Pulsed Rotating Machine Power Supplies for Electro-Thermal-Chemical Guns

By:

W.A. Walls
S.B. Pratap
J.R. Kitzmiller
G. Chryssomallis*

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W.A. Walls and S.B. Pratap
The University of Texas at Austin Center for Electromechanics, Austin, TX

George Chryssomallis
Science Applications International Corporation, Bloomington, MN

Abstract—With the recent successes in the development of electro-thermal-chemical cartridge technology, the need for an advanced repetitive fire power supply has become a more near-term problem. While capacitor banks have provided the single-shot capability necessary for optimizing charge design and the required electrical pulse shape, it is not clear that it is the best power supply for a fielded system. The primary disadvantage of the capacitor approach is the requirement for recharging the bank between shots. Conceptually, the required charging is accomplished with either a high voltage alternator and rectifier, or a battery bank which requires power conditioning (D-D converters, etc.) to achieve the required 15 to 20 kV charging voltage. In the case of the alternator-rectifier system, energy storage for multiple shots can be built into the alternator rotor (or by adding an energy storage flywheel). Since battery charging system design is typically driven by power considerations, the battery needed to perform the charging will generally store sufficient energy for several shots. In either case, the pulsed power system is composed of two distinct components: a capacitor based pulse forming network (PFN) and an energy storage/charging power supply.

Rotating machines provide the advantage of combining the two functions described above into a single smaller package. Under U.S. and Marine Corps funding, the Center for Electromechanics has been developing compact, lightweight pulsed rotating machines (compensated pulsed alternators, or compulsators) for electromagnetic guns for the past 10 years. Air-core and iron-core variants of these machines have demonstrated an ability to efficiently drive low impedance pulsed loads. Other advantages of these machines over PFNs include lower operating voltages, higher burst firing rates, and the ability to store a substantial number of shots in rotor energy. In addition, a wide variety of pulse shapes are possible and the current profile can be varied from shot to shot if needed.

This paper describes the important rotating machine power supply design considerations for two operational ETC missions. Aspects of energy storage for burst firing and prime power averaging, pulse shaping capabilities, and switching requirements are also discussed.

ELECTRO-THERMAL-CHEMICAL GUN POWER REQUIREMENTS

Conceptually, an ETC gun uses a combination of electrical and chemical energy to accelerate a projectile. The use of electrical energy, in the form of a plasma generating arc, can help in accelerating the projectile by providing uniform ignition of more energetic propellants as well as by adding thermal energy to increase performance. By tailoring the electrical energy input, the piezometric efficiency of the gun can be increased, producing increased muzzle energy over conventional propulsion without increasing the peak stress on the gun tube itself. In addition, the electrical energy can tailor the burn rate of propellants and therefore increase the progressivity of the charge. Peak pressure can thus be maintained until propellant burn-out.

A major focus of the ETC gun development effort has been the improvement of the energy enhancement factor (EEF), which is defined as the launch package muzzle energy divided by the electrical energy input at the breech. This development activity has used capacitor based PFNs exclusively. Until recently, EEF values of 4 were considered to be realistic and achievable goals for the technology [1]. At this level of EEF, between 4 and 5 MJ of electrical energy input would be required to meet the needs for future large bore anti-armor guns. In reality, only about 2.5 MJ is required to drive the rising portion of the preferred pulse shape. The residual energy delivery after the current peak is an artifact of the residual energy in the capacitor which must be dissipated and cannot sustain the peak pressure in the chamber, resulting in marginal benefit. Use of a rotating machine, which can more precisely control the delivery of energy to the load, may reduce the energy requirement closer to the 2.5 MJ value for the conventional ETC approach.

A more recent ETC approach uses a much smaller electrical energy input to simply ignite the propellant. The improved gun performance comes through the use of more energetic propellants in more progressive, higher packing density charge. Tests of this approach show the potential to achieve EEFs in the 20 to 80 range [2], which would drop the

electrical energy requirement to less than 1 MJ and maybe as low as 200 kJ. In either case, the ETC load impedance is dominated by the plasma arc which couples energy into the system. For the purpose of sizing the power supply, this impedance can be characterized as a 30 to 50 mΩ resistive load for either the ETC igniter or the conventional ETC approach. The pulse width required by the conventional ETC operating scenario is about 5 ms, and a rising current profile is preferred. Since the ETC igniter concept provides propellant ignition only, the electrical energy must be delivered over a shorter time period of perhaps 1 ms. The nominal load requirements for the two approaches is summarized in Table I. Power requirements from the rotating machine are dictated by the arc resistance, bus impedance, and the internal impedance of the machine itself. Proper compensation of the output winding can lower the overall peak power required from the machine by lowering its internal impedance. Voltage requirement for the machine may be driven by the voltage needed to initiate the plasma arc, but this can be minimized with specially designed fuses. If so, the machine voltage can be lowered to that required to achieve the necessary peak current in the load circuit within the prescribed pulse width.

