INVESTIGATION OF AN ALTERNATOR CHARGED PULSE FORMING NETWORK WITH FLYWHEEL ENERGY STORAGE

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Investigation of an Alternator Charged Pulse Forming Network with Flywheel Energy Storage

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Abstract: **One of the more promising electric gun system configurations utilizes a capacitor based pulse forming network to power the launcher, a limited duty, high power alternator to charge the capacitors and a composite flywheel for energy storage. This configuration combines the flexibility of a pulse forming network (PFN) with the high average power of an alternator and the high energy density of a flywheel. The alternator can be designed to directly charge the capacitors without the inverter/transformer typical of battery charged capacitor systems. Optimization will require trade-offs between energy density, voltage and efficiency. System integration is facilitated by direct coupling of the flywheel/alternator to a turbine or motor and modularity of the components.**

This paper presents the conceptual design of a system to power an 18 shot, salvo fire 30-mm railgun. The performance of components was selected to be slightly beyond the state of the art but achievable in the near term. For instance, the baseline PFN utilizes a 935 kJ capacitor bank made up of Aerovox 1.3 J/g, 2.5 A/J, 80% efficient capacitor technology. It was sized assuming a 33% efficiency from capacitor to launch package. These capacitors would require some development and are based on the 1.5 J/g technology developed under the BTI/Army Pulse Power Module program. The 1.5 J/g technology is based upon high voltage (24 kV), low current capacitors. 1.3 J/g is estimated for lower voltage (8 kV) higher current devices. The alternator has a power density of about 12 kW/kg. This power density is beyond the state of the art (≈ 9 kW/kg) [1] but is considered reasonable because the system does not require continuous power providing opportunities between charging cycles for cooling. Compulsators have demonstrated peak powers of 100 kW/kg [2] and are being designed to produce 500 kW/kg [3]. The energy storage flywheel design is based on the minimization of overall system mass. It is mounted integrally with the alternator rotor and is enclosed in a containment vessel. Consideration of both the flywheel and containment yields a specific geometry that has minimum mass.

INTRODUCTION

The objective of this investigation was to pursue a system approach to a capacitor based PFN for powering a railgun launcher. The gun system needed to be compact enough to be portable, utilize near term technology, yet demonstrate weapon level performances. We therefore selected a 30-mm launcher bore diameter with the following performance parameters:

Muzzle Velocity	2.15	km/s
Launch Mass	120	g
Salvo Size	6	rounds
Number of Salvos	3	
Peak Launch Acceleration	240	kgees
Rate of Fire	300	r/min

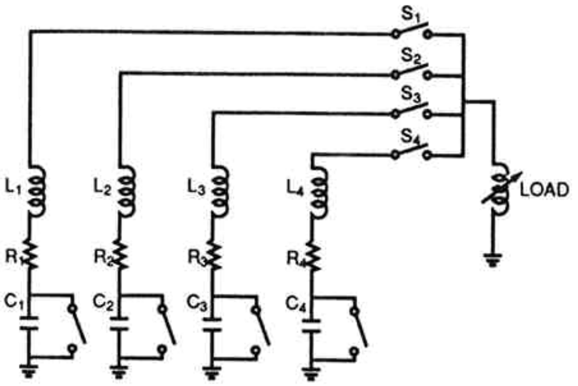
We elected to include an energy storage flywheel that stored enough energy for all eighteen shots to facilitate system integration. A system designed to store a single shot requires 6,000 to 7,000 Hp; one storing single salvo needs about 2,000 Hp and one storing all three salvos reduces the value to about 125 HP.

PULSE FORMING NETWORK

A pulse forming network (PFN) that has minimum possible weight and is capable of providing the required current is shown in Fig. 1. This PFN is composed of four modules all connected in parallel to the load. Each module is composed of a capacitor, an inductor, and a discharge switch. The modules can be fired independently. This provides some flexibility over the length and shape of the pulse. However since the capacitors are staged, the acceleration on the projectile has a higher jerk. A typical current profile obtained from this PFN is shown in Fig. 2. Four independent switches are required, each delivering a fraction of the total action but approximately the same peak current. Typically these high energy density capacitors are sensitive to voltage polarity, with the result that crowbar switches are required across the capacitor to ensure that they do not get charged with an opposite polarity.

