ROTATING MACHINES POWER SUPPLIES FOR THE NEXT GENERATION OF EM ACCELERATORS

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Introduction

The next generation of electromagnetic launchers (EMLs) will require compact, lightweight, power supplies which can generate high magnitude, repetitive current pulses of a very specific shape. Additionally, a simple, reliable system is required, in which logistic concerns are minimized. Rotating machines and, in particular, compulsators can supply these needs.

The compulsator is a specialized alternator which has been designed to produce a series of high power pulses. A number of advantages are inherent in the use of these devices for EML applications. In addition to high energy and power density and the lack of additional power conditioning components, the machines are well suited for the requirements of an electromagnetic (EM) gun circuit. The compulsator produces an alternating voltage which drives the current pulse through a current zero, achieving the desired pulse width. Therefore, the projectile leaves the gun at zero current without the need of a crowbar switch and more importantly, the magnetic energy stored in the discharge circuit is naturally recovered (as usable kinetic energy in the rotor). The compulsator is the only pulsed power supply in which energy recovery is practical without large mass and efficiency penalties.

In conjunction with the Defense Advanced Research Projects Agency (DARPA) sponsored Electric Energy Gun Study (EEGS)[1], conceptual designs of compulsator driven pulsed power systems for use in 18 missions of interest were analyzed. These missions, summarized in table 1, include a wide variety of projectile masses and launch energies. Power supplies were designed to accommodate five types of launchers for each mission: railguns, coilguns, thermal-electric guns, hybrid guns, and the advanced electric gun. The hybrid gun represents a railgun with a thermal-electric injector and the advanced gun is a hypothetical far-term coilgun. The results of this analysis, including a general description of the compulsator, design assumptions, the methods employed to achieve the desired pulse shapes, a discussion of magnetic energy recovery, gyroscopic effects, and scaling information is included. Further information on the EEGS study organization and conclusions is presented in a companion paper by Gully.[2]

Technical Discussion

Machine Description

During the EEGS, a variety of concepts were considered prior to the selection of the configuration shown in figure 1. An air core, rotating armature machine in which the outer segment forms the rotor was felt to be the most desirable in terms of energy and power density, efficiency, excitation requirements, minimal projectile acceleration, and thermal considerations. Air

Table 1. Electric energy gun missions

Mission Number	Mission Type	Flight Projectile Mass (kg)	Muzzle Velocity (km/s)	Nominal Kinetic Energy (MJ)	Allowable Accelerator ($\times 10^5 \text{m/s}^2$)	Launch Rate
1	Fire support	45	1.1	27	1.5	4 rounds in 15 s, 105 s between
2	Fire support	90	1.2	65	2.0	5 rounds in 120 s, 480 s between
3	Fire support	100	2.3	260	4.0	5 rounds in 120 s, 480 s between
4	Counter armor	5.3	1.7	7.5	6.0	2 rounds in 5 s, 22.5 s between
5	Counter armor	3.2	2.5	10	7.0	2 rounds in 5 s, 22.5 s between
6	Counter armor	2.4	2.5	7.5	7.0	2 rounds in 5 s, 22.5 s between
7	Counter armor	1.7	3.0	7.5	12.0	2 rounds in 5 s, 22.5 s between
8	Counter armor	8.0	1.7	12	6.0	2 rounds in 5 s, 22.5 s between
9	Counter armor	3.7	2.5	12	10.0	2 rounds in 5 s, 22.5 s between
10	Counter armor	2.5	3.0	12	10.0	2 rounds in 5 s, 22.5 s between
11	Counter air and missile	0.45	3.0	2.0	7.0	100 rounds in 2 s, 13 s between
12	Counter air and missile	0.45	2.0	0.9	7.0	100 rounds in 2 s, 13 s between
13	Counter air and missile	7.45	2.0	15	5.0	10 rounds per min
14	Counter air and missile	14.5	2.5	45	5.0	8 rounds per min
15	Counter air and missile	4.5	3.6	29	10.0	8 rounds in 30 s, 90 s between
16	Counter air and missile	14.5	3.6	94	5.0	0.5 rounds per min
17	Special operations	0.36	2.5	1.1	7.0	10 rounds in 10 s, 20 s between
18	Special operations	2.0	2.2	5.0	7.0	10 rounds per min

