ELECTROTHERMAL ACCELERATORS: THE POWER CONDITIONING POINT OF VIEW

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Abstract: In electrothermal (ET) guns, the projectile acceleration is governed by gas dynamics as in explosively-driven guns. In a conventional gun, however, both the energy for heating and the material to be heated are contained in the solid propellant. Electrothermal launchers allow an external electric power supply to be used to provide the necessary energy; hence, lower atomic weight propellants may be used and heated to higher temperatures while maintaining a tailored acceleration profile. Important improvements in hypervelocity performance and barrel degradation can be obtained by controlling the electric discharges via power conditioning. Complex voltage and current waveforms are achieved using complex power conditioning systems, since the existing power supplies do not conform to ET gun requirements.

This paper advances the concept of a single element power supply for ET guns, showing that compulsator-type machines with waveform flexibility (pulse shaping capability) can satisfy all the ET gun power supply and conditioning requirements while maintaining a high efficiency and low mass. Additionally, compulsators are suitable for repetitive-fire applications. Also described in the paper is a system of homopolar generators (HPGs) and inductors for laboratory applications.

Introduction

The ET gun technology is rather well advanced, already producing projectile energies rivaling those of similarly sized conventional weapons. The major benefits of the concept are: simple barrel requirements (the barrel can be very similar to those of conventional guns); controlled driving gas composition; and the high load impedance presented by the resistive capillary. The latter is important in improving launcher efficiency.

Modeling of ET guns has resulted in optimal volt-ampere requirements from the power supplies [1]. These complex characteristics can be accommodated by connecting a complicated multi-element power conditioning system between the generator and the load.

The compulsator, due to its wave shape flexibility [2], can produce directly in one element an output of the desired shape in order to achieve a discharge which optimizes the gun performance, while maintaining the uniform pressure distribution in the barrel. The compulsator-type machine performs in one unit the function of kinetic energy store, electromechanical energy conversion, and power conditioning. The repeatability (demonstrated recently for a compulsator driving electromagnetic guns at a 60 Hz frequency) is another quality which makes them attractive for ET launchers [3].

A compulsator with pulse forming (wave shape flexibility) capabilities can also be adapted to combustion augmented (CAP) guns, which are a hybrid between liquid propellant (LP) and ET launchers [4]. Such technology combines the compactness of liquid propellant guns with the controllability of ET guns. The fuel is vaporized by an electric pulse and then injected into the oxidizer; the voltage and current must have complex shapes in order to optimally control the combustion and consequently the barrel pressure in time and space.

In the following paragraphs it will be shown that the voltages and currents necessary for ET and CAP guns can be achieved naturally by a compulsator with pulse shaping capabilities. A more complex system for laboratory use, employing HPGs, storage inductors, and explosive opening switches is also described.

ET Gun Power Supply Requirements

The feasibility of a pulsed power supply for ET guns, and for hybrid guns such as the CAP gun, and the high velocity ET guns (HVET), is characterized by energy density, volt-ampere characteristic profile, reliability, and repetitive rate. The advantage allowed by the external power supply is control over the energy delivered to the capillary.

An ET gun driven by a compulsator is shown schematically in figure 1. The capillary (usually 3 to 5 mm radius and 5 cm length for a 100-kJ discharge) may be empty, or it may contain some fill material. A high voltage is applied to the electrodes on either end of the capillary, resulting in an arc which rapidly heats to a few eV. As the arc is heated by current, it begins to radiate into the surrounding material. This radiation is sufficiently intense to ablate the capillary material, which introduces more mass into the plasma, sustaining the discharge. Pressure in the capillary quickly builds and plasma is ejected through the cathode/nozzle into the gun chamber, where it interacts with a moderating fluid. The resulting mixture is still at a high pressure (several kbar), and it is this pressure that drives the projectile. High electrical efficiency is possible since the long, thin capillary plasma behaves essentially as a resistor. Based on Spitzer [5], the resistance of an arc of length ℓ (cm) and radius a (cm) is

$$R = \frac{1.7 \times 10^{-3} \ell Z \ln\Lambda}{a^2 T_{eV}^{3/2}} \beta \qquad (1)$$

where

Z = average ion change state
$\beta = (1 + \nu_{eo}/\nu_{ei})$ where ν_{eo} and ν_{ei} are the electron-neutral and electron-ion scattering frequencies
T_{eV} = the plasma temperature in eV