Another major consideration which can effect the design of the power supply is firing rate. A sustained fire rate of about 10 rounds/minute is possible in current main battle tanks, and therefore sets a nominal recharge requirement on an ETC pulsed power system. Maximum firing rates, for a 2 or 3 shot burst, are likely to be twice as high as the sustained value. For this reason, the two firing scenarios described in Table I are used for establishing power system rep-rate requirements.

Table I. Nominal rotating machine power supply requirements for the two types of ETC guns

Parameter	Conventional ETC	ETC Igniter
Breech Electrical Energy	2.5 MJ	200 kJ to 1 MJ
Pulse Width	3 to 4 ms	1 to 2 ms
Peak Current	260 kA	30 to 70 kA
Peak Power	>1.5 GW	400 to 800 MW
Pulse Shape	Rising Current	Sinusoidal
Rep-Rate	2 to 3 shot burst: 20 rounds/min Sustained: 10 rounds/min	

POWER SUPPLY DESIGN CONSIDERATIONS

The two basic types of rotating machines considered are air-core and iron-core. The power required by the load, combined with size and mass constraints will generally dictate which approach is appropriate for a given case. Due to the low field coil ampere-turn requirement for iron-based machines, they tend to be considerably more efficient than air-core variants. However, due to the low specific strength and high density of ferromagnetic materials, the rotor tip speed and energy density are severely limited. Also, operation at or near 1.8 T excitation flux is basically fixed for iron-core machines. Optimizing machines for high energy storage density and high power density favors air-core machines because of the higher tip speeds possible with low density composite rotor materials and the capability to operate at higher flux densities. Air-core machines, however, must be self-excited and therefore pay a significant overall efficiency penalty in establishing the excitation field. This efficiency penalty is significantly greater for systems which deliver relatively low energy to the load because losses in the field circuit can become dominant. On the other hand, parameters like rotor tip speed, excitation flux density, and efficiency can be optimized to provide a minimum weight and volume device.

An additional electrical design consideration is the number of phases to be used [3]. Early compulsators were configured as single phase machines wherein the required current pulse was derived from a single voltage cycle. While this approach simplifies output switching requirements, it does imply the output pulse width must be close to the voltage period provided by the fundamental machine electrical frequency. In order to minimize the size of a single phase machine given a stored energy requirement, the number of poles must be minimized to increase rotational speed. Unfortunately, the smallest machines are therefore 2-pole configurations which suffer from a variety of electromagnetic and mechanical problems, including larger end-turns and a requirement for a non-conductive shaft and bearings in air-core machines. For this reason, 4-pole machines, although slightly heavier, are generally more attractive than the 2-pole designs. The addition of compensation in single phase machines can be customized to provide a wide range of pulse shapes as desired, including a rising current wave form.

Multi-phase compulsators utilize a higher electrical frequency and then rectify the output to provide the required pulse width. This effectively eliminates the pulse width/electrical frequency constraint experienced in single phase designs. Therefore, the number of poles and rotor rotational speed can be separately optimized to provide the desirable features of higher number of pole machines with high rotor energy density. The primary tradeoff then becomes one of

machine size vs. switching hardware size, mass, and cost. Another major consideration in the multi-phase system architecture is type of rectifier selected [4]. A full wave phase controlled rectifier allows the greatest pulse shaping capability, but requires approximately twice the number of switching devices as a half-wave, phase controlled rectifier because current flows in each bridge leg at all times. In either case, quadrature compensation provides substantial benefits in optimizing machine impedance for maximum power transfer to the load and in minimizing transient over voltages resulting from rectifier commutation switching events.

