Marine Applications of Power Supply and Conditioning Interfaces for High Power Pulse Devices

by

Ronald J. Rutan

Bachelor of Electrical Engineering, Texas A&M University, 1995

SUBMITTED TO THE DEPARTMENTS OF OCEAN ENGINEERING AND ELECTRICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREES OF

MASTER OF SCIENCE,
NAVAL ARCHITECTURE AND MARINE ENGINEERING,

and

MASTER OF SCIENCE,
ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September, 2002

Signature of Author:______________________________
Department of Ocean Engineering
August 09, 2002

Certified by:______________________________
James L. Kirtley Jr.
Professor of Electrical Engineering
Thesis Supervisor

Certified by:______________________________
John Amy
Associate Professor of Ocean Engineering
Thesis Supervisor

Accepted by:______________________________
Arthur C. Smith
Chairman, Committee on Graduate Students
Department of Electrical Engineering and Computer Science

Accepted by:______________________________
Henrik Schmidt
Chairman, Committee on Graduate Students
Department of Ocean Engineering

Marine Applications of Power Supply and Conditioning Interfaces for High Power Pulse Devices

by

Ronald J. Rutan

Submitted to the departments of Ocean Engineering and Electrical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Naval Architecture and Marine Engineering and for the Degree of Master of Science in Electrical Engineering and Computer Science

Abstract

Numerous high power pulse devices are being considered for marine applications, particularly military vessels to include Electro Magnetic Aircraft Launching System, Electro Thermal Gun (ETG), Particle Beam Weapons, High Powered Lasers, and Rail Guns which are directly considered in this thesis. Currently marine vessels do not have the power generation capability to deliver the massive power over the short duration required. The weight, volume, and environment constraints inherent in marine vessels limit the development of a method to store the power and deliver it upon request with a sufficient repetition rate as needed by mission requirements.

This thesis mathematically models Flywheels, Superconducting Magnet Energy Storage (SMES), Capacitors, Compulsators, and Batteries as energy storage devices and graphically illustrates pertinent data (weight, volume, etc) per pulse power application for the ship designer to determine suitability for marine vessels.

Thesis Supervisor: James L. Kirtley

Title: Professor of Electrical Engineering and Computer Science

Thesis Supervisor: John Amy

Title: Associate Professor of Ocean Engineering

Table of Contents

Table of Tables

Table of Figures

1. Introductory Matter

1.0. Definition of Pulse Power within Marine Constraints

Numerous high power pulse devices are being considered for marine applications, particularly military vessels. These devices include Electro Magnetic Aircraft Launching System, Electro Thermal Gun (ETG), Particle Beam Weapons, High Powered Lasers, Rail Guns, and other High Order Applications. These applications require a large amount of power over a short period of time. Presently marine vessels do not have the power generation capability to deliver a massive amount of power over the short duration required. A method to store the power and deliver it upon request with a sufficient repetition rate as needed by mission requirements needs to be developed. The weight, volume, and environmental constraints inherent in marine vessels limit this development.

1.1. Statement of Problem:

Numerous high power pulse devices are being considered for marine applications, particularly military vessels. Three of these devices will be considered in this thesis and are outlined in Table 1 below. Table 1 outlines the power level, energy level, power duration (time), and the pulse repetition rate (how long before the next pulse?) requirements for EMALS, ETG, and higher order applications.

Table 1.1: Application parameters

Application	Power Level	Energy Level	Power Duration	Pulse Repetition Rate
EMALS	40 MW	121 MJ	3 sec	45 sec
ETG	160 MW*	400 kJ	2.5 msec	5 sec
Higher Order Applications	10 GW	20 MJ	2 msec	.1 sec

*Computed from a 400kJ pulse with a time duration of 2.5 msec.

These marine pulse power applications require large amounts of power over a short period of time. Marine vessels have not been outfitted with the power generation capability to deliver a massive amount of power over the short duration required. The development and installation of these systems is constrained by the weight, volume, and environmental limitations inherent in marine vessels.

The discussion of this thesis will be limited to the energy and power requirements listed above and the energy storage devices capable of delivering the required pulse power. Being mindful of naval architecture constraints, the same general arguments and numerical justifications can be used to determine the "best" energy storage device for any given high-powered application.

1.2. Solution

A math model of Flywheel, SMES, Capacitor, Compulsator and Battery energy storage and power delivery was constructed to determine the best solution for each end use demand (EMALS, ETG, Higher Order Applications). The energy storage and conditioning device modeling identifies the charging time, pulse length, power requirement, repetition rate, deliverable power, volume to power ratio, weight to power ratio, and the versatility of distribution (e.g. can the power and conditioning system be placed low in the marine vessel?). Compulsators were also considered, but a parametric math model was constructed instead of the dramatically more complicated, in depth model which would have been more accurate. Other concerns were addressed, such as the need for maintaining SMES low temperatures, containment vessels for catastrophic failures resulting in high kinetic dissipation of energy (e.g. flying debris), and other issues unique to a particular energy storage device. Trade off comparisons have been conducted and presented graphically to determine the "best solution" for the end use power demand applications.

The number of possible combinations of power supply, energy storage, end use device, and platform on which they would be installed is somewhat overwhelming and cannot all be covered in this thesis. However, the analysis method, and tools employed for one such combination can easily be applied to any other combination with adjustments by the ship designer.

This thesis will consider three end use devices (EMALS, ETG, High Order Application: "Directed Energy Weapon") on an aircraft carrier. The three end use devices were chosen to represent a broad spectrum of power requirements, which in turn may dictate a different "best" solution energy storage device. The weight and volume limitation values are intangibles dependent upon the multiple tradeoffs in ship design and are not directly considered in this thesis. Therefore, an aircraft carrier was chosen to simplify this thesis such that the reader could more easily consider the possibility of the high energy storage systems without the hard constraints of weight and volume more apparent in smaller vessels. An aircraft carrier has relatively larger mass and volume limitations and has much larger electric power plants (104MW). Of course an all-electric ship would provide an immense amount of electrical power to recharge the energy storage device while only sacrificing minimal ship speed.

1.3. Concept Level Ship Design

Using the math models in the appendices of this thesis or by devising similiar math models, a competent naval engineer can incorporate the naval architecture outputs (weight, volume, power, etc.) in a high concept level ship design. In the design spiral (a naval architecture design concept), the ship designer will provide an energy strorage system which meets the specifications of the high powered pulsed application. This in turn will drive the weight, volume, and power allocations for the rest of the ship. The use of the high pulse powered application will determine the weight group the energy storage device will be assigned (e.g. an energy storage device for an ETG will be in weight group 700). For those who are not ship designers, this is not an easy task, since every introduction of a changing variable produces rippling effects in all other variables throughout the design.

1.4. Other considerations

Since the power needed by the marine vessel will probably be larger than the power generation systems capability onboard, a priority of power delivery has to be considered. These priorities will change depending on the real world operational concerns of the ship. In friendly waters, the priority of the propulsion system would be paramount to maintain safe navigation at sea. However, in hostile waters, the priority of weapons may exceed those of safe navigation.

The changing power priorities dictates the need to route power to primary applications while restricting power to other temporally nonessential applications during the "charge" cycle.

Example 1: An electric drive aircraft carrier can afford to route the propulsion power to the power storage/conditioning device for 5-30 seconds to fully charge the EMALS and then return to propelling the ship. The "loss" of propulsion would result in a probable loss of speed from 30 to 29 knots. This is a conservative approach; the actual loss in speed would be less than one knot as

$LT := 2240 lb \qquad Mass_{carrier} := 100000 LT \qquad knts := .5144444 \frac{m}{s} \qquad Velocity_2 := 30 knts$

$$Energy := \frac{Mass_{carrier} \cdot Velocity^2}{2}$$

$$\Delta_{Energy} := \frac{Mass_{carrier} \cdot \left(Velocity_2^{\,2} - Velocity_1^{\,2} \right)}{2}$$

$$\Delta_{Energy} := 8.1 \cdot 10^6 W \cdot 57 sec$$

$$Velocity_1 := \sqrt{Velocity_2^{\,2} - \left(\frac{2 \cdot \Delta_{Energy}}{Mass_{carrier}} \right)}$$

$$Velocity_2 - Velocity_1 = 0.578 knts$$

shown below.

The speed would be regained when the propulsion power is restored. The EMALS would be ready indefinitely until the launch of aircraft when the process would be repeated.

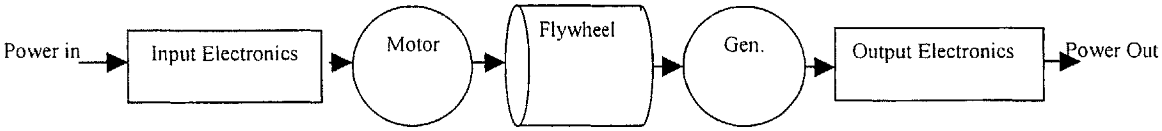
Example 2: After defensive weapons launch (Phalanx with a small ETG), the ship's vulnerability is increased until the energy is replenished in the energy storage device for the next defensive weapons launch. This vulnerability can be improved with a high pulse repetition rate for the weapon reducing the immediate need to replenish the discharged energy.

The ability to reroute power seems to be an inherent ability of the "All Electric Ship" concept being proposed by the U.S. Navy. The ability to reroute power will not be demonstrated in this thesis but can easily be simulated by changing the power supplied to the energy storage device in the math models in the appendices which will directly impact the charge cycle.

2. Flywheels

2.0. Flywheel Fundamentals

Notional flywheel schematic: The motor and generator (as well as electronics) would most likely be the same machine.



A flywheel is an electomechanical storage system which stores kinetic energy in a rotational mass.

$$E := \frac{I \cdot \omega^2}{2}$$

where,

E = the energy stored in the flywheel (N-m).
I = flywheel moment of inertia (N-m-sec^2) which is directly proportional to the mass of the cylinder.
ω = rotational velocity (rad/sec).

To increase the energy of the system, power is applied through the input electronics and variable speed motor resulting in an increased rotational speed of the flywheel. Energy is recovered from the system via the variable speed generator and output electronics. The amount of energy recovered from the flywheel system in a given time determines the power delivered.

Normally the power delivered to the flywheel system and the power recovered from the flywheel system is separated by some time interval. Therefore, the electronics and electric machine (motor or generator) can be dual purposed. In other words, only one set of electronics is needed for either power input or power output. The same applies for the electric machine. This results in reduced mass and volume thereby increasing the specific energy/power and energy/power densities.