For these discharges, the Debye shield factor for electrons, $\ln\Lambda$, is typically 2. At temperatures of about 1.5 eV, ν_{eo} and ν_{ei} are comparable, while at T_{eV} = 5 eV, ν_{eo} is much smaller than ν_{ei}. The resistance can be tailored by varying the radius, a, and the length, ℓ, of the arc. Values around 0.1 Ω are easily obtained, making it possible to achieve power levels (GW), voltages (kV), and currents (0.1 to 1 MA) in the range of usual compulsator parameters. By contrast, EM railguns require much higher currents (several megamps) for the same power levels. Relaxing the current requirements allows use of smaller and less robust buswork.

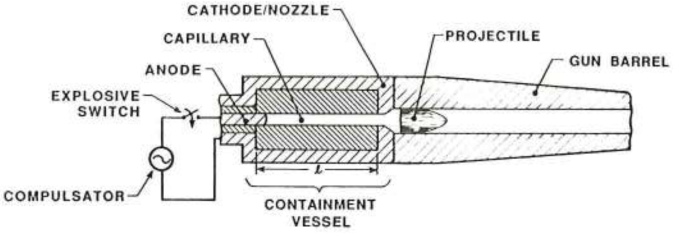

Figure 1. Simple ET gun configuration

For the special case of quasi-steady state in which we have slow current variations relative to the ratio of 2ℓ/plasma sound speed, the plasma temperature is

$$T_{eV} = 2.74 \times 10^{-2} \frac{I^{4/11}}{a^{6/11}} \left[\frac{Z \ln\Lambda}{s} \beta\right]^{2/11} \qquad (2)$$

All the parameters have already been defined with the exception of the enhancement factor, s, used in [1]. For the case of extended surface areas capillaries,

$$s = \frac{\text{total ablating area}}{2\pi a \ell} \qquad (3)$$

The plasma radiates to the capillary wall (or fill material) sufficient energy to evaporate the material. The energy required for ablating the capillary is much less than the energy radiated into the wall; thus nearly all the energy lost by the plasma via radiation is returned to the arc as a high temperature plasma [6]. This fact, coupled with the efficiency of heating a relatively high resistance, makes the transfer of energy from the compulsator to the plasma very high indeed.

How is the pulse shape determined for the compulsator which feeds an ET gun? The precise requirements for current and voltage are very complex and the connection between the input power profile and gun performance (projectile velocity and base pressure) has been solved only by linking computer simulations of the plasma dynamics in the cartridge with simulations of in-bore gas dynamics for projectile acceleration. GT Devices has developed the MAID-8 code to accomplish this, and uses an iterative procedure with a pulse forming network design code to configure a power supply that will provide the required power input in order to achieve constant-pressure acceleration [1]. For the qualitative purpose of this discussion, however, a rough approximation will suffice.

For the case of an ideal gas with adiabatic constant γ, the energy required for constant pressure acceleration P_o is

$$W(t) = \frac{\gamma}{\gamma - 1} P_o V(t), \qquad (4)$$

where the volume for gas expansion is

$$V(t) = (\text{bore cross section}) \cdot x(t). \qquad (5)$$

Now, the projectile displacement is $x(t) = \frac{1}{2} a_o t^2$ and the acceleration is the well known equation $a = P_o \cdot A_{bore}/\text{mass}$ (neglecting the gas mass). Thus,

$$V(t) = \frac{1}{2} \frac{P_o A_{bore}^2 t^2}{m} \qquad (6)$$

so that

$$W(t) = \frac{\gamma}{2(\gamma - 1)} \frac{(P_o A)^2}{m} t^2. \qquad (7)$$

The instantaneous power supplied to this volume must be

$$\frac{dW}{dt} = \frac{\gamma}{4(\gamma - 1)} \frac{(P_o A)^2}{m} t. \qquad (8)$$

Assuming the projectile base pressure equals the capillary exit pressure, then for a capillary resistance R,

$$i^2(t)R = \frac{dW}{dt}, \qquad (9)$$

so that

$$i(t) = \frac{1}{2} \sqrt{\frac{1}{\gamma - 1}} \frac{P_o A}{\sqrt{mR}} t^{\frac{1}{2}}. \qquad (10)$$

Therefore, for constant pressure acceleration and an ideal gas with no pressure drop in the bore, the current must increase with $t^{\frac{1}{2}}$. In truth, the current should increase more rapidly than this, due to losses in the bore pressure and the cooling of the plasma in advanced propellant designs (e.g., including a light fluid). This analysis is helpful in pointing out that an increasing current is required in ET guns (compared with a constant current for railguns).

