerates the projectile, driving it into the injector. The projectile is traveling at 35 m/s which gives it sufficient energy to overcome frictional losses as it enters. Approximately 5 ms are required for loading the projectile into the injector. At a time corresponding to the next appropriate firing angle of the compulsator, the controller triggers the ignitron, initiating the injector pulse. The injector pulse and the main acceleration pulse are over in about 3 ms. During this time, the autoloader is subjected to a severe pressure blast from the railgun, but is significantly robust to survive undamaged. The autoloader remains in the stopped position for 9 ms after the shot before accelerating to the next firing position. The entire process is then repeated on 50 ms intervals.

The mechanism has been tested in a four shot mode into a velocity measurement device which closely approximated the bore of the injector. The test verified the performance of the device and confirmed the timing sequence. With minor modification, this concept can be expanded to serve as a continuous duty loading system. The ignitors are very small and can be incorporated into the projectile. The autoloader barrels would be modified to accept a projectile which is passed off from a bulk handling device, resulting in a loading system for EM guns which will function in a field portable weapon system.

Injector

The initiation of the discharge pulse must be very accurately timed in order for the projectile to exit the gun at a current zero. A 100 μs variance in the pulse initiation is the maximum allowed if the muzzle

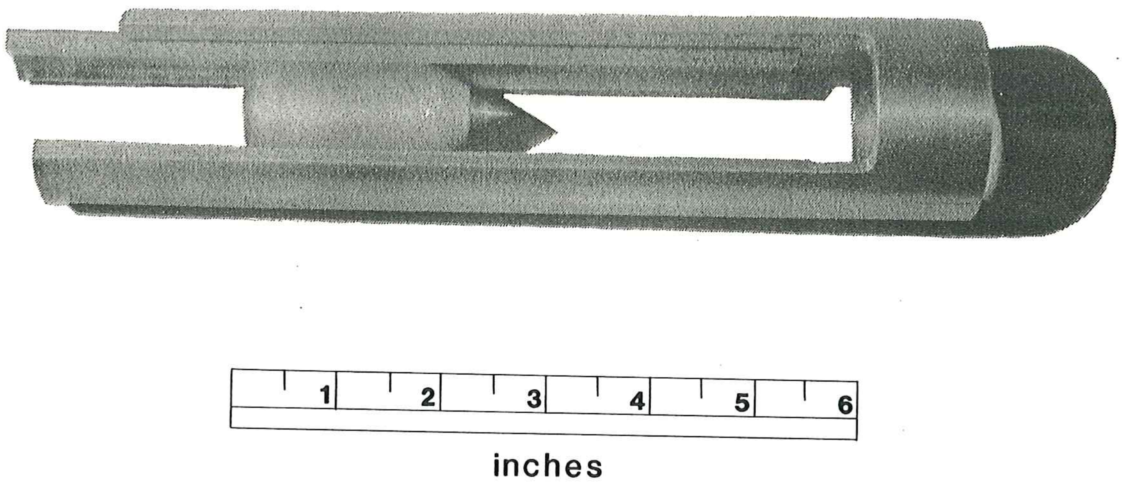

Fig. 5. Augmented-turn railgun injector - rails and 80-g projectile.

current is to be kept to an acceptable level. The injector must therefore accelerate the projectile from rest to 200 m/s and deliver it to the 3-m gun in a very repeatable manner. It must also maintain the correct phase relationship to the open circuit voltage of the compulsator as the machine frequency is changing. It is further desirable that this phase relationship (which determines the firing angle) can be varied independently for each shot to maintain a constant pulse width. The combination of these requirements makes the use for conventional solenoid actuated mechanical accelerators or light gas accelerators unfeasible. An electromagnetic injector, driven by the compulsator, will apparently satisfy these requirements.

The electromagnetic injector is actually a short railgun, which incorporates an augmented turn and steel laminations to produce a high inductance gradient. A high inductance gradient is desirable in the case of the injector to reduce the current level and the gun length required. The injector, shown in Fig. 5 above, has been built and tested. Using capicator bank power supplies, the injector has accelerated 80-g projectiles to 320 m/s. The injector requires a 300 kA, 1.2 ms pulse, and has a 15 cm (6.0 in.) barrel. Injector performance, measured over a number of tests has been very predictable and repeatable.

Railgun

Initial studies indicated that bulk melting of the uncooled rail surface would occur after four to five shots in a 2.5 cm (1.0 in.) bore gun at the design performance level. Based on this, three guns, connected in parallel and operating in sequence, will be fabricated. In addition to the difficult requirements normally encountered in EM guns, the rapid-fire gun must also remain in sufficiently good shape to refire without any reconditioning and stand off many cycles of open circuit generator voltage after the projectile exits the muzzle. This leads one to design a low voltage generator which contributed to the present 2 kV design.

The railgun will be similar to the CEM 1-m railgun which has performed successfully. The gun will be a round, 3.18 cm (1.25 in.) bore gun, utilizing copper rails and polycarbonate insulators. The rails and insulators fit tightly into a wound s-glass tube which is clamped in a four-piece, bolted-steel structure. The gun will be bolted to the injector, and the bores of the two guns will be finished together to ensure a smooth continuous bore.

CONCLUSION

CEM-UT has designed and is in the final stages of fabrication of a rapid-fire compulsator-driven railgun system. Testing of the system will begin in the spring of 1986. This project is significant to the future of EM weapon systems in that it will prove the feasibility of compulsator-driven railguns in a switchless mode and provide insight to the problems of rapid-fire operation.

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