Flywheels are typically constructed of either steel (to increase mass) or of a composite material (to increase maximum rotation velocity). Although steel is thought to be a relatively strong material, the maximum tensile stress is quickly reached at high rotational speeds. Highly complex carbon fiber materials are being used in flywheel systems to achieve speeds of 60,000 rpm. Where the steel flywheel relies upon the mass of the cylinder for energy storage ($E \alpha I$), composite flywheels rely upon the rotational velocity to maximize stored energy ($E \alpha \omega^2$).

As the density of the flywheel is reduced in composite flywheels, higher rotational speeds can be achieved for the same tensile stress. Kinetic energy is proportional to density (ρ) and velocity (v) squared ($KE= .5*\rho*v^2$). Whereas stress is proportional to $\rho*v$. This implies for the same stress, energy density is inversely proportional to ρ. (e.g. halving ρ and doubling v results in the same stress but a higher KE)

2.1. Energy Losses

2.1.1. Windage Losses

To decrease and nearly eliminate windage losses, the containment vessel for the flywheel is usually evacuated (of air). Maintaining a vacuum on the containment vessel is a parasitic energy loss, but is less than the expected windage loss.

2.1.2. Energy Conversion

The input power to the flywheel system is converted numerous times before it is in turn delivered to the end use item (output power). The AC input power is converted to direct current which is in turn converted to a variable frequency for the variable speed motor. The electrical energy is then converted to kinetic energy via the electromagnetic coupling of the variable motor. The losses are all encountered again converting the kinetic energy to the final output of the flywheel system.

2.1.3. Other Losses

Other losses can be expected from rotational friction of the flywheel bearings. Some flywheel systems are being proposed and constructed using superconducting magnetic bearings which have no frictional losses. However, other parasitic losses are introduced in order to maintain the very low temperatures required by the superconducting material. The bearing losses were lumped with other parasitic losses in accordance with the parametric assumptions for the M4 DC Flywheel

Power System of AFS TRINITY Power Corporation. No differentiation was made between types of bearings due the limitations of this thesis.

2.2. Two types of flywheels

As can be seen by the following table, two major types of flywheels can be developed.

	Flywheels: low- speed	Flywheels: high- speed
Maximum Power Rating	1650 kW	750 kW
Maximum Power Duration	~ 30 sec[Ref 35]	Minutes
Response Time	< 1 cycle (60Hz)[Ref 35]	< 1 cycle (60Hz)[Ref 2]
Capital Cost:		
Power- related, $ / kW	300[Ref 35]	400-800[Ref 2]
Balance- of- Plant	~ 80 $ / kWh[Ref 35]	~1000 $ / kWh[Calculated w/ Ref 2]
Operating Features:		
Efficiency	0.9[Ref 35]	0.93[Ref 2]
Parasitic energy reqt.	~ 1%	30 W/ kW
Lifetime/ Replacement	20 yrs[Ref 35]	20 yrs[Ref 1]
Size: This is area where volume/weight is the issue with marine vessels.	6.6 ft^2 / kWh[Ref 35]	3 - 4 ft^2 / kWh[Ref 2]
Siting Issues:		
Marine Vessels	Gyroscope effects	Gyroscope effects[Ref 1]
Environmental	None	None
Safety Issues	Containment	Containment
Technology Readiness	Commercial products	Low volume production

Table 2.1 Flywheel Comparisons (Ref #'s IAW Bibliography)

Although presently the low speed flywheel stores a larger amount of energy for a lower cost, the future development of composite rotors and implementation of High Temperature Superconductor (HTS) bearings will lower the cost of high speed rotors and increase the rotor energy density. Even with present commercial technology, the high-speed rotor flywheel has a higher volume/energy density than the low speed rotor flywheel.

2.3. Advantages

There are numerous advantages to using flywheels for energy storage. The advantages listed are vaguely intuitive and will not be discussed. These advantages will be more easily realized with the expected technological improvements in the future. However, the advantages of

- increased energy density,
- increased power density,

- long life (20 years?),
- low life cycle costs,
- compactness,
- self containment,
- no hazardous associated chemicals, and
- no flammable gases

have to be compared with the advantages of other energy storage methods such as SMES, batteries, compulsators, and capacitors.

An additional advantage to flywheels is the easy determination of energy available based on rotational speed of the flywheel.

2.4. Disadvantages

2.4.1. Safety

The largest concern with flywheel technology is if the flywheel rotor bursts from internal catastrophic stress fractures. Therefore the flywheel rotor must be encapsulated in a structure capable of withstanding impacts from rotor debris which may exceed several hundred meters per second. Or the flywheel must be subject to extremely high quality control assurance to obviate any chance of failure. It should be noted here that steel or titanium flywheels are similar to turbine wheels; we all ride around on jet airplanes, which seldom fail in this manner.

2.4.2. Technological Maturity

Flywheel energy storage relies on moving parts (rotating cylinder). In a static environment, the flywheels are not subject to accelerations in the other 5 degrees of movement (pitch, roll, heave, surge, sway) assuming yaw does not have a detrimental affect on the parasitic losses of the flywheel. Since flywheels have yet to be built and tested on marine vessels, demonstrated data is not yet available. Use in hybrid vehicles may be demonstrative of the expected parasitic losses onboard ships.

2.5. Other Considerations

The ship designer will initially be interested in the deliverable power, total energy available, specific power, specific energy, power density, energy density, and cost of the flywheel energy storage system. However, the versatility to distribute the system throughout the ship should also be considered.

Since the flywheel system may be made up of numerous modules, they may be distributed throughout the ship to minimize vulnerability and increase flexibility in overall ship design. But as stated above, the untested shipboard movements to which flywheels will be subjected may limit the installation to the center lower part of the ship thereby inhibiting overall ship design.

3. SMES

3.0. Fundamentals

Superconducting magnet energy storage (SMES) is a scalable technology, which uses cryogenically cooled superconducting material to inductively store vast amounts of energy. This stored energy is deliverable as pulsed power. The SMES storage capacity can range from less than 0.001 MWh to more than 10,000 MWh ($3.6X10^4$GJ).

3.0.1. How Does a SMES Store Energy?

A cryogenically cooled coil of superconducting material can carry a DC current, which in turn creates an electromagnetic field. No power dissipation will occur with a resistance free SMES coil. If not for the parasitic power consumption of maintaining the very low temperature (4.2 Kelvin for American Superconductor SMES units) for the superconducting material, the SMES coil could store the energy indefinitely.

3.0.2. There Are Two General Configurations For SMES Coils

3.0.2.1. Solenoid

A SMES coil can simply be an open ended cylindrical coil of conducting material. The magnetic fields would be concentrated in the center of the coil. Each line of the magnetic field would extend out the "north" end of the coil, and wrap through the air to the "south" end of the coil. This is the same pattern young students observe with the magnet and iron filings in basic science classes. The larger the DC current in the coil, the larger the magnetic fields. The larger magnetic fields in turn produce forces on the coil as the magnetic fields attempt to radially expand the coil, and coil resists the radial expansion.

3.0.2.2. Toroid

Instead of a cylindrical coil of wire with open ends, the two open ends can meet forming a toroid (a ring) restricting the magnetic fields to within the toroid. Although the forces are more complex and the structure is heavier, this eliminates the stray electromagnetic fields, which is an environmental concern for personnel. Presently no concrete data has demonstrated that exposure to high electromagnetic fields are hazardous to personnel (such as high power lines near residential houses), however, the public concern is such that manufacturers provide a radial distance from the SMES where leakage electromagnetic field strength drops to 5 gauss.

3.1. Applications:

Inductive energy storage, generally for use with pulsed-duty applications, has been evolving over the last decade. Cryogenically cooled aluminum inductors have been developed for low-loss, very short-term energy storage in pulse-forming networks. SMES as described above was developed for use in high-power, directed-energy weapons applications but has evolved into commercial applications for long-term energy storage for uninterruptable power sources.

The key technological challenges for SMES development in the future are: superconducting materials, shielding large EM fields produced by SMES, and high-strength composite materials for containment of the large forces associated with magnetic energy storage. Trends in these areas would indicate that practical superconductors operating above 100 K and composite materials with yield strengths exceeding 188 kpsi may become available 20 to 30 years hence.

The overall technology of cryogenics and superconductivity is such that SMES for small-scale, power-quality applications is being built today. SMES units appear to be feasible for some commercial utility applications at a cost that is competitive with other technologies. This is quickly outweighed by the key technological challenges listed above as discussed below.

3.2. Advantages:

The advantages to using SMES technology is listed below:

- The energy is stored in a magnetic field (no moving parts).
- No conversion of electrical energy (to kinetic/chemical) required, although voltage/frequency conversions may be required.
- Self-contained: assuming the subsystems providing vacuum, cooling, etc is within the containment.

- Contains no hazardous chemicals, although the extreme temperature of the cryogenic fluid is considered to be hazardous.
- Super conducting wires result in virtually no losses
- No Flammable Gases, and
- Large amounts of electrical energy can be released (or stored) in fractions of a second. This would be very useful in recovering kinetic energy when recovering aircraft.

3.3. Disadvantages:

The advantages are offset by the disadvantages listed below:

- Cryogenic Hardware is required
- Basic Systems are DC, but can be converted to AC, and
- Small perturbations in temperature may cause the SMES to quench. This can be presumably corrected with a well-designed SMES.
- Shielding stray fields may require a large mass of iron.
- The SMES coil requires extensive reinforcement to contain the large forces associated with the magnetic fields.

3.4. SMES Challenges

3.4.1. Quenching:

Quenching occurs when the SMES transitions from its superconducting state to a normal state. When a small portion of the SMES becomes normal, a resistance is introduced to the large circulating DC current which in turn generates excessive heat. This causes other portions of the SMES to go into a normal state. This chain reaction causes the entire SMES to go into a normal state within seconds. The heat generated is enough to vaporize the cooling medium (normally helium) which in turn pressurizes the containment vessel. Quenching is addressed by electronically providing an alternate path for the DC current in the case of a quench. Failure to control a quench and subsequently vent the vessel may result in high kinetic containment failure (e.g. explosion).

To compensate for quenching and subsequent containment pressurization, the mass of the containment vessel is increased.

3.4.2. Field containment

Another difficulty is the magnetic field containment and the resultant forces applied within the SMES coil. All the energy of the SMES is contained within the magnetic field, therefore a strong structure must be constructed to contain the field which may reach a density of 30T. This is not an inconsequential tasking. The structure must be able to withstand pressures (tensile, shear, and torsion) of as much as 2 MPa (300psi). The advantages gained from weight and volume can be quickly eliminated by the structure needed to contain the magnetic fields.

New approaches are being explored and developed to address these issues. The most promising is a Force Balanced Coil for Large Scale SMES to address the strength characteristic needed in the containment vessel. Even if the stress can be balanced throughout the SMES material, the maximum energy storage capacity will still be limited by the working stress of the SMES material and the volume of the SMES.