In ET guns, a current zero upon projectile exit is not too critical. Continuing current in the cartridge will not necessarily damage the gun (as long an excessive pressure or temperature does not develop). It will, however, reduce the efficiency. For this reason, the current should be zero upon projectile exit.

The ET gun models electrically as a nonlinear, time-varying resistance, determined by the capillary geometry and plasma material, temperature, and pressure. This provides an easily coupled load for the power supply. Values of the capillary resistance have ranged up to 100 mΩ, and may go higher [1]. The resistance has been successfully held constant for widely varying current pulse shapes.

The CAP concept is a hybrid system which tries to combine the compactness of liquid propellant with the controllability of ET guns [4]. The electrical pulse from the power supply vaporizes the fuel (stored as a solid) which is injected into the oxidizer (stored as a liquid). The CAP control mechanism is based on the fact that plasma injection controls combustion and consequently, controls the pressure. A computer model calculates the output electrical pulse, matching the pulse shape to internal ballistics and to the varying impedance of the load. Finally, in the case of the HVET gun, the need for a distributed, AC medium-high frequency power supply is envisaged. An increasing (rising) frequency is necessary to keep pace with the accelerating projectile.

Compensated Pulsed Alternators with Current Waveform Flexibility

Figure 2 represents the power pulse shape in time given by the power conditioning system shown schematically in figure 3 from [7]. Curve B represents the power pulse shape supplied by a compulsator with pulse shaping capabilities. Figure 4 shows that such a compulsator concentrates all the functions of energy storage, electromechanical conversion and power conditioning in one machine. The single element philo-

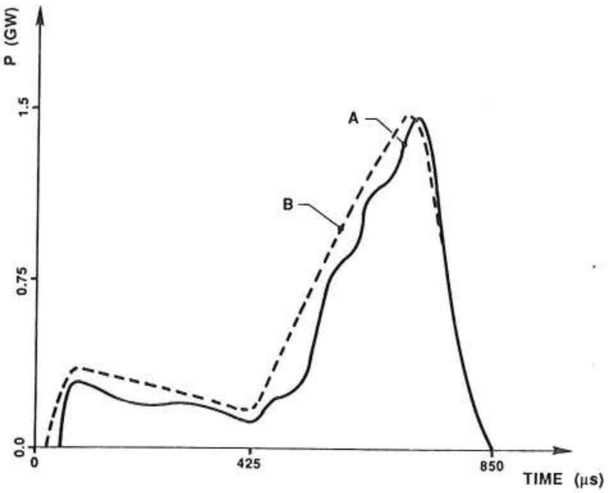

Figure 2. Experimental power pulse shape
A) supplied by system in figure 3 (from [6])
B) supplied by compulsator with pulse shaping (fig. 4)

sophy represented in figure 4 tries to convey the notion that what is called "power conditioning" is the inability of classical power supplies to furnish the energy in the exact pulse shape which maximizes the efficiency and the operation of the accelerator. The complexity of the power conditioning system measures the inadequacy of the power supply for the ET accelerator.

The compulsator is the appropriate device for pulse shaping for ET accelerators [8], having besides the excitation and armature windings, the shield (passive compensation) and/or the active compensation winding. All these elements represent degrees of freedom which can be modified in order to achieve a certain change of the output current profile.

Conceptually, we can consider the compulsator as a source of induced electromotive force having an internal impedance which varies during the pulse, such that the time profile of the output current can be shaped and controlled, for a given external impedance. Functionally there are two general methods for pulse shaping: topological distribution of conductors and dynamic interactions between conductors. These can be used separately or in conjunction.

