Alternator Power Conditioning for Launchers

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ABSTRACT

A high-energy pulse-discharge is needed to drive an electromagnetic (EM) or an electro-thermal-chemical (ETC) launcher. Various pulse power generators have been examined and used. Capacitor-based power supplies are convenient for laboratory launchers, but supplies based on rotating machines—alternators and homopolar generators—are generally more weight efficient and practical for storing, generating and shaping pulses for multi-shot, fieldable launchers. Alternators are the most flexible of the rotating machines, are better matched to the variable impedance of the launcher, and avoid the use of opening switches which are difficult to implement for repetitive and reliable operation. Also, a single pulse generator can be used to power several lethality and survivability platforms.

Several alternator configurations are possible, each involving different pole geometries, numbers of poles and output phases. These configurations are in turn associated with a power converter system. The switch requirements can be met for small-caliber EM railguns and for ETC guns of all caliber by near-term silicon thyristors. For large caliber EM railguns, triggered vacuum switches are viable, although they may have to be augmented with diodes or other devices to ensure their recovery after each cycle. In the long term, thyristors based on silicon carbide offer the most promise for all applications because they can operate at 3 to 5 times the current density and electric field intensity of silicon devices.

1. INTRODUCTION

The launcher applications of current interest to the military are guns of medium and large caliber (40 mm to 120 mm). Depending on whether the application is anti-armor, air defense or artillery, the projectile launch energy can be up to about 1 MJ for medium- or cannon-caliber guns but may be between 10 MJ and 30 MJ for large-caliber guns. In order to be competitive with conventional guns, electric guns must be capable of firing at least a few rounds in a burst-fire mode using energy that is stored and immediately available in the system. Also, for many applications, especially anti-armor, there is an advantage to achieving launch velocities up to 2.5 to 3.0 km/s. Electric launchers under consideration are ETC guns and the EM railguns. ETC guns derive most of their launch energy (typically >75%) from a chemical propellant. Electrical energy is used only as an igniter to tailor the acceleration profile of the projectile or to modestly

augment the propellant pressure in the ETC gun. Typically, ETC guns require a pulse power system capable of delivering from 300 to 500 kJ (ETC igniter concept) to 3 to 5 MJ (ETC gun) for 1 to 4 ms at 12 to 18 kV and up to 50 kA. In contrast, the EM railgun will require 20 to 60 MJ delivered to the breech at up to 7 kV, and up to 4 MA for about 5 ms. Furthermore, the requirement to store a few shots for rapid or immediate fire means that the pulse power system has to store up to 200 MJ.

The pulse power and energy storage technologies available are capacitor-based PFN, rotating machines, inductors, batteries and magneto-cumulative generators. Capacitor-based PFN are capable of storing about 2 MJ/m³ or 1 MJ/ton. They can satisfy the requirements for the ETC-igniter power systems, and possibly, for some ETC gun systems because power supplies that weigh no more than a few tons are compatible with some ground-mobile platforms. Present capacitor-based power supplies do not meet the storage density requirements for other electric guns. The state-of-the-art for capacitors that employ PVDF film dielectric is about 7 MJ/m³. The other power supplies that are mentioned above can satisfy the energy density requirement. Rotating machines, even with conductors embedded in composite rotors which limit the tip speeds to about 600 m/s, can achieve stored energy densities of 135 MJ/m³. Furthermore, alternator designs have been proposed that can satisfy the power delivery requirement.

Although other types of power supplies can store energy at even higher density than alternators, these supplies are limited by their inability to provide the power levels and voltages (for batteries and homopolar generators), by the difficulty of obtaining fast reliable opening switches (for homopolar generators and inductors) or by the technical immaturity for specific powers and pulse durations of interest (e.g., for magnetocumulative generators) [1,2].

2. PULSE ALTERNATOR DESIGN

Continuous-duty alternators have operated reliably in the utility industry for many years. They operate at powers of interest (1500 MW) and at voltages well in excess of those needed for electric guns. However, they do not satisfy the EM gun systems' weight and volume constraints. In addition, they do not properly match the variable load characteristics of a railgun. For the large caliber electric gun application, two types of alternator have been designed: a compensated pulse alternator (CPA) [3] by Center for Electromechanics at The

University of Texas at Austin (UT-CEM) and the Pulsed Disk Alternator (PDA) [4] by Kaman Electromagnetics Corporation (KEC). The CPA has a drum rotor and the PDA features a disk rotor. Despite the different rotor topologies, some of the basic features of the machines are similar. They are both air-core, rotating-field machines, they both incorporate composite materials in the rotor and the rotors in both machines operate at high speed to achieve the required energy densities. A sub-scale version of the CPA is currently under test.