Energy = Working stress of material X Volume of Structure under tension

3.4.3. Summary

In reviewing table 3.1 below, specific energy and energy densities are listed for two different considerations. The first is when the energy storage device is considered independently of the pulsed power application. This is typically the published values of the commercial manufacturers. The second is when the energy storage device is considered in use with the pulsed power application. The impact derives from the level of power and the duration of the power required by the pulsed power application. The energy released by the energy storage device is the only energy needed, which of course reduces the specific energy and energy density of the energy storage device.

	EMALS	ETG	HOA
Specific.Power (kW/kg)	0.484	116.197	242.078
Specific.Energy_application (kJ/kg)	1.467	1.475	1.468
Specific.Energy_storage_device (kJ/kg)	1.467	1.467	1.467
Power.Density (KW/m^3)	16.502	3.96E+3	8.251E+3
Energy.Density_application (kJ/m^3)	50	50	50
Energy.Density_Storage_device (MJ/m^3)	0.05	0.05	0.05

Table 3.1: SMES Summary

To achieve the improvements in capacity and reductions in size and weight required by naval applications, while maintaining safety for personnel, continued development of materials and manufacturing methods for SMES systems is required.

4. Capacitors

4.0. Fundamentals

A capacitor typically consists of two thin conducting materials (plates or foils) separated by a thin insulating material. By applying voltage across the physically separated plates, energy is stored in the polarized insulating material.

$$E = \frac{CV^2}{2}$$

The greater the voltage or the greater the capacitance, the greater the energy. Capacitors can be charged over a long or short time interval and then discharged over a long or short time interval. This provides the capability to charge with a relatively small power source and then discharge at a much greater power level (over a shorter time interval).

The operating performance of the capacitor depends on the construction material of the plates or the insulation material and also depends on the construction geometry. The nomenclature of the capacitor typically describes the construction material and geometry.

4.1. Ceramic Capacitors

Ceramic capacitors provide moderate energy density, high power density, and are available in very small (picofarad) to moderate size (10–100 F, 5–500 Vdc) capacitance values. Ceramic capacitors are typically configured for surface mounting on low voltage DC circuit boards. Therefore ceramic capacitors will not be considered for high energy, pulsed power applications.

4.2. Electrolytic Capacitors

Electrolytic capacitors provide moderate energy and power densities, but have high equivalent series resistances (ESR) and high dissipation power factors (Lossy). Electrolytic capacitors are normally constructed of either liquid impregnant (Aluminum) or dry impregnant (Tantalum) for the dielectric medium. Electrolytic capacitors also are polarity dependent resulting in usage primarily in DC circuits involving filtering, rectified circuits, some pulsing circuits such as strobe lights and silicon controlled rectified (SCR) commutation circuits, and fractional horsepower motors. Typical sizes consist of moderate to large capacitors (1 – 100,000μF) at up to 600 V. Therefore, electrolytic capacitors will not be considered for high energy, pulsed power applications.

4.3. Film or Foil Capacitors

Film capacitors are readily scalable from nanojoules to hundreds of kilojoules. Film capacitors can provide high reactive power (>1 KVAR) at modest energy density (0.1–1.5 kJ/kg) and high power density (>50 KVAR/kg). Film capacitors are polarity independent. They have a low equivalent resistance (ESR <1% loss through heat dissipation), low equivalent series inductance (ESL< 10nH), and a very low dissipation factor (<1%). Film capacitors can operate at higher voltages (1-100kV) and have larger capacitances (>100F) for uses in high power electronics pulse-duty circuits, high frequency filtering, continuous ac operation, solid state switch snubbers, SCR commutation circuits, power factor correction, and fractional to large horsepower motor start and run capacitors. Therefore film capacitors will be explored for use in high energy, pulsed power applications in the following section.

4.4. Metalized Electrode Capacitors (MEC)

The need for graceful-aging pulsed capacitors which deliver energy over time periods of milliseconds through seconds (e.g., high energy weapons, electromagnetic guns, EMALS) has precipitated the development of large metallized electrode pulsed capacitors. These capacitors differ radically from capacitors that use discrete aluminum foil electrodes resulting in large pulsed energy discharge capacitors in the voltage range of 2–35 kVand volumetric energy densities up to 2.5 MJ/m^3 (the analysis shows only $2MJ/m^3$).

Metallized electrode capacitors are extremely consistent and can be designed at high energy densities, for cycle-lifes up to 50,000 discharges, without the infantile failure mode problem common in solid aluminum foil capacitors. The known, predictable aging rate stems from internal faults being cleared through vaporization or oxidation before significant current flows into the fault site. This results in tens of thousands of cycles before the capacitor capacitance is substantially reduced (by 5%). The capacitor end of life is 95% of original value determined from the swelling of the capacitor case during vaporization when faults are cleared.

High energy density metallized electrode pulsed capacitors typically have a life, when held at peak charging voltage, of fewer than 100 hours; during this period of time the capacitor is continuously clearing. Comparative experiments have shown that capacitance reduction for either 20 seconds of at-charge voltage or a single charge-discharge cycle combined with a 5 seconds charging time to full charge voltage are equivalent. Thus a tradeoff, for the same life, is possible of dc at-charge time against desired operational cycle life of the system.

Operating the capacitors below 80% of rated voltage results in a very long cycle-life (dominated by thermal aging). Low level testing of the capacitors can be done for extended periods of time with minimal, if any, consumption of life.

The one main operational design limit is the permissible peak current output during discharge. Managing the current capability of the capacitor is an important part of the capacitor design. The same characteristic that prevents the current-induced single point failure through concentrating currents at a fault site will prevent the charge from leaving the capacitor too quickly. A rapid discharge, such as a high-current crowbar fault, would cause a high percentage of the metallized electrode to fracture. The capacitor capacitance will be severely reduced but could not be measured under dc conditions. The capacitor will still withstand voltage but will no longer accept a charge. Series current limiting fusing will constrain faults from reaching this intrinsic current limit.

The peak current capability of a typical modern design, 16 kV, 50 kJ, 0.7 J/g, 10 000 shot capacitor is:

- design peak current 40,000 A;
- design limit for full life operation 100,000 A;
- fault capacity with minor degradation 200,000 A.

Crowbarring this capacitor with a peak current in excess of 400,000 A will cause the damage described above. A 200,000 A discharge will result in a measurable, but slight, degradation. The capacitor will perform to specifications if the peak current is kept below 40,000 A.

The math modeling of MEC in Appendix D were conducted at much reduced currents to minimize degradation.

4.5. Chemical Double Layer Capacitors (Ultra Capacitors: A developing technology)

Chemical Double Layer (CDL) capacitors are a new and novel form of liquid electrolytic capacitors, optimized for use below the electrolysis point of the impregnant, thus allowing very high capacitance's to be achieved. In contrast to conventional electrolytic capacitors, the CDL capacitor is a fully bipolar (i.e., polarity insensitive) capacitor when operated within its ratings.

CDL capacitors lend themselves to high energy density, lower power density, and modest dc voltage. Individual capacitors typically have voltages of 2.5 VDC. Combining the capacitors in series and parallel have been demonstrated to 100 VDC. Higher voltages are expected in the future. Applications could consist of energy storage for electric vehicles, reservoir capacitors for switched mode power supplies/systems, and power multipliers for battery powered systems (their equivalent series resistance (ESR) being far less than modern batteries for discharge times down to fractions of a second).

CDL capacitors have not been demonstrated at the number of parallel circuits being modeled in this thesis.

4.6. Advantages:

There are numerous advantages to using capacitors for energy storage and pulsed power delivery. The advantages listed are vaguely intuitive and will not be discussed. These advantages will be more easily realized with the expected technological improvements in the future. However, the advantages of

- high energy and power density,
- long life (50,000+ charge/discharge cycles),
- low life cycle costs,
- compactness,
- self containment,
- no hazardous associated chemicals, and
- no flammable gases

have to be compared with the advantages of other energy storage methods such as SMES, batteries, compulsators, and flywheels.

An additional advantage to capacitors is the easy determination of energy available based on the voltage of the capacitor (knowing capacitance).

4.7. Disadvantages:

High energy pulsed power capacitors form a very small part of the total capacitor market in general and the film capacitor market segment specifically. Incentives for the commercial market will be economically difficult for research and development and later manufacturing.

4.8. Summary

In reviewing tables 4.1 and 4.2 below, specific energy and energy densities are listed for two different considerations. The first is when the energy storage device is considered independently of the pulsed power application. This is typically the published values of the commercial manufacturers. The second is when the energy storage device is considered in use with the pulsed power application. The impact derives from the level of power and the duration of the power required by the pulsed power application. The energy released by the energy storage device is the only energy needed, which of course reduces the specific energy and energy density of the energy storage device.

	EMALS	ETG	HOA
Specific.Power (MW/kg)	0.178	0.179	0.178
Specific.Energy_application (kJ/kg)	0.712	0.693	0.712
Specific.Energy_storage_device (kJ/kg)	0.712	0.715	0.713
Power.Density (MW/m^3)	211.211	211.953	211.46
Energy.Density_application (MJ/m^3)	0.845	0.822	0.845
Energy.Density_Storage_device (MJ/m^3)	0.845	0.848	0.846

Table 4.1: MEC Summary

	EMALS	ETG	HOA
Specific.Power (kW/kg)	0.595	0.595	0.595
Specific.Energy_application (J/kg)	1.786E+3	5.952	4.464
Specific.Energy_storage_device (kJ/kg)	14.063	14.063	14.063
Power.Density (MW/m^3)	0.595	0.595	0.595
Energy.Density_application (kJ/m^3)	1.786E+3	5.952	4.464
Energy.Density_Storage_device (MJ/m^3)	14.063	14.063	14.063

Table 4.2: CDL Summary

CDL capacitors have not been demonstrated at power levels being proposed by this thesis.

5. Compensated Pulsed Alternators (CPA)

5.0. Compulsator (CPA) Fundamentals

Compensated Pulsed Alternators (CPA), also known as Compulsators, is another form of kinetic energy flywheel storage device. Injection of kinetic energy originates from a prime mover such as a turbine, hydraulics, or even the electric machine itself (in the motor configuration). The kinetic energy is then converted to electromagnetic power to be delivered to the load in nearly the same manner as a classical electric machine (in the generator configuration). The difference lies in the amount and duration of power delivered to the load.

Some classical electric generators use a portion of the armature windings electric output to excite the field windings (self-excitation). The field windings in turn generate a rotating magnetic field, which generates the armature windings electrical output. The electric generator is a power amplifier with the output power (armature windings) to the excitation power (field windings) being the ratio. The self-excitation begins with the residual magnetism of the machine (very small) and builds to full power capacity at the magnetic saturation of the machine. This physical limitation is due to the ferrous magnetic material of the machine.