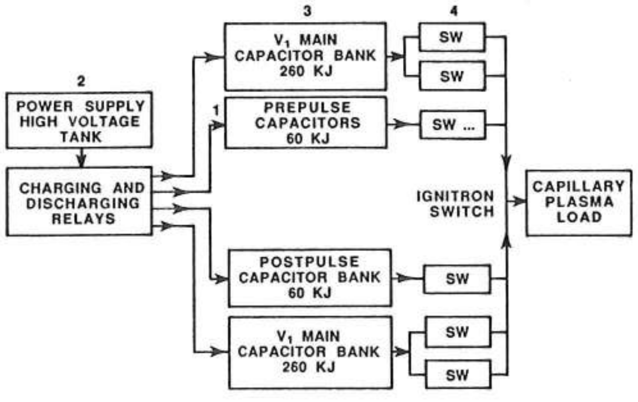

Figure 3. 20 mm ET power conditioning (from [6])

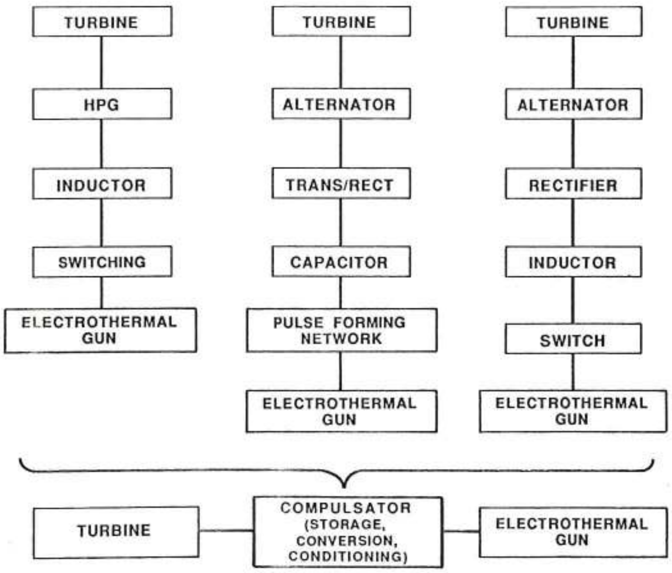

Figure 4. Single element philosophy (energy conversion, storage, and power conditioning)

The topological distribution approach includes the method of "harmonic synthesis." An appropriate choice of even harmonics will create a flat current pulse, while a synthesis of odd harmonics will result in a peaked current output.

The dynamic interaction category includes altering a basic magnetic flux distribution, created by the field coils, by using a nonuniformly distributed shield or compensating winding. This compresses the magnetic flux in selected areas, leaving the flux unchanged in the rest of the machine, and so "dynamically" shapes the pulse.

Classification of methods for pulse shaping can also be made according to the technology used:

- Excitation winding distribution (harmonic synthesis method, multiple Gramme ring type field coils, etc.)
- Electromagnetic nonuniformity in the shield (passive compensation)
- Asymmetric active compensation
- Nonuniform distribution of the armature winding (changing pole pitch and phase shift)
- Change of alignment (change of axis between different machine windings: field, active compensation, armature, shield)
- Use of a pulse transformer incorporated in the machine.

Only the latter two will be discussed here.

Pulse Shaping by Variable Alignment of Magnetic Axes

In this section, a machine is described which provides different output current versus time profiles by a change in the alignment of the magnetic axes of the compensating winding and the excitation field winding.

For simplicity, a two pole machine is considered. This machine has a lap wound, full pitch armature winding which occupies 30 to 80% of the pole pitch. The winding is composed of stranded and transposed wire which is epoxy bonded to the stator or rotor. The compensating winding is also two pole, lap wound and full pitch. The compensating winding is the primary current pulse shaping component. A cylindrical shield made of a highly conductive material is also provided. This shield is placed on the same member as the compensating winding but further from the armature winding compared to the compensating winding. The shield is the secondary pulse shaping device. The magnetic axis of the compensating winding is displaced about 50 to 70 electrical degrees from the axis of the excitation field. There is no galvanic contact between any pair of windings; the only coupling is through the magnetic field produced by these windings.

The basic principles involved in pulse shaping in this case are:

1) a short circuited coil will maintain its initial flux linkages when subjected to a changing magnetic field. The flux linkages are maintained at the initial value by a current set-up in the coil and oriented in a manner to exclude the changing magnetic field.

2) The power output of an alternator is limited by the internal inductance of the alternator.