A number of other features are incorporated in the designs in order to provide the power and energy within the weight budgets. The first of these features is the ability to generate magnetic induction of about 3.5 T at the rotor field windings on account of the high strength of the composite structure. This is higher than is possible in iron-core machines but carries with it the burden of having magnetic energy in the field windings that is a substantial fraction of that provided to the gun. Hence there is a requirement that the field coils be self excited rather than driven from an external power supply. A small capacitor is used to provide a field sufficient for a self-excitation operation from the armature output. The self-excitation principle is well-known and has been demonstrated on other machines [5]. With proper design, the field coil currents can be lower than 200 kA and charging times can be as low as tens of milliseconds, thereby minimizing ohmic losses provided that the field energy is recovered immediately after each shot.

A direct-current input is essential for an efficient breech-fed railgun operation, as it is for self-excitation of the field coils. The output converter on the alternator must therefore rectify the armature output into a 5 ms gun pulse from a train of sub-pulses that are generated each time a field pole passes an individual armature winding. In this way, the pulse length can be decoupled from the pole-passage time which is governed by the rotor diameter and rotation speed. Of particular importance is that a multipole, multiphase system is possible and this enables the designer to minimize the armature self-inductance and stray fields. In contrast to earlier designs [6], the multipole, multiphase design promotes higher overall efficiency and structures with lower mass.

It is possible to incorporate a separate compensating winding in drum-type machines. A compensation winding reduces the output impedance of the machine and reduces voltage spikes. However, there is a penalty: Compensation windings take up space between the field and armature coils and so decrease the magnetic coupling and overall power delivery capability. The final trade-off depends on a specific design and is difficult to make for the general case.

3. DESIGN DRIVERS FOR CONVERTER CIRCUITS

The move toward high-speed multiphase, multipole alternators has had a significant effect on the design of the power conversion equipment. These types of alternators tend to run at very high peak power and relatively high frequency. In addition, the need for flexible phase control and stored magnetic energy recovery limits the

possible choices of devices to controllable, symmetric devices (or modules made up of opposite asymmetric devices) that recover voltage standoff following current zero. Both of these developments have increased the electrical stresses applied to devices used in power converters, and in some cases, disqualified devices from consideration for use because they cannot recover voltage standoff capability before phase voltage is reapplied. The ranges of peak electrical operating stresses and other operating parameters that might be seen in power converters for electric guns in the 10^1 to 10^2 MJ range are shown in table 1, and a typical power system is illustrated in figure 1. Examination of the figure and the table reveals that if conventional switching devices are used, then the design of the power conversion equipment will be driven by symmetric voltage rating and the desire to avoid thermal runaway within a single device. Both of these requirements are due to the very fast current rise and fall times seen in present day electric gun power systems. Therefore, a designer will first consider the use of high voltage devices that can turn on and off quickly. However, these requirements tend to be mutually unattainable in most off-the-shelf devices that operate at power levels sufficient to keep parts counts and converter size to manageable levels.

Table 1. Typical range of operating parameters for an electric gun power converter.

Parameter	Range	Unit
Current	0.1 — 5	MA
Action	10^{-1} — 10^3	MA ² ·s
V_{sym}	2 — 20	kV
di/dt_{on}	2 — 20	kA/μs
di/dt_{off}	2 — 20	kA/μs
t_q (min)	700 — 100	μs
Number of phases	2 — 6	--
Converter Types	Full-wave, Half-wave, bi-directional	--

Figure 1. Typical EML power conversion system

4. SILICON DEVICES

If a semiconductor switch is used as the switching element in an electric gun power converter, then it is likely to be a SCR. The very high peak operating power and the need for reverse voltage recovery and stand-off generally preclude the use of IGBT, GTO, MCT or any thyristor that is asymmetric. While these devices may operate at very high switching speeds, they usually have low action capacity or low voltage stand off. Asymmetric devices require the use of a reverse recovery element. The use of this element generally means that the converter mass will double because each phase control device must usually be paired with a recovering device.

The problem with high-power SCR that are rated at high voltage is their switching speed. High voltage SCR tend to have limited critical di/dt ratings and long recovery times (t_{rr}). Faster SCR tend to be rated for lower voltage and action. Table 2 shows the ratings of two off-the-shelf SCR. One is a large diameter, high voltage device manufactured by Silicon Power Corporation (SPCO). The other is a fast recovery device that is sold by Powerex. The SPCO device is the largest diameter, highest voltage device in their catalog [7]. The Powerex device is one of the higher voltage large-diameter fast recovery devices in their catalog [8].

Faster, lower voltage devices tend to lose in the design trade analyses because additional series elements are required. High voltage SCR tend to win but they have recovery times that are too long. However, the converter design based on high voltage devices tends to be limited by the allowable critical rate of current rise to prevent thermal runaway. As a result, the extra action capability provided by their larger diameter is not used and the designs tend to represent an inefficient use of silicon.