An air core is used in the latest compulsators to remove the limitations of iron core saturation with the peak flux density normally exceeding two Tesla. Using positive feedback, the field windings cause a nearly exponential rise in power output of the armature windings. This implies that the machine could be destroyed from thermal excesses for high power applications. However, if the power is limited to a very short duration, then the power output can be quite high without thermal ramifications. The intensity and duration of the pulse are the tradeoffs to prevent thermal excesses.

Self-excitation applied to all types and topologies of electrical machines (homopolar and heteropolar, synchronous and asynchronous, steady-state and pulsed operation), will achieve almost exponentially (due to the positive feedback connection) high values of the excitation flux densities. But since these values are maintained for a short duration, the excitation losses are limited to reasonable values.

5.1. Applications

The Cannon Caliber Electromagnetic Gun (CCEMG) generator (built at University of Texas) is a self-excited compulsator of high power density and compactness capable of delivering 1.2 MJ to a railgun for three five-round salvos at a short repetition rate of 5 Hz. The self-excited compulsator stores 40 MJ at 12,000 rpm and weighs 2045 kg.

Parametrically evaluating the CCEMG generator results in a compulsator(s) weighing 409 metric tons for EMALS, 818 metric tons for ETG, and 51,125 metric tons for Higher Order Applications. Parametrically evaluating the CCEMG generator may not be accurate since a larger compulsator may have a greater specific power, specific energy, power density, or energy density. The stability and efficiency may also be questionable at very high power levels.

Thermodynamics prevents using Compulsators for EMALS or any other high power pulse of significant time duration. However, Compulsators seem to be ideally suited for rail guns, which require short, high-powered pulses with a high pulse repetition rate.

5.2. CPA Summary

Electric machines, which are used for electromagnetic launch and other pulsed power applications are typically specialty machines with unique arrangements of windings, not usually found in standard textbooks on electric machines. For machines used in pulsed power applications, a good dynamic model is very important and very complicated. Compulsators should be studied further to determine the applicability for very high order pulsed power of very short time duration. The designing challenge will be to conduct tradeoff studies of pulse duration, pulse intensity, volume, and weight limitations.

In order to drive weight and volume down, compulsator designers will strive for higher frequency and higher gain for the field excitation. Higher frequency will result from either higher rotation speeds or more poles, both of which will result in a smaller machine. The gain of the field exciter circuit is a function of the volts generated per field amp and the resistance and inductance of the field circuit.

6. Batteries

6.0. Battery Fundamentals

A plethora of plate material, plate thickness, containment vessels, and electrolyte is available to construct batteries. The SAFT nickel cadmium battery is commercially available and has been proposed and is being used for high-power and high-energy commercial applications. The nickel cadmium battery is modeled in this thesis since nothing serves as a greater selection process to weed out weak products than the American capitalist system.

The following description of the charge/discharge cycle of the nickel cadmium battery is taken directly from the SAFT tech manual provided at their website.

$$\mathrm{2NiOOH + 2H_2O + Cd} \xrightleftharpoons[\text{Charge}]{\text{Discharge}} \mathrm{2\ Ni(OH)_2 + Cd(OH)_2}$$

The nickel cadmium battery uses nickel hydroxide as the active material for the positive plate, and cadmium hydroxide for the negative plate. The electrolyte is an aqueous solution of potassium hydroxide containing small quantities of lithium hydroxide to improve cycle life and high temperature operations. The electrolyte is used for ion transfer; it is not chemically changed or degraded during the charge/ discharge cycle. In the case of the lead acid battery the positive and negative active materials chemically react with the sulfuric acid and electrolyte resulting in an aging process.

The steel support structure of both plates is unaffected by the electrochemistry, and retains its characteristics throughout the life of the cell. In the case of the lead acid battery, the basic structure of both plates is lead and lead oxide which both play a part in the electrochemistry of the process and are naturally corroded during the life of the battery.

6.1. Charge/Discharge Cycle

During the discharge the trivalent nickel hydroxide is reduced to divalent nickel hydroxide, and the cadmium at the negative plate forms cadmium hydroxide. On charge, the reverse action takes place until the cell potential rises to a level where the hydrogen is evolved at the negative plate and oxygen at the positive plate which results in water loss.

Unlike the lead acid battery, there is little change in the electrolyte during charge and discharge. This allows large reserves of electrolyte to be used without inconvenience to the electrochemistry of the couple.

Thus, through it's electrochemistry, the nickel-cadmium battery has more stable behavior than the lead acid battery, giving it a longer life, superior characteristics, and a greater resistance against abusive conditions. Nickel Cadmium batteries have a nominal voltage of 1.2 Volts per cell.

6.2. Other batteries

Other combinations of metals and electrolytes for batteries can be used to improve the impact on individual characteristics such as the environment, the initial cost, better the life cycle, etc. However, no dramatic improvement has been demonstrated for improving the recharge rate to competitively challenge other pulse power storage devices (including Nickel Cadmium Batteries).

6.3. Analysis

The recharge rate for batteries is far too slow for the military applications being considered in this thesis. To show this, all the following parameters in the math model in Appendix G are assumed to be the under the best of conditions to present the best recharge rate possible.

Assumptions:

- Temperature degradation will not be considered.
- The voltage will be assumed at the greatest value for each cell.
- The deliverable amperage will be at the largest value even though the battery may not be fully charged.

- No other losses will be considered.
- The recharge rate will be at the "fast" recharge rate.

6.4. Advantages

Without being specific to actual values or directly comparing to other energy storage devices, batteries have:

- a high specific power
- high specific energy
- high energy density
- high power density
- low initial cost
- and represent a mature technology.

The specific power and power density are not very impressive when comparing other energy storage devices.

6.5. Disadvantages

All the above claimed advantages and not greatly investigated since the recharge time (greater than 79 hours for EMALS) negates any perceived advantages.

Other disadvantages include:

- Hydrogen production during recharge
- Life cycle is dependent on the depth of charge/discharge
- Determination of energy within the batteries is difficult
- Maintenance requirements

7. Conclusion

7.0. Analysis Description

In order to use pulsed high powered devices onboard ships, a method must be devised to deliver vast amounts of power (short in duration) from power supplies which are not capable of providing the required power levels. Assuming the relatively low power production of the ship can be stored in an energy storage device over an extended time, the stored energy could then be delivered to the high powered device for a short time duration thereby increasing the power delivered.

The five energy storage devices that have been considered in this thesis are:

- Flywheels
- SMES
- Capacitors
- Compulsators
- and Batteries.

The three pulsed high-powered devices considered to which the power would be delivered are:

- EMALS,
- ETG,
- and Higher Order Applications.

This is not inclusive of all possible high-powered pulsed devices but does represent a somewhat broad spectrum of possible pulses that may be required onboard a ship. Other pulsed power devices and pulses can easily be considered using the outlined mathematical approaches in the appendixes.

Combinations of an energy storage device that have high energy storage but low power output capacity which could be routed to an air inductor (or capacitor bank) designed to power up and then dump into the pulsed power device was not considered.

The math model assumed a three-phase power source of 450V and 2000A to recharge the energy storage devices. With a larger power source, the recharge time would be significantly reduced and vice versa. The recharge times are available in the appendices.

Matching voltages between the energy storage device and the pulse power application were not taken into consideration with the exception of Ultra Capacitors (CDL) where it is necessary to route the output through a dc to dc converter due to the low voltages inherent in CDL capacitors.

To keep the naval architecture plausible in considering the different energy storage devices, an aircraft carrier was chosen to maximize the available weight and volume. Additionally, an aircraft carrier has a greater electrical power production capacity thereby shortening the recharge time for any energy storage device.

7.1. Disclaimer

Presently none of the listed energy storage devices have been demonstrated at the power levels suggested by this thesis for EMALS, ETC, or HOA, although Flywheels and SMES have shown the greatest promise with commercial utility systems.

Questionable assumptions made by the author include:

- Parallel series connections for capacitors on the order of thousands of cells.
- Compulsators are being demonstrated on the order of 4kW. It is a great leap to assume compulsators will be stable at the much greater suggested power levels in this thesis.
- Neglecting complicated mechanical and electrical interfaces, which are far beyond the scope of this thesis, may have been detrimental to the overall analysis.
- General assumption for all energy storage devices that stability will be maintained at the higher power levels being considered in this thesis.

7.2. Elimination from Consideration

Prior to conducting a 5-way comparison to determine the initial best choice, some of the energy storage devices can be eliminated for not meeting the minimum requirements.

7.2.1. Batteries

Batteries have a very large energy density (91.6MW/m^3). However the specific power and power density are not very impressive. In order to meet the power levels of the pulsed power devices, a very large number of batteries have to be used. This drives the applied energy density down to 260 kJ/m^3 for EMALS and 173 J/m^3 for ETC. Although this is very detrimental to the batteries competitiveness for consideration, it is the recharge rate of the batteries which eliminates batteries from any further considerations.

The recharge rate for batteries is:

- EMALS: 79 hours
- ETC: 13 minutes
- Higher Order Applications: 16.5 hours

These are insurmountable numbers and therefore batteries will not be considered further.

7.2.2. SMES

The specific power of the SMES is very impressive, especially for the shorter pulsed applications. This is greatly offset by the energy density, which is dismal at best. Normally this would not be sufficient to eliminate SMES from the competition, however, SMES also has severe personnel hazard issues. A SMES stores energy in a large electromagnetic field using large currents in a cryogenic inductor made of superconductor material. The immediate area around the SMES would be hazardous to personnel from the large magnetic field present outside the inductor, unless contained. Additionally, if the SMES were to quench, all the stored energy would be released thermally and kinetically. A very heavy iron containment vessel would be required for both hazards. These safety issues negates SMES from further consideration.

7.3. Comparisons

7.3.1. Specific Power

The specific power of the Metalized Electrode Capacitors at 178 kW/kg far exceeds the other energy storage devices as shown in Figure 1.