As the armature winding spins with the rotor, the mutual inductance between the armature and compensating windings, and therefore the flux linking the compensating winding, changes with rotor position. The variation of the mutual inductance is more or less sinusoidal with angular position. The mutual inductance is maximum when the magnetic axes of the armature and compensating windings are aligned as shown in figure 5. In this position, the flux produced by the armature winding is confined in the gap between the two windings because of the current in the compensating winding, and so the inductance of the armature winding is minimum. When the magnetic axes of the two windings are perpendicular to each other as shown in figure 6, the mutual inductance between the two windings is zero. In this position the flux produced by the armature winding permeates the entire region within the shield, bringing the inductance of the armature winding to its maximum. This cycle of maximum and minimum inductances occurs twice per rotor revolution.

The current pulse is initiated when the mutual inductance between the two windings is close to, but less than the maximum value. Since the inductance of the armature winding is low in this position, the current in the armature winding rises rapidly. This continues until the mutual inductance starts to decrease and the armature inductance begins to increase. The increasing armature inductance limits the power output of the machine, thus leveling the output current pulse. Toward the end of the pulse the mutual inductance begins to increase, reducing the armature inductance.

In the absence of the shield, the maximum inductance of the armature winding would be much higher. The current pulse would then drop significantly, giving a current pulse with a valley in the center (fig. 7), having the potentiality of giving the right pulse shape required by the ET gun (see from comparison in figure 2). Therefore the shield is a pulse-shaping component. Figure 7 gives an output curve which conforms to the energy output required by ET guns or by other hybrid guns (such as CAP guns). It was obtained for a displacement of magnetic axes with 78.5° and for a firing angle of 36° after the machine voltage passed through zero. The compulsator can give a curve in which the maximum is obtained in the first part of the pulse (before the valley) for magnetic axes displaced 90° and the firing angle remaining the same (fig. 8).

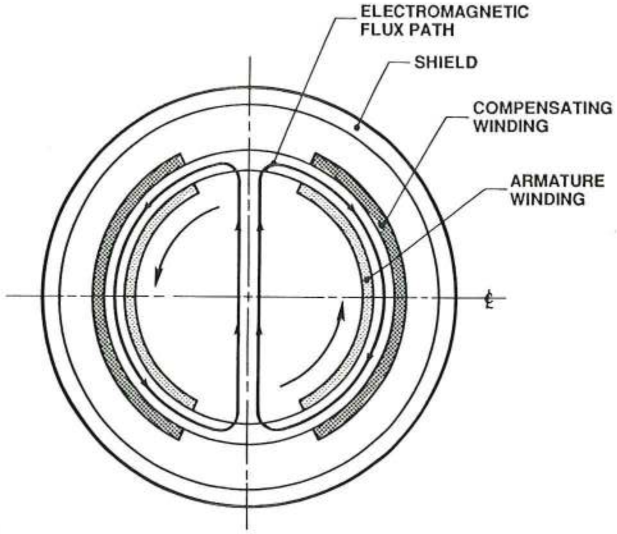

Figure 5. Machine in maximum mutual inductance position: flux is compressed in the air gap

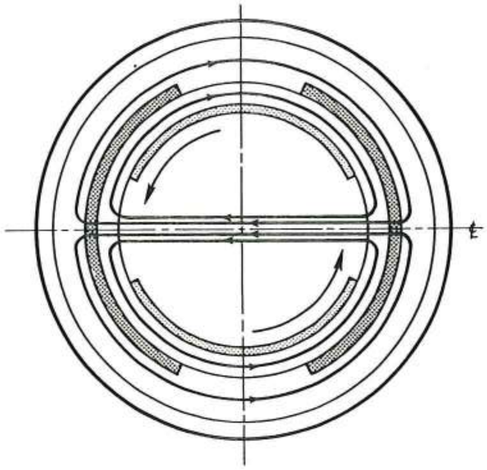

Figure 6. Machine in zero mutual inductance position: flux permeates the entire space within the shield

Pulse Shaping by the Use of a Pulse Transformer Incorporated in the Machine

The machine described in the previous section was designed assuming the load was connected to the armature winding, with the pulse initiation switch also provided in the armature circuit. Pulse shaping can also be obtained by connecting the load to the compen-