Figure 1. Near-term compulsator configuration

core refers to the use of epoxy reinforced composite materials for the majority of the rotor and stator structural components rather than the commonly used ferromagnetic materials. Due to the extremely high

strength and stiffness-to-density ratios of these materials, composite rotors can operate at much higher speeds, thereby achieving sizable gains in energy and power densities. Dramatically increased excitation requirements in terms of stored energy in the field and dissipative losses are the penalties of the concept.

Until recently, dissipative losses in the field coil were prohibitively large and necessitated the use of a cryogenically cooled winding for most missions. This problem has been addressed by the use of a secondary armature winding which is optimized for the self-excitation process. The secondary winding operates at a much higher voltage than the primary (20 to 40 kV) and therefore greatly reduces the charging time. After the discharge, the process is reversed and the energy stored in the magnetic circuit is recovered as kinetic energy in the rotor. Since the entire process only requires approximately 100 ms, the total losses have been reduced from tens of megajoules to a few hundred kilojoules. With this dramatic improvement in performance, a room temperature, water cooled aluminum winding may be utilized. A small capacitor provides the start-up current for the process and is recharged each cycle by the machine.

The machine can be described as ten basic components: the rotor, primary armature, secondary armature, end plates, bearings, brush mechanism, compensating winding, field coil, field coil support structure, and stationary shaft. The hollow cylindrical rotor is formed of concentric rings of glass reinforced epoxy composite and the two armature windings, composed of stranded and transposed aluminum litz wire, are epoxy bonded to its bore. A closed loop cooling system utilizing high pressure helium gas is employed to reject losses in the armature. Glass, rather than graphite composite is used in the majority of the rotor structure due to its high electrical resistivity (minimizing eddy current losses). The rotor is supported on either end by titanium plates which rotate on ceramic rolling element bearings. Ceramic rolling element bearings have tremendous advantages in terms of auxiliary requirements and electrical isolation and are capable of operating in these conditions.

The majority of the stator (inner segment of the machine) is composed of the field coil. The winding is contained by a graphite composite banding overwrap. A stationary compensating winding is epoxy bonded to the banding overwrap. The compensating winding can be connected in series with the armature or may consist of shorted turns in which currents are induced. Compensating currents can have the effect of lowering or raising the armature inductance and provide a primary method of high power generation and pulse shaping. The interaction of the compensating current and the rotating armature field produces a discharge torque in the stator which is transmitted through the field coil banding, support structure, the stationary shaft, and to the platform. Mounting the shaft compliantly to ground greatly attenuates the magnitude of the torque and reduces the size of the shaft and support structure.

Pulse Shaping

Optimum performance is obtained by maximizing the ratio of average-to-peak acceleration of the projectile which requires a specific current-time waveform. For the

launchers considered, it is possible to categorize the wave shapes into the two basic types shown in figure 2: (1) a flat topped current pulse as required by railguns and coil guns and (2) a wave shape with a ramp from zero-to-peak current, followed by a sharp drop, as required by thermal-electric guns.

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Figure 2. Basic current waveforms for electric guns

The compulsator is a versatile power supply which (through variation of the internal inductance of the machine) can provide both of these wave shapes. This is accomplished primarily by two methods, active and selectively passive compensation.