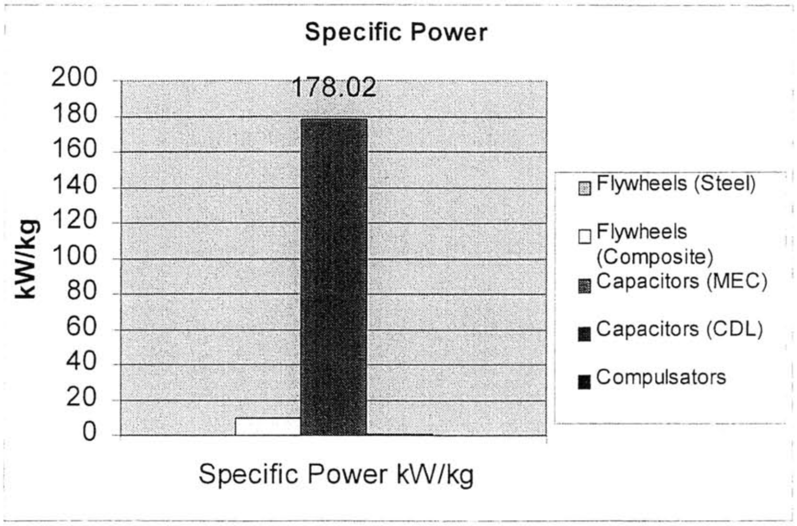


Figure 1. Specific Power

7.3.2. Specific Energy per Energy Storage Device

In Figure 2, the specific energy of each energy storage device was compared ignoring the application for which they could be applied. This is the claim the manufacturer is expected to make with regards to their product. The result shows that the Composite Flywheels far exceed the nearest competitor as shown.

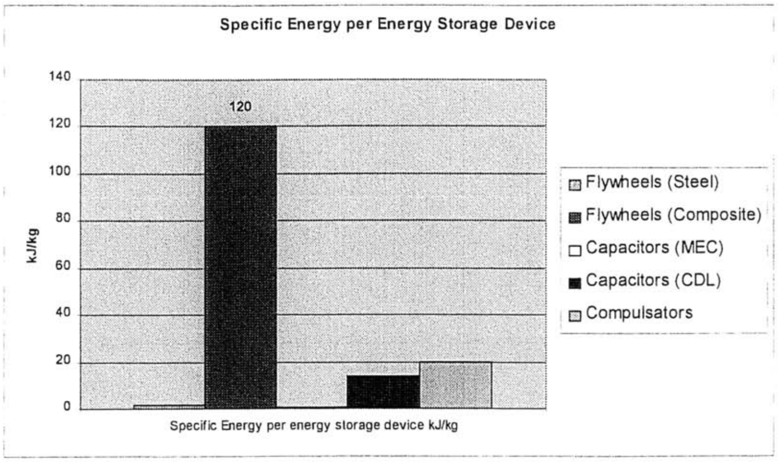


Figure 2. Specific Energy per Energy Storage Device

7.3.3. Specific Energy per Pulse Power Applications

The specific energy for Composite Flywheels when used for EMALS is 30 kJ/kg, much higher than the nearest competitor as shown in Figure 3. There is a dramatic increase in the separation between Composite Flywheels and the nearest competitor when EMALS is considered.

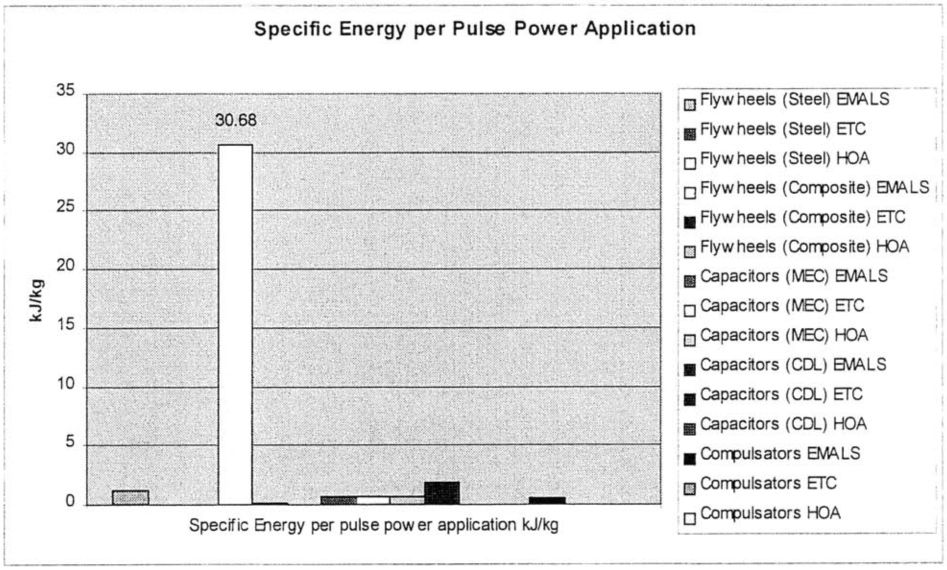


Figure 3. Specific Energy per Pulse Power Application

When only ETC and HOA are considered, it is obvious that Metalized Electrode Capacitors far exceed the performance of the other energy storage devices as shown in Figure 4.

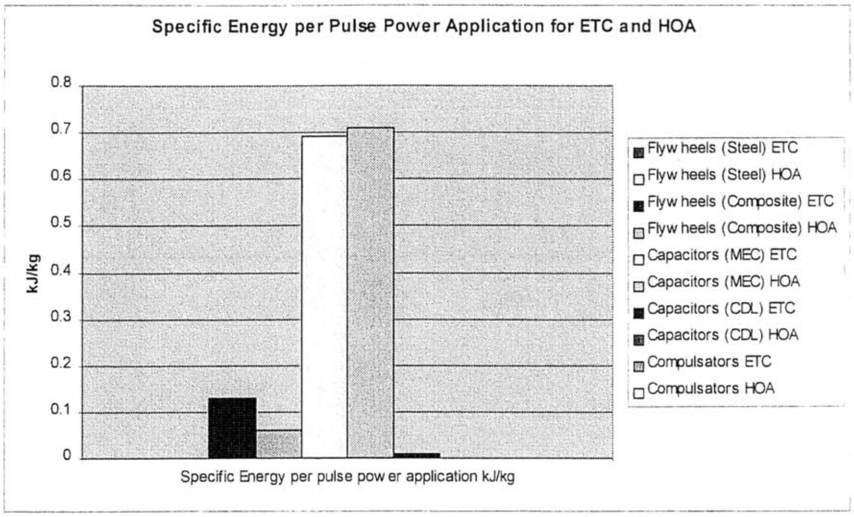


Figure 4. Specific Energy per Pulse Power Application for ETC and HOA

7.3.4. Power Density

The power density is more prominent in the Metalized Electrode Capacitors far exceeding any other energy storage device with 211 MW/m^3 as shown in Figure 5.

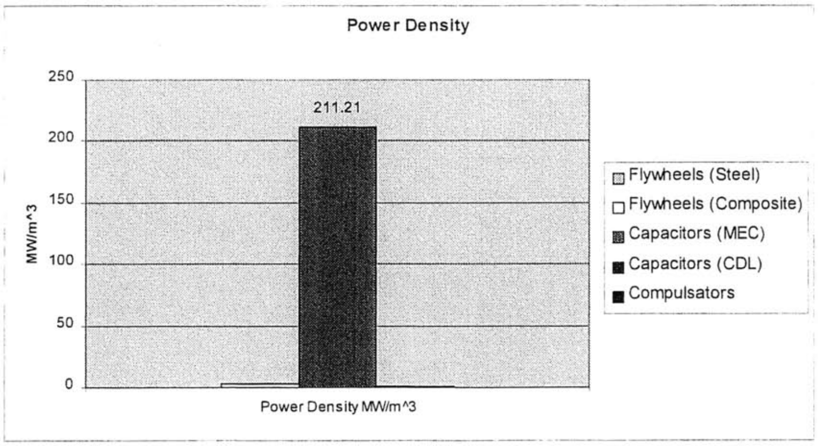


Figure 5. Power Density

7.3.5. Energy Density per Storage Device

The energy density comparisons in Figure 6 show the energy density of Composite Flywheels is at least twice the value of the nearest competitor, Ultra Capacitors (CDL).

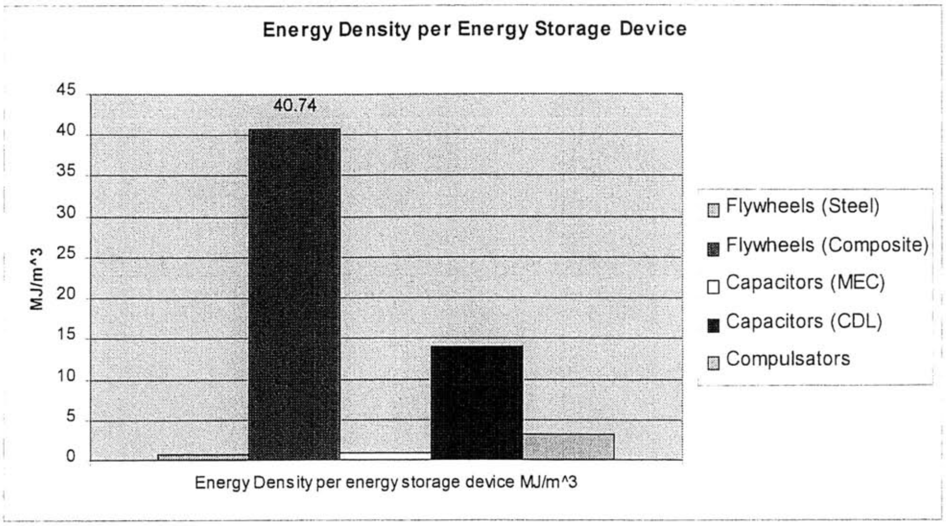


Figure 6. Energy Density per Storage Device

7.3.6. Energy Density per Pulse Power Application

Each energy storage device was compared when applied to a pulsed powered device. The energy density for the Composite Flywheels dropped to 10.42 MJ/m^3. But the separation from the nearest competitor increased dramatically as shown in Figure 7.