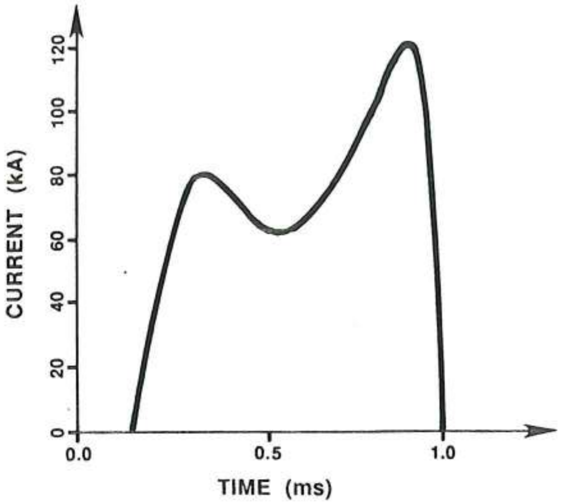

Figure 7. Output current pulse shape: lead coil connected to armature winding, magnetic axes displaced 78.5°, and firing angle 36° after zero voltage

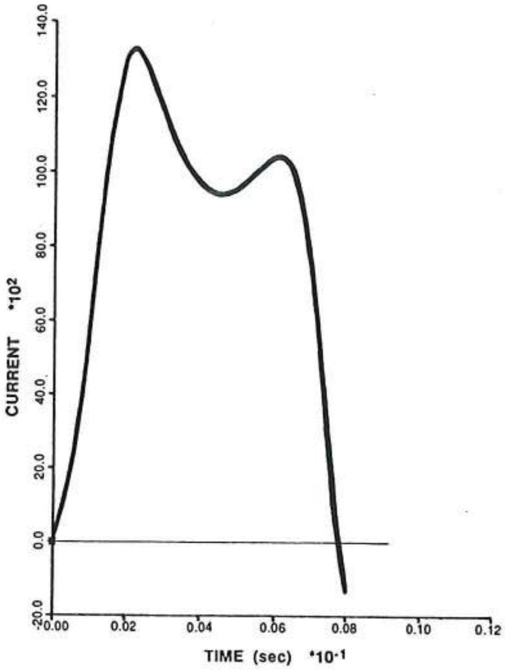

Figure 8. Output current pulse shape: lead coil connected to armature winding, magnetic axes displaced 90.0°, and firing angle 36° after zero voltage

sating winding and initiating the pulse in the armature circuit. Since the armature and compensating winding are magnetically coupled, a current pulse in the armature winding induces a pulse in the compensating winding. Figure 9 shows the current in the compensating winding arising from the armature winding current in curve B. Therefore, by using a machine similar to the one described in the previous section and connecting the load to the compensating winding, a different family of pulse shapes can be obtained.

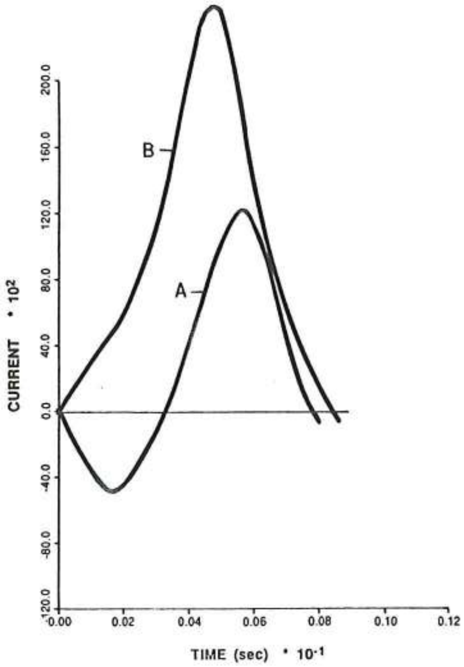

Figure 9. A. Current in the compensating winding (pulse transformer incorporated in the machine)
B. Current in the armature winding (pulse transformer incorporated in the machine)

Pulse Shaping for ET Guns Using HPG Charged Inductors and Explosive Opening Switches