Figure 3 shows the schematic operation of an actively compensated machine. It is comprised of an armature winding moving relative to the excitation field, similar to a conventional, single-phase alternator. There is also a compensating winding, stationary with respect to the excitation field, and connected in series with the armature winding through brushes and slip rings. As the armature winding spins, relative to the compensating winding, the machine undergoes an inductance variation. In position A, the inductance is at a maximum since the current in both windings produces a flux in the same direction. In position C, which is 180° after position A, the inductance is at a minimum since the two currents

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Figure 3. Actively compensated compulsator

produce flux in opposite directions. The inductance of the machine therefore undergoes one complete variation for each variation of the generated voltage cycle. It is possible to position the compensating winding to provide a given phase difference between the inductance and generated voltage. This phase difference is important from the standpoint of current pulse shaping.

The difference between active and selectively passive compensation, shown in figure 4 is that the compensating winding is not in galvanic contact with the armature winding, but is instead short-circuited on itself. The only coupling between these windings is through magnetic induction. Induced current in the compensating winding flows in a direction to exclude the flux produced by the armature winding. Therefore, when the magnetic axes of the two windings are aligned, as in position A or C (fig. 4), the armature inductance is at a minimum. In position B, there is no coupling between the two windings and the armature inductance is at a maximum. The inductance of the armature winding thus undergoes two variations for each variation of the generated voltage cycle. As applied to the loads represented by the guns studied, active compensation is used to drive a ramped pulse required by the thermal electric guns, and selective compensation is used to supply a trapezoidal shaped pulse for the railguns and coil gun. More detailed explanations of these pulse-shaping techniques have been previously published in reference [3].

Figure 4. Selectively passive compensator

Gyroscopic Effects

A vehicle-mounted compensator will produce some gyroscopic moments on the chassis as it is maneuvered. If the compensator is mounted transversely in the vehicle, moments tending to tip the vehicle onto its side will be generated as the vehicle is pivoted or makes a high-speed turn. Calculations indicate that these effects will not impose significant maneuverability constraints on a

120,000-lb chassis. It is estimated that a vehicle would have to pivot at a rate of one complete revolution in 4 s before the overturning moment would be sufficient to lift one side. This concern and other vehicle perturbations due to discharge torques may be addressed through the use of a counter-rotating machine or by multiple machines which have an opposite sense of rotation. Counter-rotating machines have a disadvantage for single pulse concepts in that the pulse length is too short if high speed rotors are used. Consequently, if lower speed rotors are utilized many of the gains of the composite materials are lost.

A pair, or multiple pairs of machines, with the rotor of each machine rotating in an opposite sense, addresses the mounting concerns without a significant loss of performance. It is possible to operate two machines in parallel, in series, or staged in time to produce the desired pulse to the gun. Machine synchronization, historically, a concern with the use of multiple machines, can be addressed easily during the excitation stage by operating the secondary armatures in series or parallel. For the purposes of this study, single machines were sized, and the use of two machines would add approximately 10% to the mass estimates for each mission.

Magnetic Energy and Energy Recovery

The compulsator produces an alternating voltage which, when properly timed, drives the current to zero as the projectile leaves the gun. There is a phase difference between the voltage and current waveforms such that the generated voltage changes polarities during the latter part of the pulse. Since the current is always positive, it is evident that the direction of energy flow has reversed during this period and the stored energy of the compulsator is actually increasing.

This is shown graphically in figure 5. This figure has been generated based on the 9 MJ range gun design, but similar trends have been experimentally observed when discharging the rapid-fire compulsator (iron-core machine) into a railgun. There are three energy storage mediums and two dissipative terms which enter the discharge circuit. In addition to kinetic energy storage in the flywheel of the machine, energy is stored magnetically in the field produced by the armature compensating windings and bus. Also, magnetic energy is stored in the gun. Energy is dissipated or absorbed by the gun (including rail resistive losses, armature losses, projectile drag, and projectile kinetic energy) and resistively in the windings and bus. The gun losses represent what is generally referred to as delivered energy to the gun, and the change in rotor energy is displayed, with positive values representing energy loss.