A new device developed by SPCO and based on their SPT401 SCR addresses the requirement for faster turn off and higher critical rate of current rise. The preliminary ratings for this device, the SPT402B are shown in table 2. The device, shown in figure 2, uses an involute gate structure to increase critical di/dt without a large sacrifice in action capability, and it is doped to provide a faster recovery time. This device represents an improved trade-off between device diameter, voltage stand-off and switching speed, and it should result in the development of lower mass converters for electric gun power systems

5. TRIGGERED VACUUM SWITCHES

Triggered vacuum switches (TVS) show promise for use in electric gun power conversion circuits. Their specific power and power density ratings are well above those of silicon devices. Ratings for commercially available and developmental TVS are shown in table 3. TVS are extremely robust devices that can survive over-voltage, over-current, and reverse-current faults that would damage SCR. TVS are also capable of extremely fast recovery. As a result, they can be used in higher frequency circuits in the place of large-diameter, high-voltage SCR which can require up to several hundred microseconds to recover. In addition, the TVS' low cost

Table 2. SCR ratings

	Px TD2045	SPCO SPT401	SPCO SPT402B	Units
V_{sym}	4.5	5.0	5.0	kV
Diameter	100	125	125	mm
di/dt_{crit}	200	100	$\geq 1000^*$	A/ μ s
Action	8.7	20	15	MA ² ·s
t_{rr}	50—100	400	$\leq 100^*$	μ s

*single shot, measured in test

Figure 2. SPCO Involute gate SCR

Table 3. Device ratings for VEI triggered vacuum gaps [10]

	RVU40	RVU43	units
I_{pk}	150	200	kA
V_{sym}	20	25	kV
Charge	80	120	C

per kilowatt make it attractive for use in switching circuits that would otherwise require the use of large series and parallel arrays of silicon devices [9].

The main difficulties in designing with TVS are the relative lack of performance data at high current and frequency, and the apparent inability of the TVS to recover reliably under reversing current and voltage conditions after passing a peak current greater than 20 kA [9]. As a result, the designer must increase the number of devices in parallel or employ some type of recovery-assist circuit.

The poor recovery performance of the TVS at high current would seem to preclude its use in high-power converters. However, its other attributes, when compared to other switching devices, are very attractive. The recovery performance can be enhanced greatly through the use of recovery-assist components such as saturable reactors, active magnetic assist, series diodes, and a switched parallel branch that allows the TVS to recover under favorable conditions.

The use of saturable reactors to improve the performance of TVS has been attempted by at least three

researchers [11,12,13] with mixed results. In addition, the amount of magnetic material needed to provide the required volt/second rating may be quite large. Active magnetic assist has been proved in principle and requires further development [14], perhaps along the lines suggested that have been successful for vacuum interrupters [15,16]. In addition, research into other recovery-assist methods is confidently expected to result in devices that can be used successfully in very high power converters.

6. SILICON CARBIDE (SiC)

The use of silicon carbide (SiC) devices in electric gun power converters will result in a substantial reduction in the mass and volume of the overall power system. Silicon carbide-based devices, when compared to silicon devices, will be able to stand off higher voltage, operate at higher temperature and withstand faster current rise. These attributes will result in converters with much higher specific power and power density. These attributes will also allow alternators to operate at higher speed and therefore greater energy density. The high avalanche breakdown strength of SiC will permit the use of a thinner base layer, and the high thermal diffusivity of SiC will reduce the thermal gradient within the device. As a result, the allowable di/dt will be increased and thermal fracturing will be inhibited during the plasma spreading interval. The improved thermal conductivity of SiC will also act to inhibit the formation of hot-spots. This improved thermal conductivity, along with silicon carbide's 900°C intrinsic temperature, will allow operation at much higher current density before current-funneling and thermal runaway occur. A SiC device capable of operating at 10 to 20 kA/cm² and di/dt that is 2 to 4 times greater than that allowable in silicon has been projected based on experimental data and simulation.[17] If these improvements are realized in practical devices, then they will have a substantial impact on power converter design. The number of devices used in the power converter systems will be reduced, resulting in reduced size and weight and improved reliability.

7. CONCLUSION

Symmetric controlled rectifiers based on silicon technology are capable of satisfying the needs for converting power from a multipole, multiphase pulse alternator driving a practical EM railgun. A lower parts count and a more robust converter would result from the use of triggered vacuum switches, but some effort needs to be expended on identifying the most cost and weight efficient recovery-assist circuitry to ensure that conduction ceases and symmetric control can be exercised after each sub-pulse. Controlled rectifiers based on silicon carbide offer the potential for a factor-of-six improvement in mass relative to silicon devices, but large wafers with, for example, low enough defect density are not available at this time.

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