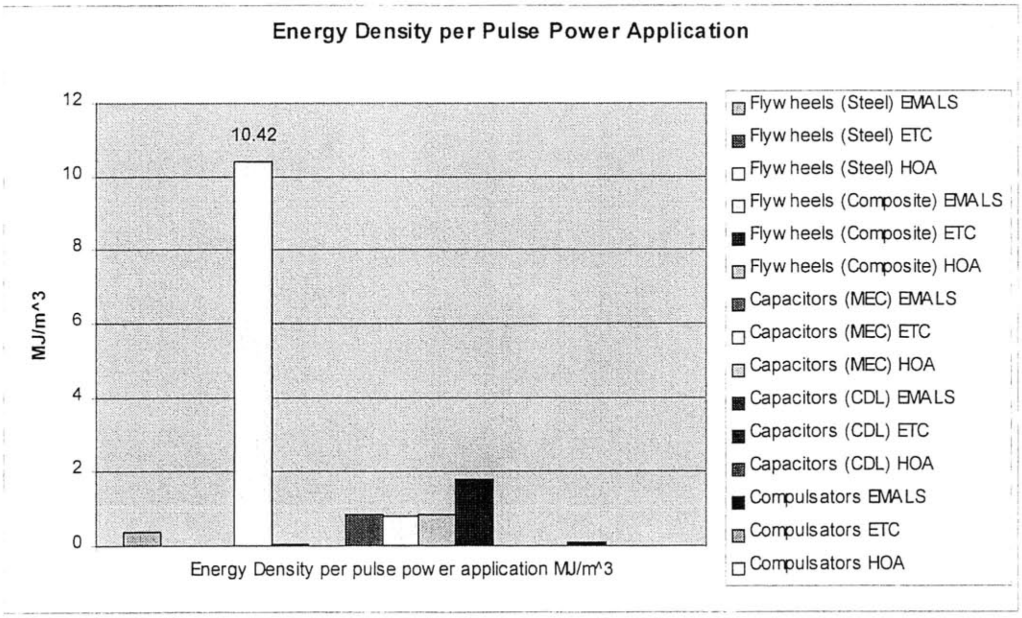


Figure 7. Energy Density per Pulse Power Application

7.4. Pulse Power Device Comparisons

7.4.1. EMALS

The comparisons in section 7.3 seem to imply that Composite Flywheels should be used for EMALS whereas Metalized Electrode Capacitors seem to be the choice for the shorter pulses used with ETC and HOA.

This is again outlined with the size and weight of the energy storage devices which would be required if they were used for EMALS, ETC, or HOA below.

The weights of the energy storage device required to power EMALS are displayed in Figure 8 where it is easily seen that batteries are the heaviest energy storage device being considered.

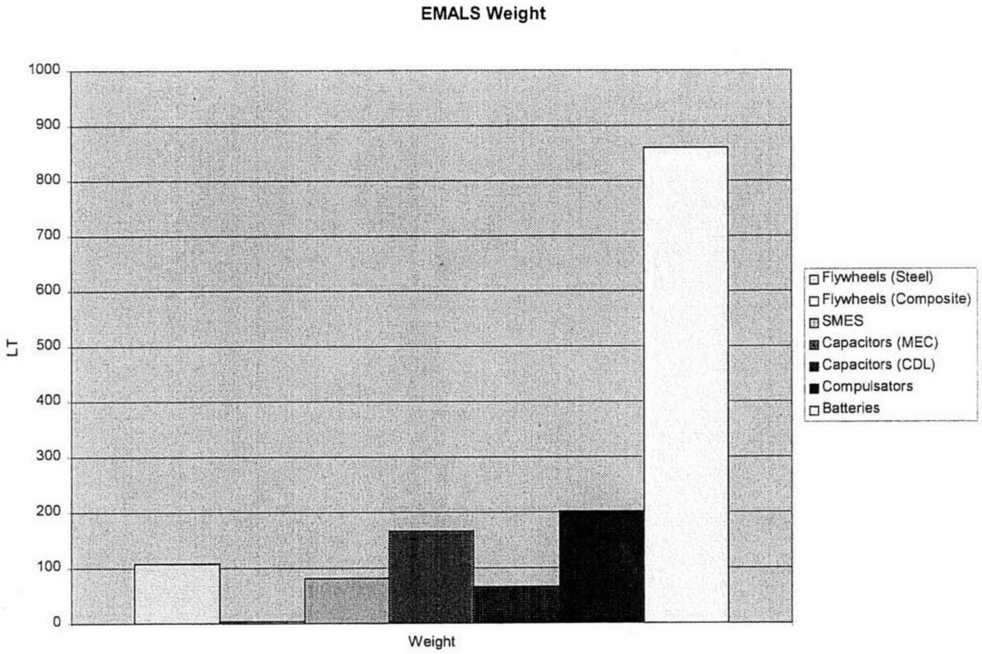


Figure 8. EMALS Weight

The volumes of the energy storage device required to power EMALS are displayed in Figure 9 where it can be seen that SMES takes up the largest volume of the energy storage devices being considered.

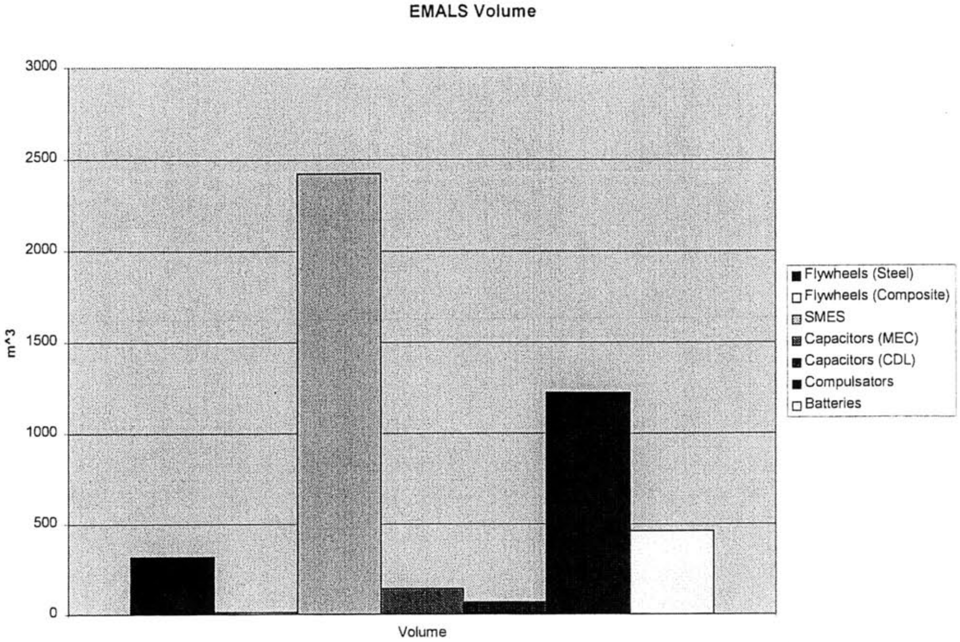


Figure 9. EMALS Volume

Unfortunately the larger weight and volumes are shown, but the data of interest is the minimum values for weight and volume as outlined in the next two figures below. Figure 10 shows the Composite Flywheels are the lightest energy storage device considered for use with EMALS.

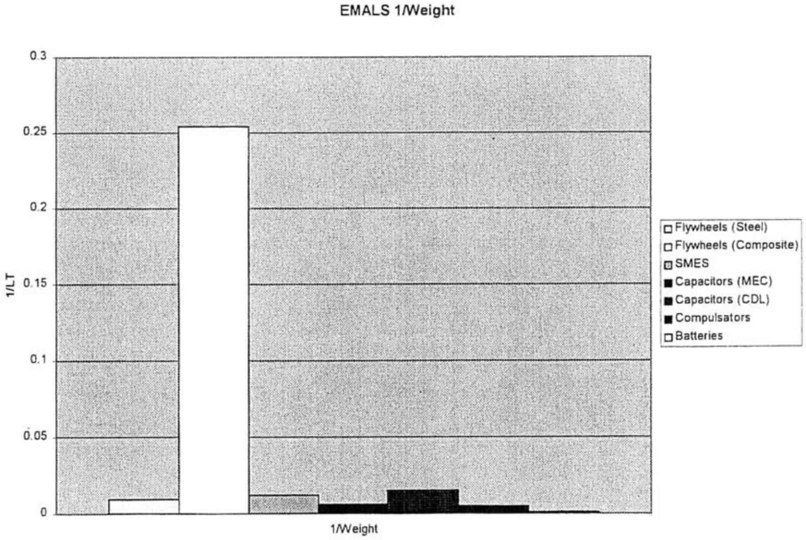


Figure 10. EMALS Inverse Weight

Composite Flywheels are also occupy the smallest volume of space when comparing the energy storage devices being applied to EMALS as shown in Figure 11.

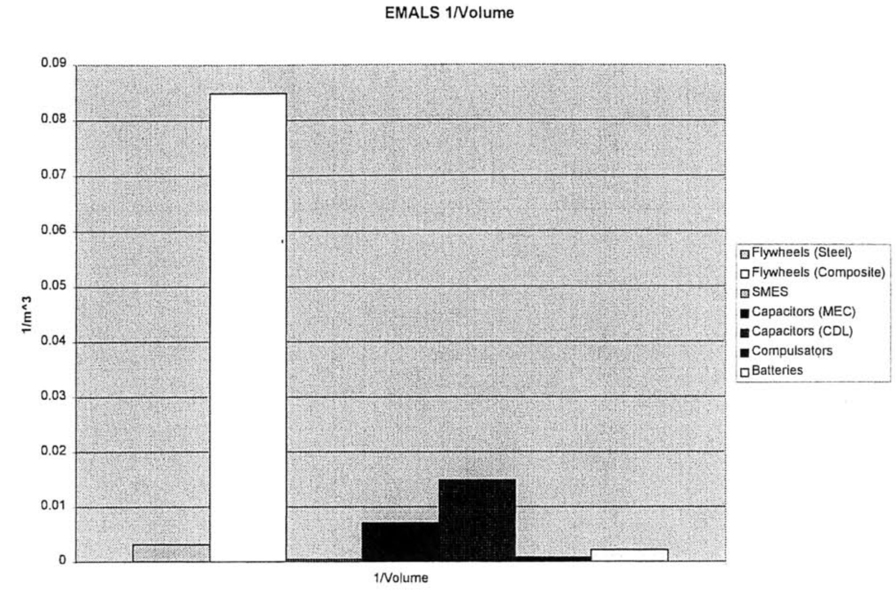


Figure 11. EMALS Inverse Volume

7.4.2. ETC

The weights of the energy storage device required to power ETC are displayed in Figure 12 where it is easily seen that batteries are the heaviest energy storage device being considered.

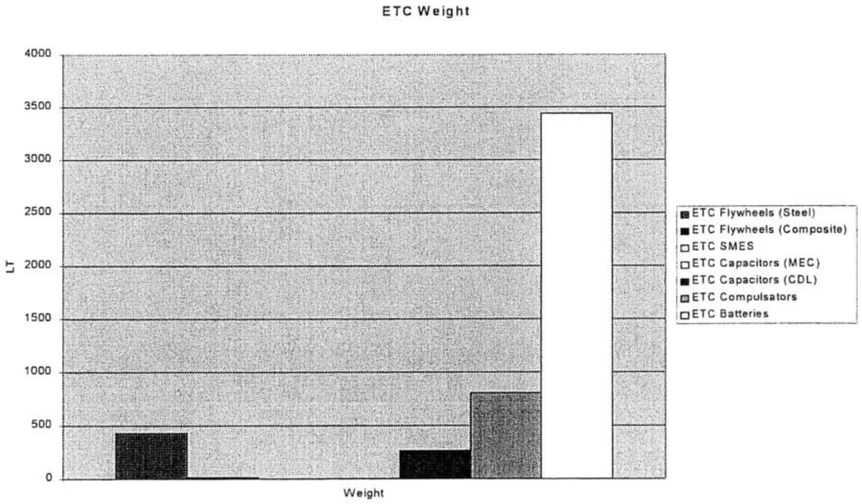


Figure 12. ETC Weight

The volumes of the energy storage device required to power ETC are displayed in Figure 13 where it can be seen that Compulsators takes up the largest volume of the energy storage devices being considered.