Obviously, the dissipative sums are constantly increasing, representing energy lost from the circuit, and since current is zero at the end of the pulse, no magnetic energy is left in the system. Since no additional dissipative elements have been introduced (such as resistive crowbar) the magnetic energy has been deposited in the other terms. There is therefore an interaction between the storage mediums as energy is transferred between these elements. During the pulse, a large portion of the energy extracted from the rotor is stored magnetically. Initially, this energy is primarily in the

Figure 5. Compulsator driven railgun energy vs. time

fields produced by the armature and during the later stages of the pulse, the gun magnetic field represents the dominant storage medium. Although these elements are connected in series, the magnitude of stored energy is displaced in time due to changing inductance. The compulsator circuit reaches a peak inductance midway in the pulse and then decays while the gun inductance is dependent upon the position of the projectile, and therefore rises rapidly near the end of the discharge.

The change in rotor energy peaks (representing maximum energy extracted) at approximately 3.8 ms for this example. At this time, the magnetic energy in the armature is decaying and at $\approx 50\%$ of its peak value, the gun magnetic energy is near its peak, and the energy delivered to the gun is about 60% of its full value. From this point on, stored magnetic energy in the armature and gun is driving the circuit. The remainder of the energy being dissipated in the gun, windings, and bus, and the recovered kinetic energy in the rotor are being supplied from these stores.

At the end of the pulse, the rotor has lost 24 MJ; 18 MJ being delivered to the gun, and 6 MJ dissipated resistively into the windings and the bus. However, during the pulse, a maximum of 36 MJ was extracted from the machine, 12 MJ of which was later recovered.

Design Assumptions

A list of assumptions used in the study is presented in table 2. The list includes the actual parameters of the present CEM-UT 9 MJ range gun system and those assumed for the near and far-term systems.

The allowable peak shear stress of the epoxy system encapsulating the armature winding is a critical assumption. The peak power which the machine is

capable of generating and, therefore, the machine size for a given mission is related to this parameter. The current value of 3,500 psi has been verified by numerous tests at CEM-UT over the last eight years. Based on a study by PDA Engineering [4], the assumption of 8,000 and 12,000 psi for the near- and far-term missions is justified.

Table 2. Compulsator design assumptions

	PRESENT	NEAR TERM	FAR TERM
Outside Rotating Geometry	no	yes	---
Counter-Rotating Geometry	no	no	yes
Cryogenic Field Coil	no	no	no
Superconducting Field Coil	no	no	no
Epoxy Shear Stress (peak) (psi)	3,500	8,000	12,000
Tip Speed (m/s)	550	800	1,000
Average/Peak Acceleration	0.6	0.65	1
Rotor Material	glass	glass	graphite
Allowable Rotor Stress (ksi)	160	275	300
Bearing System	hydrostatic	ceramic rolling element	ceramic rolling element
Heat Rejection Equipment (kW/kg)	---	5	7
Capacitor Energy Density (kW/kg)	3	9	17

The compulsator designs are based upon four inputs from the EEGS Propulsion Panel: delivered energy to the gun, pulse length, time between shots, and number of shots per burst. It is assumed that the railgun missions will require voltages of approximately 10 kV, while the other accelerators will need voltages greater than 20 kV for efficient operation. This assumption has driven the design of the primary armature and has an influence on the rotor stresses, armature temperature rise, and armature loss calculations.

In addition to the compulsator, several auxiliary systems are necessary. These include the self-excitation diodes, start-up capacitor, and bus. Requirements of the auxiliary systems, with the exception of the controls, have been sized individually for each mission. The capacitor is sized to provide a start-up current of one-tenth the peak field current. Diodes (required for the self-excitation process) are estimated from P_{avg} (per unit) = 188 MW/t^{1/2} and mass (per unit) = 15 lb.[5]

The estimate of required prime power includes: (1) the energy supplied to the gun, (2) resistive losses in the armature, field coil, compensating winding, and buswork, (3) losses in the bearings and seals, and (4) the energy supplied to the start-up capacitor for each shot.