The system block diagram for pulse shaping using HPG charged inductors is shown in figure 10. This is no longer a single element pulse shaping system, it does, however, represent a valuable, rugged laboratory power supply. It is based on the Balcones HPG power supply in operation at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). The power supply has 60 MJ stored energy and a capability of 9 MA. The pulse shaping is obtained by sequentially discharging the six elementary power supplies. There are two phases to the discharge. All six HPGs are brought up to speed over 2 min and then the excitation fields are turned on. This produces terminal a voltage at the generators. The brushes on all six HPGs are then lowered to initiate the electrical discharge. Currents rise in all six inductors over a 150 ms time frame. The current waveforms of each inductor have a 10 to 20 ms flat top about peak current. It is during this interval that the staged ET gun discharge is initiated. Explosive switch 1 is detonated and isolation switch ignitron 1 is turned on. Current from storage inductor 1 is commutated into the ET gun. All other isolation ignitrons are off at this time, so the other charged energy stores do not communicate with the gun and conversely the switched stores communicate only with the load and not with the unopened switches. Subsequent stores will switch their current according to programmed delays, thus allowing different current waveforms to be generated. When subsequent stores discharge, their current transfers into the gun and not into previously discharged energy stores because of the developed insulation strength in the opened switches and the large reactive impedance of the energy store itself. Such a system will have a relatively low efficiency.

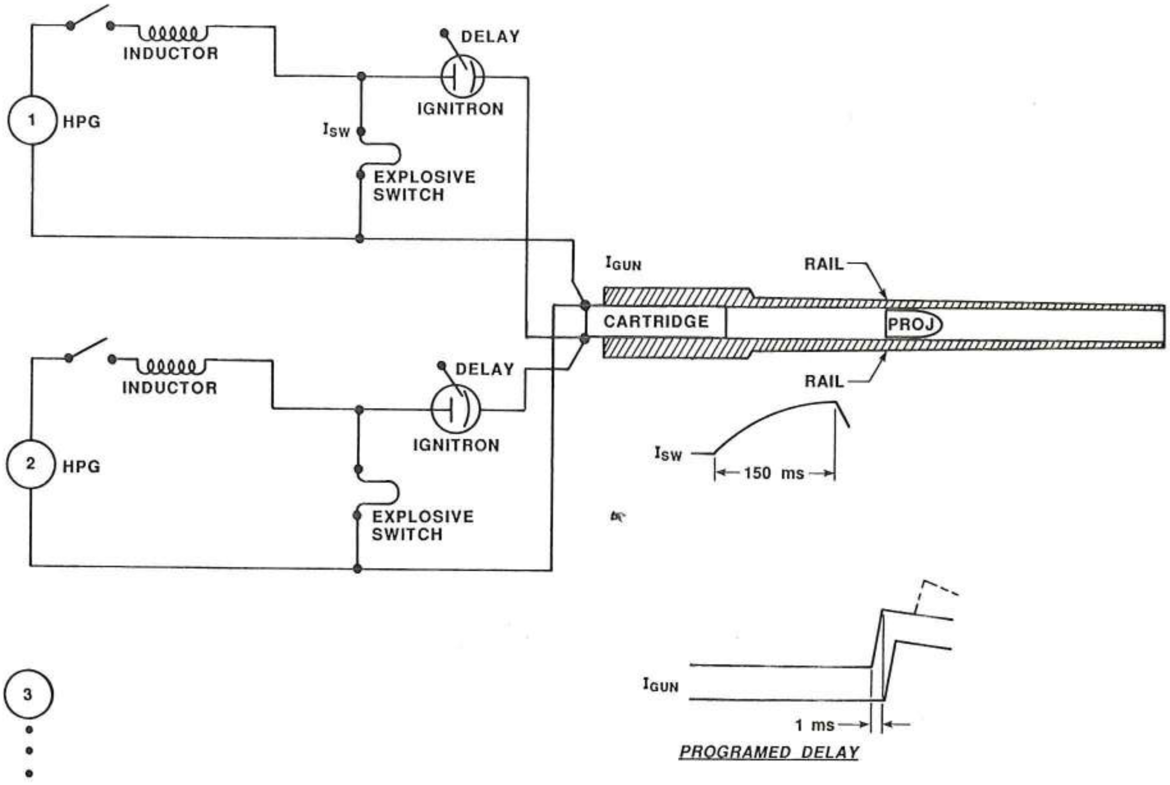

Figure 10. HPG charged inductors system pulse shaping for ET guns

Conclusions

The above treatment shows that the compensated pulsed alternator with output waveform flexibility is an optimal power supply for an ET accelerator due to its capability to conform to the load requirements while still performing the energy storage and electromechanical energy conversion functions in one element. Compulsators have also the highest power density reported for an electrical machine and have demonstrated, at CEM-UT, the repetitive rate operation, at 60 Hz. A simulation of an existing laboratory based 60 MJ HPG power supply driving an ET gun was also presented.

Acknowledgements

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