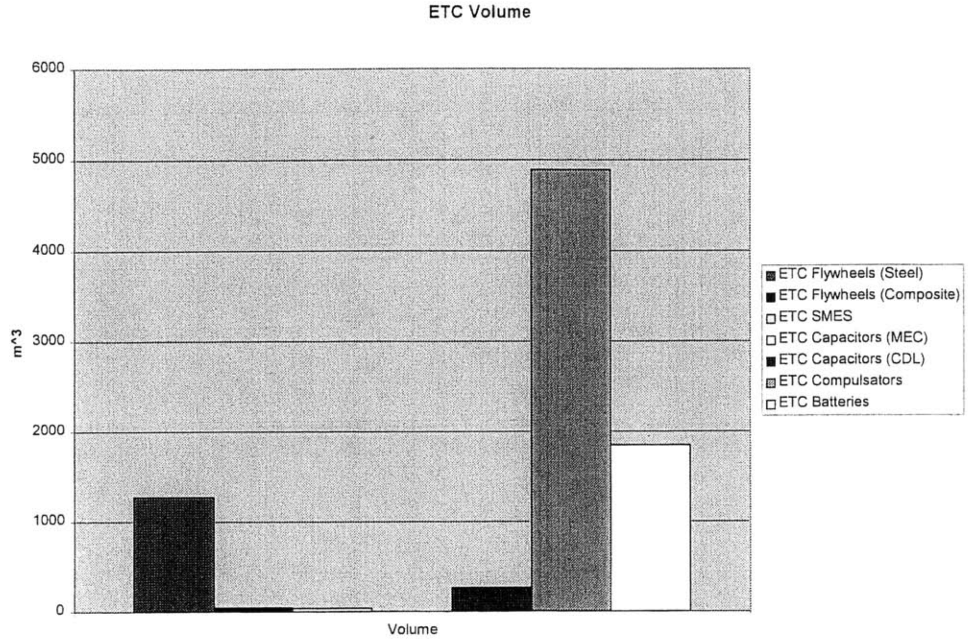


Figure 13. ETC Volume

Unfortunately the larger weight and volumes are shown, but the data of interest is the minimum values for weight and volume. These are outlined in the next two figures below.

Figure 10 shows that SMES are the lightest of the energy storage devices which are considered for use with ETC. However, SMES is not to be considered as discussed earlier due to disqualifying characteristics as discussed above. If the safety issues can be addressed, SMES may be a viable solution with ETC.

The lightest energy storage device being considered is the Metalized Electrode Capacitor bank.

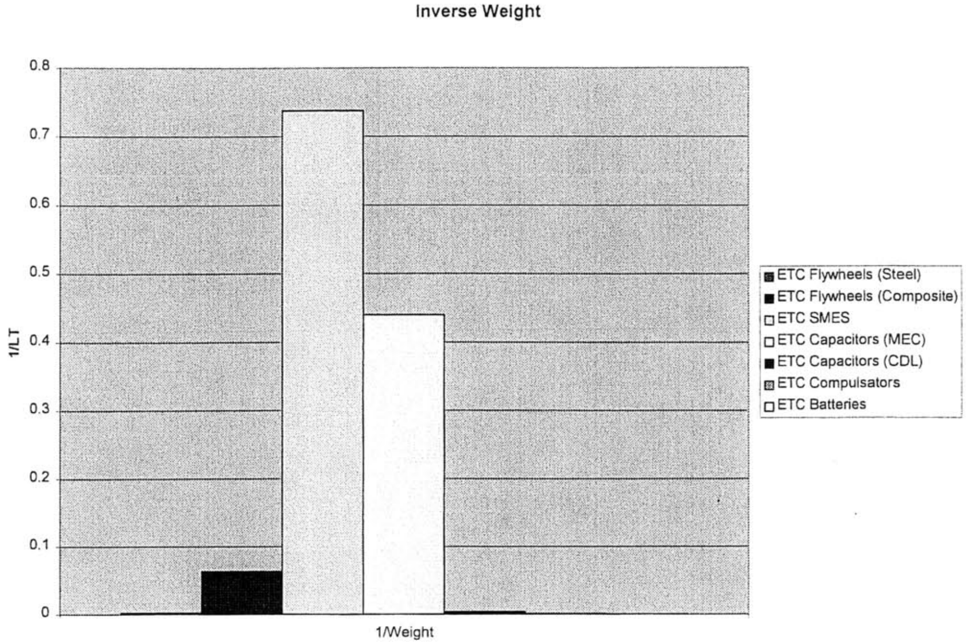


Figure 14. ETC Inverse Weight

Metalized Electrode Capacitors also occupy the smallest volume of space when comparing the energy storage devices being applied to ETC as shown in Figure 15.

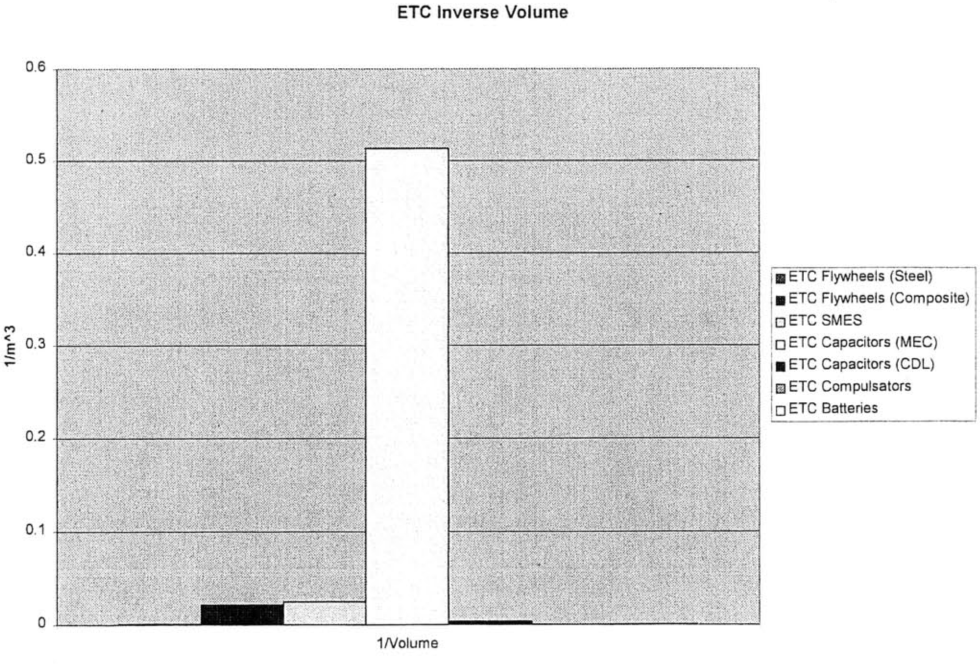


Figure 15. ETC Inverse Volume

7.4.3. HOA

The weights of the energy storage device required to power HOA are displayed in Figure 16 where it is easily seen that batteries are the heaviest energy storage device being considered.

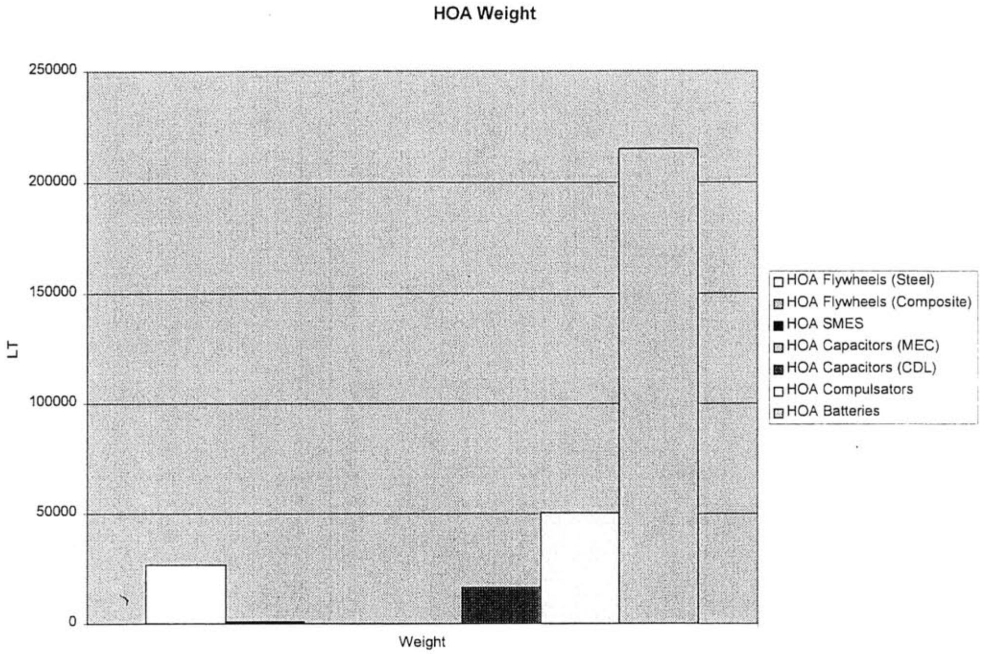


Figure 16. HOA Weight

The volumes of the energy storage device required to power HOA are displayed in Figure 17 where it can be seen that Compulsators takes up the largest volume of the energy storage devices being considered.