For the 16 missions with burst requirements, the prime power requirement is minimized through the use of an energy storage flywheel. The flywheel operates at a much higher energy density than the compulsator since the additional structural concerns of power generation

are not imposed. A value of 75 kJ of delivered energy per kg of flywheel mass was assumed. This is based on an 1,100 m/s tip speed and assumes the flywheel (which is hard coupled to the compulsator) slows to 87% of the original speed during the burst (25% energy extraction). The flywheel is sized to provide sufficient energy for a burst of shots, allowing the prime power to be delivered steadily over the time between bursts, as well as during bursts.

Design Process

The input variables include: the rotor tip speed, inner and outer radii, angular span of the field coil, average excitation flux density, peak current in the field coil, peak voltage of the secondary armature (used to drive the field coil), the ratio of the average field coil radius to the armature winding radius, the thickness of the armature conductor and number of turns per pole, and a factor which modifies the calculated rotor length. From these variables and the constants, approximately 74 dependent parameters are calculated and used to determine the total system mass. These parameters include a wide variety of relevant calculations such as: dimensions, component masses, impedances, stresses, temperature rise estimates, current densities, magnetic fields, an energy balance, and auxiliary requirements.

Results of these dependent parameter calculations are then examined with respect to various constraints. The most obvious requirements are: (1) store sufficient energy for field excitation, (2) deliver required energy to the gun, (3) provide the required pulse length for projectile acceleration, (4) observe shear strength (power surface density) limitations, (5) observe tensile limitations of composites (minimum thickness of flywheel), (6) provide sufficient voltage, (7) provide sufficient volume for the field coil, and (8) observe temperature limits for windings and bus. All together, 37 constraints are checked to ensure that a workable design has been reached. Input variables are then altered to produce an optimum design.

Results

Results of the compulsator system designs for the 18 missions and five types of launchers are presented in table 3. The table presents compulsator mass, flywheel mass, total power conditioning mass (compulsator, flywheel, and auxiliaries), volume, prime power (shaft input power), and heat rejection rate.

Scaling Relationships

The algorithm required to perform the detailed designs is very complicated and requires that the user have considerable insight and experience in the field for proper utilization. Consequently, an alternate scaling method has been derived for simplified estimation. The scaling relationships shown are based on curve fit routines or averages of the parameters derived in the detailed design process. Caution should be used in exercising these algorithms as an error band of up to 50% is present for some cases.

It was found that the compulsator mass can be correlated with the ratio of delivered energy to pulse width:

$$E_{del} / M_{comp} = 4.509 + 2.742 \log (E_{del} / T_{pulse})$$

where

$$\begin{aligned} E_{del} &= \text{the delivered energy per shot in MJ} \\ M_{comp} &= \text{compulsator mass in kg} \\ T_{pulse} &= \text{pulse length in ms} \end{aligned}$$

The compulsator volume can be estimated using a machine density of 2,200 kg/m³.

The length-to-diameter ratio of the machines has fallen in the 1 to 2 range. Using an average value of 1.2, one can determine the envelope dimensions from

$$\text{diameter} = \left(\frac{4 \times \text{volume}}{1.2\pi} \right)^{\frac{1}{3}}$$

$$\text{length} = 1.2 \times \text{diameter}$$

Prime power is based on a calculated average efficiency of 0.78 (ratio of E_{del} to E_{del} + losses). Therefore, with a flywheel:

$$\text{power} = (E_{del} \times \text{shots} / \text{burst}) / [0.78(T_{burst} + T_{between})]$$

where

$$\begin{aligned} T_{burst} &= \text{duration burst} \\ T_{between} &= \text{time between bursts} \end{aligned}$$

Without a flywheel,

$$\text{power} = E_{del} / (0.78 \times \text{time between shots})$$

The average heat rejection rate is equal to the fraction of prime power dissipated in losses:

$$\text{heat rejection rate} = \text{power} \times (1 - 0.78)$$

Based on averaging the results of the detailed designs, auxiliaries mass may be estimated as 7.3% of compulsator mass.