Weight Considerations

The main issues associated with the capacitors in a PFN are the weight and output current capability. The peak current in the 30 mm railgun is approximately 620.0 kA. This corresponds to a peak acceleration of 240 kgee using an



	CIRCUIT ELEMENT PARAMETERS			
	1	2	3	4
C (mF)	17..95	17.95	17.95	11.96
L (µF)	2.35	2.35	1.2	0.5
R (mΩ)	0.583	0.583	0.583	0.875
S (DELAY TIME mS)	0	0	0.5	0.8

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Fig. 1. PFN circuit diagram. A minimum-weight PFN consists of four modules connected in parallel to the load.

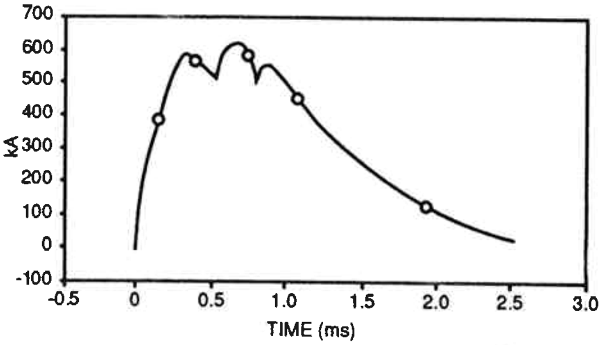

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Fig. 2. Current delivered to the gun by the PFN. Four switches are required, each delivering a fraction of the total action but approximately the same peak current.

augmented gun, on a launch mass of 120 g for a muzzle energy of 277 kJ. The typical efficiency obtained with this system is approximately 30%. This efficiency is the ratio of the launch package muzzle energy to the initial energy stored in the capacitor and therefore includes the PFN transfer efficiency. This implies that the energy stored in the capacitors must be about 930 kJ. At higher currents (1.2 A) the transfer efficiency of the PFN would be low. Initial estimates indicate a charging efficiency of about 80% with 1.3 J/g capacitors and 95% with 0.77 J/g capacitors.

At least two manufacturers produce capacitors that can provide high currents at high energy densities—Maxwell Laboratories and Aerovox. Table I summarizes the result of the comparison between different capacitor technologies for these manufacturers.

TABLE 1. CAPACITORS FOR A 1.1 MJ PFN

Manufacturer	Energy Density (J/g)	Current per Unit Energy (A/J)
Maxwell Labs	0.33	3.0
Maxwell Labs	0.77	1.2*
Aerovox	0.77	2.5

* Private communication with pulse power Government labs

The 0.33 J/g capacitor can provide the high currents without any capacitor modifications; however they are also the heaviest. The other two capacitors can also supply the required currents provided that the internal modules that comprise the 50 kJ capacitor unit are wired in parallel. This means that the operating voltage of the capacitor will be divided by the number of internal modules, which in the case of the Aerovox capacitors, is three. This operating voltage reduction is not a problem for railgun applications. Specifically the 50-kJ Aerovox capacitor used for the 11-MJ mobile PFN at FMC can provide 125 kA current at 5.33 kV.

Very recently, Aerovox has made available a capacitor with an energy density of 1.5 J/g. Unfortunately, this capacitor cannot provide the current levels required for railgun applications. However, with some risk, a capacitor can be developed with the 1.5 J/g technology to provide the required current. The improvement in output current, however, will be associated with a decrease in energy density. The energy density at which the capacitor will provide the required current is 1.2 to 1.3 J/g. In this case the total weight of the capacitor bank will be 719 kg. One must note that the 1.5 J/g capacitor technology is less efficient than the 0.77 J/g technology. This puts additional burden on the prime mover and alternator requirements.