From an operational systems standpoint, the rotating machine power supply for an ETC gun system will likely store enough energy for a number of shots. This allows the shot energy to be accumulated in the kinetic energy of the rotor over a relatively long period at low power, thereby eliminating the need for a large continuous power draw from the main engine during extended firing scenarios. Another consideration is power supply response time. Since the rotating machine must be spinning at a minimum of 70% rated speed to generate the voltage needed to fire a shot, the time needed to bring it to speed can become an issue if the rotor inertia is large. One would have to anticipate the need to fire the gun several minutes before doing so, but this would require only minor changes in procedure. Also, the time delay between giving the command to shoot and energizing the field coils in the machine must be considered and will dictate how long the fire control system must hold the gun on target. Realistic systems must keep this response time down to a few tens of milliseconds. Thermal management within the power supply can also be a major issue, especially in air-core machines wherein rotor cooling is difficult because it operates in an evacuated stator to minimize windage losses.

CONVENTIONAL ETC POWER SUPPLY

To meet the needs of the assumed conventional ETC gun, the rotating machine power supply must deliver 2.5 MJ of electrical energy to the breech. Assuming a 60% overall system efficiency, a 10 round/minute firing rate and no energy storage; prime power input would need to be 715 kW (960 hp) for sustained operation. Since most main battle tanks have only 1 MW of installed engine power dedicated primarily to meeting mobility needs, it is more attractive to store several shots in the kinetic energy of the rotor. Given the power requirement and the energy storage needs, an air-core rotating machine will be significantly smaller and lighter than an iron-core design for the conventional ETC case. The number of shots to be stored in the rotor must obviously be optimized within the vehicle system and the operating doctrinal contexts, but a machine storing 18 shots was designed as an initial sizing exercise. This would allow firing of all "ready rounds" in

the current M1 without taxing the main engine at all.

Since the compulsator can only deliver about half its energy, the rotor will have to store 160 MJ to provide the 4.3 MJ/shot for all 18 shots. In order to provide the preferred rising current pulse, a four-phase, full-wave rectified machine was chosen. Based on switching requirements, rotor mechanical stresses, and including a constraint that the rotor must fire at least 24 shots without cooling; a 12,000 rpm machine with 6 poles was chosen. The compulsator designed for this sizing exercise is about 0.9 m in diameter, 1.2 m overall length, and weighs 1,450 kg. The field rectifier and output switching will occupy 0.5 m^3 and weigh about 650 kg. Other auxiliaries, including bearing lubrication and vacuum pumps will weigh approximately 200 kg, bringing the overall pulsed power system mass to 2,300 kg and its volume to 1.7 m^3. Operating parameters and characteristics for the machine are provided in Table II, and the output pulse shape is compared with capacitor PFN pulses in Fig. 1. Note that reduced energy from the compulsator is due to its ability to rapidly drive the current to zero after reaching the peak value.

If the 1 MW engine prime power can be dedicated to spinning the machine up from a standstill, about 3 minutes is required. After firing a full compliment of 18 rounds, the rotor will be at half energy so only 1 to 2 minutes would be needed to replenish the rotor energy. Several important factors will require optimization for a fieldable system. First, the number of shots requiring storage in the rotor may be reduced since some prime power can likely be provided during the firing mission. This will reduce the size of the machine. Second, because cooling of the rotor is likely to take several minutes, it may be necessary to allow accumulation of up to 40 rounds worth of resistive losses in the rotor. An offsetting increase in machine size and mass will result in this case. Setting of requirements for the compulsator should also be done in light of other potential vehicle systems which can utilize pulsed power, and whether the compulsator rotor energy can effectively be used to load level the mobility requirements (in an electric drive system) by recovering braking energy and boosting acceleration power [5].