The compulsator stores enough energy for one shot. For missions with bursts, the compulsator provides the energy for the first shot. Rather than provide prime power to reaccelerate the compulsator for each shot in the rest of the burst - a prohibitive power requirement for many of the missions - a flywheel can be used to provide the energy needed for the subsequent shots. The prime power source then has the time between bursts as well as during bursts to provide energy to the system.

The flywheel is sized to supply the energy for all of the shots in the burst after the first, minus the energy contributed by the prime power source during the burst. Thus, the required flywheel mass at 75 kJ/kg delivered is

$$m_f = (\text{shots} / \text{burst} - 1)(E_{del} / 0.78 - T_{shot}P_{in}) / 75$$

where

$$\begin{aligned} T_{shot} &= \text{time per shot} \\ P_{in} &= \text{prime power input in kW} \end{aligned}$$

Table 3. Mass, volume, shaft input power, and heat rejection of compulsator systems

GUN		MISSION																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Compulsator Mass (tons)	Rail	7.9	12.8	26.6	2.4	2.7	2.5	2.3	3.5	3.5	3.5	1.2	0.8	3.4	7.1	4.4	12.6	0.9	1.7
	Thermal	3.4	5.8	33.2	1.5	2.5	2.6	---	2.6	---	---	---	0.4	2.5	7.8	---	---	0.5	1.0
	Coil	6.7	13.1	43.9	2.6	3.1	5.4	5.2	3.6	4.6	5.5	1.8	0.7	3.7	8.6	12.8	---	0.9	1.7
	Hybrid	---	---	28.8	---	2.1	2.0	1.8	---	3.4	3.0	0.8	---	---	6.2	3.3	9.9	0.7	1.2
	Advanced	6.4	10.5	20.1	2.4	1.8	1.6	1.4	2.9	2.2	1.9	0.8	0.7	2.8	5.5	3.1	7.3	0.9	1.3
Flywheel Mass (tons)	Rail	2.42	5.97	22.7	0.21	0.29	0.27	0.29	0.36	0.46	0.50	11.6	4.58	---	---	5.54	---	0.39	---
	Thermal	0.92	2.58	33.8	0.14	0.34	0.36	---	0.29	---	---	---	2.72	---	---	---	---	0.24	---
	Coil	1.74	5.60	35.4	0.16	0.31	0.28	0.76	0.27	0.54	0.74	10.3	3.43	---	---	19.0	---	0.27	---
	Hybrid	---	---	24.2	---	0.21	0.20	0.25	---	0.47	0.46	8.29	---	---	---	4.45	---	0.21	---
	Advanced	1.53	3.99	15.0	0.11	0.14	0.12	0.13	0.18	0.19	0.21	4.58	2.29	---	---	3.48	---	0.14	---
Total Power Conditioning Mass (tons)	Rail	10.9	19.7	51.2	2.8	3.2	3.0	2.7	4.2	4.2	4.3	12.8	5.4	3.7	7.6	10.3	13.5	1.4	1.8
	Thermal	4.6	8.8	69.4	1.7	3.0	3.1	---	3.0	---	---	---	3.2	2.7	8.3	---	---	0.75	1.1
	Coil	8.9	19.7	82.6	3.0	3.7	6.1	6.3	4.2	4.5	6.6	12.2	4.2	4.0	9.2	32.7	---	1.2	1.8
	Hybrid	---	---	55.1	---	2.4	2.3	2.2	4.1	3.7	9.2	---	---	---	6.7	8.0	10.6	1.0	1.3
	Advanced	8.4	15.3	36.6	2.7	2.1	1.8	1.6	3.3	2.6	2.2	5.4	3.0	3.0	5.9	6.8	7.9	1.1	1.4
Total Power Conditioning Volume (m ³)	Rail	5.1	9.4	25	1.3	1.5	1.4	1.3	1.9	1.9	2.0	6.7	2.8	1.7	3.5	5.1	6.1	0.64	0.83
	Thermal	2.1	4.2	34	0.81	1.4	1.5	---	1.4	---	---	---	1.6	1.2	3.8	---	---	0.37	0.49
	Coil	4.2	9.3	40	1.4	1.7	2.8	2.9	1.9	2.5	3.1	6.3	2.1	1.8	4.2	16	---	0.58	0.83
	Hybrid	---	---	27	---	1.1	1.1	1.0	---	1.9	1.7	4.8	---	---	3.0	4.0	4.8	0.45	0.59