ALTERNATOR FLYWHEEL SYSTEM DESCRIPTION

Discussion on the Charging Technique

This portion of the study details fundamental considerations in the choice of a system to repetitively charge a capacitor bank on a continuous basis. The problem is further defined as follows:

Capacitor bank size	935 kJ
Charging Voltage	5.33 kV
Charging frequency	5 Hz
Number of charging cycles	18

In order to charge at the desired rate, a minimum average power consumption is implied:

$$(935\ \text{kJ}) \times (5\ \text{cycles}/\text{s}) = 4.675\ \text{MW}$$

At these power levels, losses become important both from an energy storage viewpoint and from the standpoint of the requirement to dissipate waste heat. Significant differences in cycle efficiencies can occur depending on the manner in which charging is accomplished. In general, in order to maximize the efficiency of charging a capacitor, the charging must be accomplished in the maximum time permissible. This is in contrast to the charging of inductors where the time must be minimized. Three basic charging schemes for capacitors can be identified:

- Constant voltage charging
- Constant current charging
- Resonant charging

With constant voltage charging, a series resistor is employed to limit the peak current through the capacitor. With this scheme, the energy dissipated in the series resistor can be shown to equal the energy delivered to the capacitor at the end of each charging period. This limits the maximum efficiency to less than 50% and it is therefore undesirable.

The constant current charging scheme is considerably more efficient and inherently protects against overcurrents into an initially uncharged capacitor. Constant current charging is the most efficient of the various charging schemes, thus yielding a benchmark technique which can be used to establish fundamental limitations and to evaluate other charging techniques.

The constant current charging scheme has a power requirement which increases linearly with time, being a maximum at the end of the cycle. This maximum power is twice the average power. The resonant charging scheme provides two advantages over the constant current charging scheme:

- it reduces the power requirement on the rectifiers by 25%
- it eliminates active control of the firing angle on the SCR's to maintain constant current

It provides these advantages at a slight penalty in the efficiency which is lower by about 20% compared to the constant current case. For this application, the time between shots is relatively large-0.2 s. This implies that the resonant frequency must be 2.5 Hz. The inductor required in series with the capacitor is therefore quite large (0.305 H). This value is obtained using the relation:

$$L = \frac{1}{(2\pi f_o)^2 C}$$

here,

f_o = 2.5 Hz
C = the capacitance to be charged

A fourth charging scheme which has significant potential combines advantages of the constant current scheme with the constant voltage scheme. The constant voltage charging scheme as it is commonly applied has poor efficiency because of a current limiting series resistor. In the hybrid scheme the internal impedance of the alternator on the ac side of the rectifier is used to limit the peak current. Since the internal impedance of the alternator is predominantly inductive, the losses are negligible. The current therefore remains fairly constant initially until the capacitor voltage reaches a sufficiently high value after which the current is allowed to droop, thus reducing peak power. Active control of the firing angle of the SCR is not required, thus simplifying the rectifier. Initial designs and simulations of this scheme show promise, and it should be investigated further.

BASELINE PFN CHARGING SYSTEM DESCRIPTION

The charging system is comprised of an alternator which generates 3-phase ac power at fairly high frequencies-700 to 500 Hz. The alternator generates the required voltage internal to the machine and is connected directly to a three phase rectifier. The output of the rectifier is connected to the capacitors which are arranged in parallel. Charging of the capacitors is accomplished in less than the available time interval of 0.2 s. This charging is done at constant or near constant current.

Adequate energy is stored in the flywheel to complete three salvos without remotoring between shots. The drop in energy over one engagement is about 50% which implies a drop in speed to about 70% initial value. The voltage of the alternator is maintained at the desired value, when the speed drops, by adjusting the field current. The technical specifications of the alternator are given in Table II.

BASELINE FLYWHEEL DESIGN

The alternator flywheel design for the system is based on the minimization of over all system mass. To reduce the number of bearings and couplings, the flywheel is mounted integrally with the alternator rotor (Fig. 3). The material used for the flywheel is a combination of fiberglass and graphite composites. Due to their high specific strengths, these materials can store more energy per unit volume than metallic material. Since stored energy is proportional to the

TABLE II. TECHNICAL SPECIFICATIONS OF THE ALTERNATOR

Parameter	Units	Value
Generator type	---	3 Φ--Wye connected
Peak outer current generated voltage/phase	kV	4.57
Peak outer current generated line to line voltage	kV	7.91
Machine speed	rpm	18,800
Number of poles	---	4
Electrical frequency	Hz	626.0
Synchronous reactance	Ω	16.144
Transient reactance	Ω	0.75
Transient time constant	s	0.16
Machine resistance per phase	mΩ	12
Peak power	MW	8.5
Field coil resistance	mΩ	100
Field coil current	A	64