Table II. Compulsator characteristics for an 18 shot conventional ETC gun system

Characteristic	Value
Rotor Energy	160 MJ
Rotor Tip Speed	650 m/s
Phase Voltage	7 kV
Electrical Frequency	600 Hz
Rotor Energy per Shot	4.3 MJ
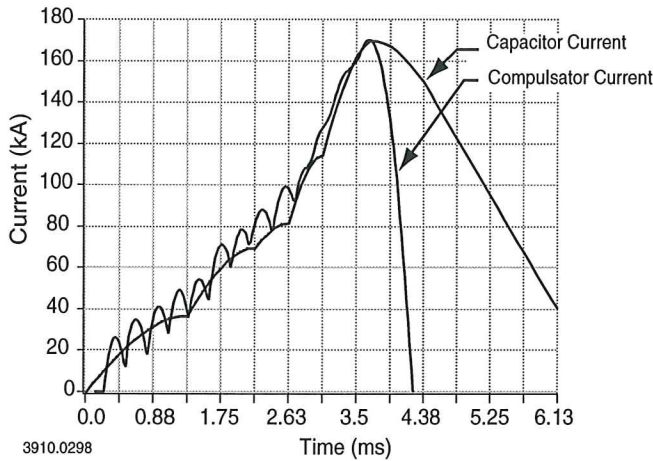
Fig. 1. Pulse shape from a multi-phase air-core compulsator
into a conventional ETC load

Table III. Iron-core compulsator characteristics for an
ETC igniter power supply

Characteristic	Value
Rotor Energy	1.1 MJ
Rotor Tip Speed	200 m/s
Phase Voltage	4.5 kV
Electrical Frequency	120 Hz
Rotor Energy per Shot	360 kJ

ETC IGNITER POWER SUPPLY

Because the ETC igniter concept is relatively new, the energy requirements are not well known. At the low end of the anticipated energy range, it is almost certainly more appropriate to use an iron-based rotating machine. To test this hypothesis, a point design for a iron-core machine was generated for a 300 kJ/shot system. Initial simulation results showed that efficiencies of 85% were reasonable, even when the field coil power source is considered. This type of machine has been successfully built and tested for driving a railgun load [6][7], so design codes are well validated. Because iron based machines with windings installed on the rotor are limited to about 200 m/s, they are not efficient energy storage devices. Therefore, this machine was designed to deliver the required power without regard to its energy storage capability. Also, for this initial design, a single phase compulsator was chosen for simplicity. The resulting 4-pole machine weighs 550 kg and stores only 2 shots, but occupies only 0.08 m^3. Including switching and auxiliaries, the system mass is 700 kg and its volume is about 0.1 m^3.

Energy storage for additional shots may not be required for this system since the 360 kJ of rotor energy required per shot can be provided with roughly 60 kW in the worst case 10 round/minute firing scenario. However, since the capability to fire without the main engine running is important, storing the energy for several shots can be provided by either integrating an energy storage flywheel into the compulsator, or using batteries to motor the rotor. Of the two options, the batteries provide significantly more flexibility, and can provide continuous power at low level to overcome bearing friction and rotor windage losses. Using new high power density lead-acid or metal-hydride battery technologies would allow up to 40 shots (15 to 20 MJ) to be stored in about 100 kg and less than 0.1m^3 [8]. Parameters for the point design machine are provided in Table III.

In these low energy ETC systems, thermal management becomes significantly easier. Since the compulsator rotor cavity does not require evacuation, cooling of the rotor can be accomplished by blowing ambient air through the air gap of the machine. Auxiliaries can also be minimized through the use of sealed, grease lubricated bearings and by self exciting and self motoring the machine. While this requires separate windings on the compulsator stator, the resulting system (Fig. 2) is extremely compact.
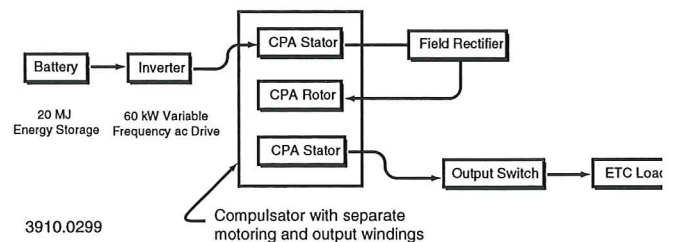
Fig. 2. Battery/compulsator ETC igniter pulsed power system
architecture

CONCLUSIONS

Development of compensated pulsed alternators for electromagnetic guns has been an ongoing effort for more than a decade. As ETC cartridge technology evolves toward fieldable designs, adaptation of compulsators for use as ETC power supplies appears very feasible and very attractive. While air core rotating machines are more attractive for the higher energy needed by the conventional ETC gun approach, the higher efficiency offered by iron based devices is more attractive for the ETC igniter concept at low end of its anticipated energy range. Should higher energies (up to 1 MJ) for the ETC igniter be needed, both air-core and iron-core machines should be optimized and studied within the overall vehicle systems context to determine which approach is preferable.

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