	Advanced	3.6	6.8	18	1.1	0.95	0.84	0.75	1.5	1.2	1.0	2.8	1.5	1.4	2.7	3.3	3.6	0.51	0.63
Shaft Input Power (MW)	Rail	2.87	1.72	6.54	2.58	3.54	3.23	3.58	4.33	5.63	6.08	80.5	31.8	7.60	17.6	8.71	2.59	3.29	3.12
	Thermal	1.09	0.74	9.74	1.69	4.17	4.39	---	3.49	---	---	---	18.9	6.35	23.9	---	---	2.00	2.26
	Coil	2.07	1.62	10.2	1.95	3.79	3.45	9.19	3.33	6.55	8.96	74.5	23.9	7.75	18.9	29.9	---	2.26	2.58
	Hybrid	---	---	6.98	---	2.57	2.40	3.01	---	5.72	5.62	57.6	---	---	15.1	6.99	2.17	1.74	1.96
	Advanced	1.82	1.15	4.34	1.39	1.77	1.52	1.60	2.16	2.35	2.58	31.8	15.9	4.78	11.5	5.47	1.50	1.22	1.53
Heat Rejection Rate (MW)	Rail	0.65	0.39	1.48	0.58	0.80	0.73	0.81	0.98	1.27	1.37	18.2	7.19	1.72	3.97	1.97	0.59	0.74	0.71
	Thermal	0.25	0.17	2.20	0.38	0.94	0.99	---	0.79	---	---	---	4.27	1.44	5.41	---	---	0.45	0.51
	Coil	0.47	0.37	2.31	0.44	0.86	0.78	2.08	0.75	1.48	2.02	16.8	5.39	1.75	4.28	6.75	---	0.51	0.58
	Hybrid	---	---	1.58	---	0.58	0.54	0.68	---	1.29	1.27	13.0	---	---	3.42	1.58	0.49	0.39	0.44
	Advanced	0.41	0.26	0.98	0.31	0.40	0.34	0.37	0.49	0.53	0.59	7.2	3.59	1.08	2.60	1.24	0.34	0.27	0.34

Far-Term Designs

The far-term compulsator designs assume a polyphase winding and an advanced gun that can accept ac current; therefore, the machine can supply several pulses during discharge. This alleviates the constraint on pulse width, and the machine may be sized by power considerations such as tip speed, shear stress, and acceleration ratio. Based on these factors, the far-term systems should achieve $E_{del} = 28 \text{ kJ/kg}$ with the same machine density of $2,200 \text{ kg/m}^3$ and the same relationship between length, diameter, and volume as the near-term designs.

Summary

Compulsator designs have been calculated for the 18 missions of interest for each of the five accelerator types. During the course of the study, several important improvements have been incorporated which have drastically reduced the size of the devices. Most notable among these are the use of a second armature winding to efficiently excite the field coil and eliminate the need for liquid nitrogen (or any cryogenic fluid) and the utilization of ceramic rolling element bearings. The assumptions made are, for the most part, slightly conservative, and certainly achievable within the near-term time frame. For each design, over a hundred different parameters have been calculated and 37 constraints are satisfied, ensuring a realizable and consistent result. The machines have been sized to account for all magnetic energy requirements and the compulsator is unique in its ability to efficiently recover magnetic energy from the launcher. Finally, a simple method of estimated compulsator mass and size has been presented.

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