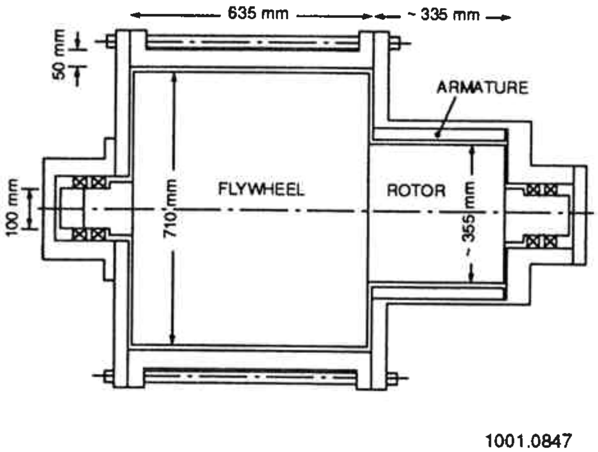

Fig. 3. Flywheel/alternator. An 800-m/s composite flywheel is integrated with the 4.675-MW alternator to provide a compact PFN charging supply and energy store.

radius^4 and linear with length, then minimization of the flywheel weight requires the flywheel to have a large diameter and a short length. However if the containment vessel mass is to be included, then that mass is proportional to the radius^2 and linear with length. This implies that a small diameter with a long length will minimize the containment mass. Calculation of the total system mass over a range of radii for a given stored energy will show that there is a minimum mass or minimum volume system.

In order to calculate the containment mass for the flywheel requires consideration of the mode of failure of the flywheel. An energy balance before and after the failure can be written as:

$$\frac{1}{2} I_1 \omega^2 = \sum_n \frac{1}{2} I_{2i} \omega_{2i}^2 + \sum_n \frac{1}{2} M_{2i} v_{2l}^2 \qquad (1)$$

where,

n = the number of fragments

Also an angular momentum balance before and after can be written as:

$$I\omega = \sum_n \frac{1}{2} M_{2i} vr \sin\theta + \sum_n I_{2i} \omega_{2i} \qquad (2)$$

where,

θ = the angle the segment flies off at

r = the distance from the original rotor center of mass (COM) to the segment

Consideration of the kinematic conditions immediately before and after the fragmentation provides a third equation relating the variables ω_2, v_2 and θ.

The rotor containment vessel has to contain the translation portion of the kinetic energy in (1). If the rotor fails in two fractions, then it can be shown [4] that the translation energy will be 46% of the in initial energy. If it fails in many small pieces then the translational energy fraction will rise to a higher percentage.

Depending on the angle θ that the fragment comes off at, the fragment will impact the containment wall and then rotate (counter to the rotor rotation direction) about the impact point. This means the translational energy will be split into a direct radial pressure energy and further rotational energy. This rotational energy along with the rotational energy term from (1) will exert itself as a torque on the machine structure. For a two piece failure, the radial energy is 26.4% of the initial energy. For many small sectors the radial energy fraction rises.

Using the above assumption that the rotor is expected to fail in to several large fragments, one half of the rotor energy will have to be absorbed as pressure energy and the remaining half will be absorbed as torsional energy.

In a containment vessel, there are three forms in which energy can be stored. The product of cavity pressure and the cavity volume is the internal stored pressure energy in the cavity. The product of the pressure and the change in volume due to elastic expansion of the containment is the energy stored elastically by the containment vessel. Finally, the product of the pressure and the change in volume of the cavity due to plastic growth of the containment vessel is the plastic energy. The first two forms of energy storage are non dissipative and will be present after the explosion is over. The last form is dissipated during the explosion. This is the energy form that needs to be maximized to lower the risk of containment failure.

In a thick walled vessel that undergoes plastic deformation, the elastic stored energy is very small compared to the plastic energy dissipated. Also for a rotating machine, there is likely to be a minimal gap between the rotor outer diameter and the containment inner diameter. This means that there will be little pressure energy stored in the rotor cavity. Hence this leaves the predominant part of the rotor energy to be absorbed as plastic energy.

To calculate the thickness of the containment wall, an approximate number can be derived from the following analytical method. The energy balance is written as;

$$\Delta E = P \Delta V \tag{3}$$

where,

E = the rotor energy to be dissipated
P = the pressure to plastically yield the containment vessel
ΔV = the change in volume as plastic deformation occurs

Also assume that the pressure can be expressed as (4) from thin wall theory [5].

$$P = \sigma t / r \tag{4}$$

where,

σ = the material yield stress

The change in volume is expressed as

$$\Delta V = \pi\left(r_2^2 - r_1^2\right) 1 \,(1 - ev) \tag{5}$$

where,

r_2 = the radius after the plastic growth
r_1 = the radius at the onset of plastic growth
(1-ev) = the change in length due to Poisson's ratio

To determine r_2, the maximum permissible plastic elongation (e) the material can undergo prior to failure must be known. For Titanium, 6A14V it is approximately 15%. For 6061 Aluminum it is approximately 10% and for 304 stainless steel it is approximately 50% [6]. The radius r_2 can now be expressed in terms of r_1 by

$$r_2 = r_1(1 + e) \tag{6}$$

substituting (4), (5), and (6) into (3) and rearranged for the required wall thickness as

$$t = \frac{\Delta E(1 = e)}{\sigma r_1\left[(1+e)^2 - 1\right]\pi 1 (1 - ev)} \tag{7}$$

Several assumptions have been made. They are that perfect plasticity occurs without any work hardening. Thin wall theory applies. Once plasticity starts it occurs across the whole wall section. No account is made for fastening on the end plates of the containment vessel.

A second method used to verify the required wall thickness (once an estimate from the above was made) was by using the numerical finite element method and summing up the total strain energy and the total plastic strain energy expended in expanding the containment vessel. Although easy to incorporate, work hardening effects were not incorporated due to the lack of work hardening models. The finite element formulation also accounted for the thinning of the wall thickness as the vessel expanded. The assumptions of thin wall theory or total plasticity across the wall were not made. This method provides a more accurate value of the necessary wall thickness.

Flywheel Design

The flywheel design was performed with a computer code that models a set of concentric rings assembled together with interferences [7]. The program had the capability to model isotropic and transversely isotropic materials. The criteria to satisfy in the design was that the rings have to remain in radial compression at all speeds. The rotor tip speed of 800 m/s was derived from the study of minimizing system mass. 800 m/s is well within the state of the art for composite flywheels. Table III gives the mass breakdown for two alternator/flywheels (40 and 14 MJ) using 1.3 J/g capacitor technology.

TABLE III. WEIGHT BREAKDOWN OF THE ALTERNATOR FLYWHEEL SYSTEM

Component	Mass (kg) Three salvos stored--40 MJ	Mass (kg) One salvo stored --14 MJ
Rotor	194	194
Flywheel	385	137
Shaft	58	38
Bearing	8	8
Laminations	231	231
Containment tube	485	121
End plates	248	92
Total	1609	822

SUMMARY

In summary, we have presented the design of an flywheel/alternator/PFN based power supply for driving a salvo fire, 30-mm railgun. We attempted to select performance parameters slightly beyond the state of the art and to configure the components as one would if system integration were required. Weight budgets for two systems, one using 0.77 J/g technology and one using 1.3 J/g technology are shown in Table IV.

TABLE IV. WEIGHT BUDGET

Component	Weight @ 0.77 J/g (kg)	Weight @ 1.3 J/g (kg)
Capacitors	1,214	719
Inductors	26	26
Buswork**	67	67
Coax lines** (2 m long)	56	56
Fuses	32	32
Switches*	54	54
Dump System	28	28
Crowbar System	54	54
Triggering circuitry	23	23
Back	60	60
Total PFN system	1,614	1,119
Total flywheel and alternator	1,355	1,609
Total rectifier	191	227
GRAND TOTAL	**3,160**	**2,955**

* The switches considered here are PI spark gap switches. They have been successfully used in FMC's 11 MJ PFN.

** A major issue in the design of this PFN is heat dissipation. The weight of the coax lines had been estimated so that the total temperature rise after 18 shots is about 55° C.

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