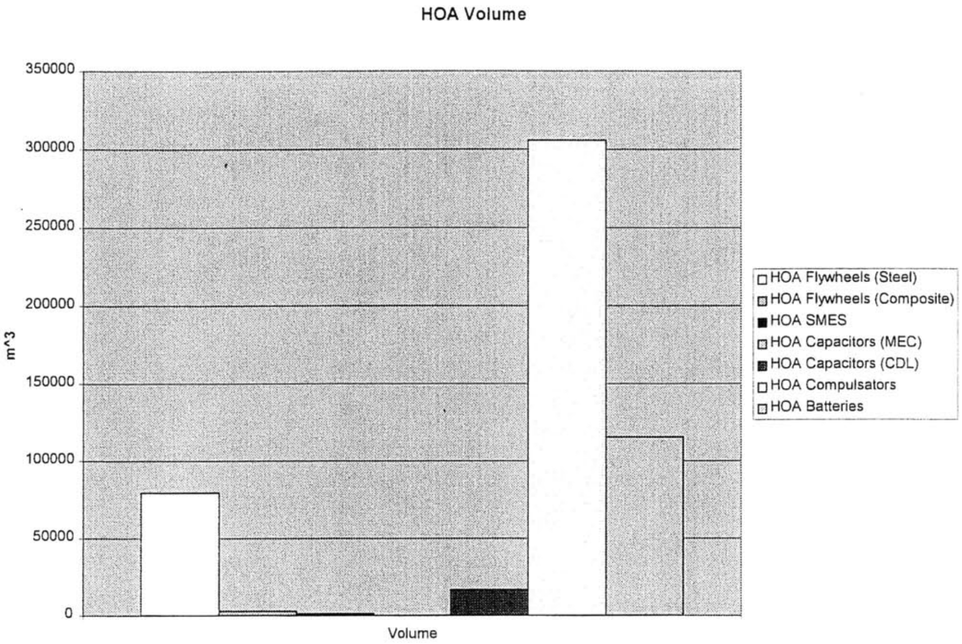


Figure 17. HOA Volume

Unfortunately the larger weight and volumes are shown, but the data of interest is the minimum values for weight and volume. These are outlined in the next two figures below.

Figure 18 shows that SMES is the lightest of the energy storage devices that are considered for use with ETC. However, SMES is not to be considered as discussed earlier due to disqualifying characteristics as discussed above. If the safety issues can be addressed, SMES may be a viable solution with ETC. The lightest energy storage device being considered is the Metalized Electrode Capacitor bank.

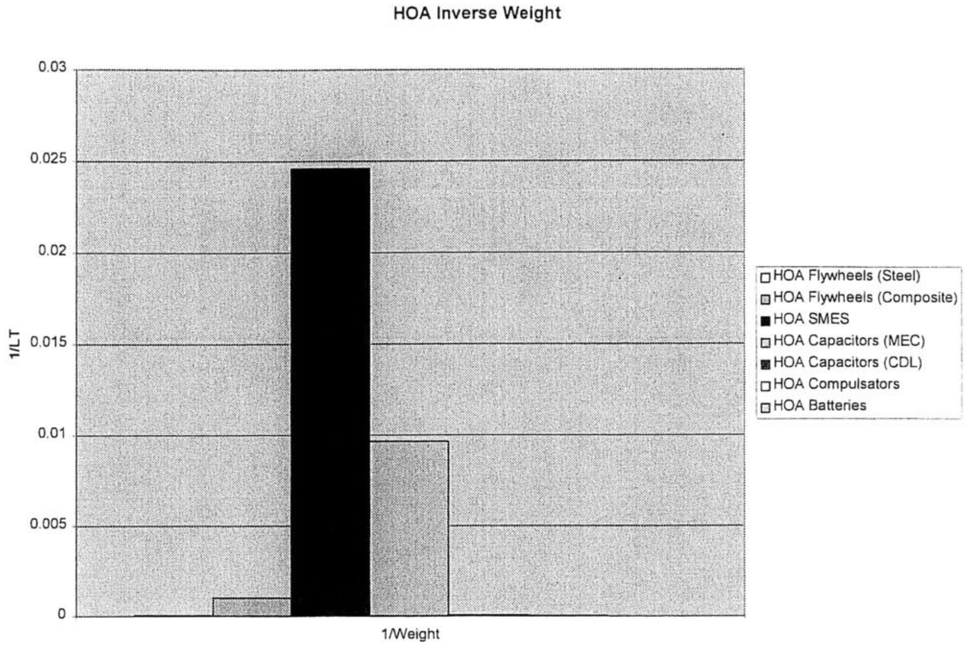


Figure 18. HOA Inverse Weight

Metalized Electrode Capacitors also occupy the smallest volume of space when comparing the energy storage devices being applied to ETC as shown in Figure 19.

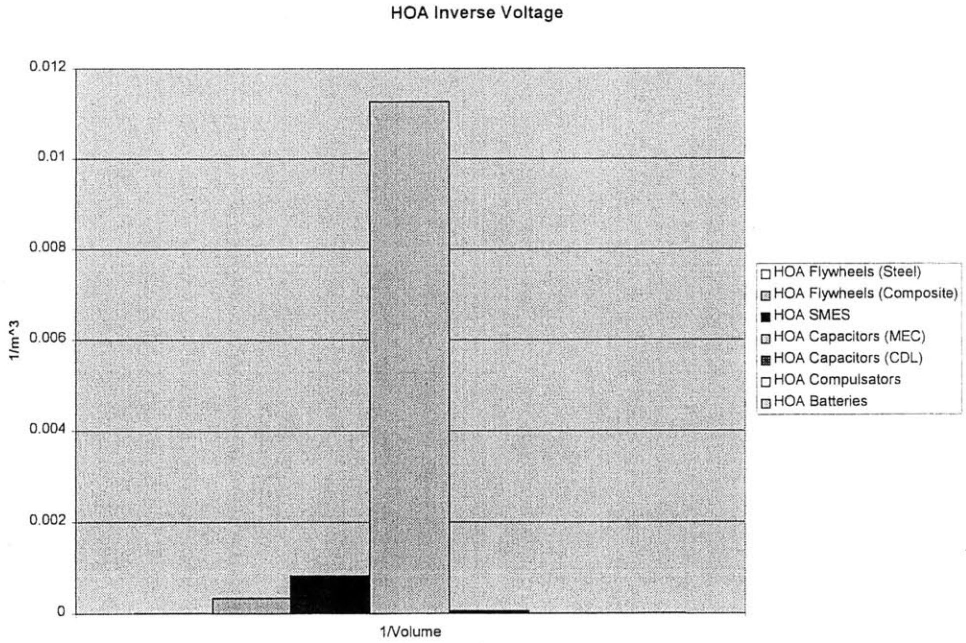


Figure 19. HOA Inverse Volume

7.5. Summary

Currently the best choice for EMALS is Composite Flywheels and the best choice for either ETC or HOA is Metalized Electrode Capacitors. This may change depending upon the following:

- Other information may become available which was not considered due to the ignorance of the author.
- Technology improvements not currently forecast.
- Assumptions by the author that are inaccurate (Voltage matching between energy storage device and pulse power device, PRR, rise time requirements, etc).

Appendix A: Flywheels of Steel

Flywheel of steel :

Flywheel technology is new and manufacturers are reluctant to publish some relative parameters which are proprietary. Therefore some assumptions are made and noted below.

Constants and conversions:

$MW := 1000000W$	Mega Watts	$rpm := 2\cdot\frac{\pi}{min}$	Conversion from radians to RPM.
$GW := 1000MW$	Giga Watts	$LT := 2240lb$	LongTons
$kJ := 1000J$	kilo Joules	$USD := 1$	U.S. Dollars
$MJ := 1000000J$	Mega Joules	$MD := 1000000USD$	Million Dollars
$msec := \frac{sec}{1000}$	milli second	$BD := 1000MD$	Billion Dollars
$MWh := MW\cdot hr$	Mega Watt hour: A measurement of energy.	$MWh = 3.6\times 10^{9} J$	
$MPa := 1000000Pa$	Mega Pascal		

Inputs:

$V_{in} := 450V$		Voltage available to apply to flywheel from shipboard source.
$I_{in} := 6000A$		Total Current available to apply to flywheel.
$P_{in} := V_{in}\cdot I_{in}$	$P_{in} = 2.7MW$	Total Power deliverable to energy storage device.

$$P_{Device\_required} := \begin{pmatrix} 40MW \\ 160MW \\ 10GW \end{pmatrix}$$

Power required of flywheel to power device (EMALS, ETG, HOA).

$$P_{flywheel\_module} := 10MW$$

Power of each flywheel module.

$$Modules_{required} := ceil\left(\overrightarrow{\frac{P_{Device\_required}}{P_{flywheel\_module}}}\right)$$

How many modules are required? Round to next highest integer.

$$Modules_{required} = \begin{pmatrix} 4 \\ 16 \\ 1 \times 10^{3} \end{pmatrix}$$

$$P_{flywheel\_system} := \overrightarrow{\left(Modules_{required} \cdot P_{flywheel\_module}\right)}$$

$$Mass_{flywheel\_module} := 30LT$$

Mass of each flywheel module.

$$Vol_{flywheel\_module} := 3.5m \cdot 3.5m \cdot 6.5m$$

Volume of each flywheel module.

$$Disks_{per\_module} := 4$$

Number of flywheel disks per module.

$$Mass_{disk} := 3LT$$

Mass of each disk.

$$Speed_{max} := 2700rpm$$

Max speed of flywheel in rotations per minute is 4500RPM.

$$Speed_{tip\_max} := 600\frac{m}{s}$$

Max tip speed of flywheel. (ref 35)

$$Radius_{disk} := \frac{Speed_{tip\_max}}{Speed_{max} \cdot 2 \cdot \pi} \qquad Radius_{disk} = 0.338m$$

Radius of flywheel disk.

$\mathrm{Area}_{\mathrm{disk}} := \pi \cdot \mathrm{Radius}_{\mathrm{disk}}^{2}$

$\mathrm{Max}_{\mathrm{stress}} := 810\mathrm{MPa}$

$\mathrm{Tensile}_{\mathrm{Stress}} := \mathrm{Speed}_{\mathrm{tip\_max}}^{2} \cdot \dfrac{\mathrm{Mass}_{\mathrm{disk}}}{\mathrm{Radius}_{\mathrm{disk}} \cdot \mathrm{Area}_{\mathrm{disk}}}$

$\mathrm{Tensile}_{\mathrm{Stress}} = 9.067 \times 10^{3}\ \mathrm{MPa}$

$\mathrm{Moment}_{\mathrm{of\_inertia}} := \left(2\mathrm{Radius}_{\mathrm{disk}}\right)^{2} \cdot \mathrm{Mass}_{\mathrm{disk}}$

Tensile Stress cannot exceed Max stress for steel. RPM's can be increased only to the extent of maximum RPM of 4500. To further increase RPM's, the radius must reduced such that the tip speed is reduced as well.

$\mathrm{Energy}_{\mathrm{module\_max}} := .5\mathrm{Moment}_{\mathrm{of\_inertia}} \cdot \mathrm{Speed}_{\mathrm{max}}^{2}$

$\mathrm{Energy}_{\mathrm{module\_max}} = 5.559 \times 10^{7}\ \mathrm{J}$

$\mathrm{Pulse}_{\mathrm{length}} := \begin{pmatrix} 3\mathrm{s} \\ 2.5\mathrm{msec} \\ 2\mathrm{msec} \end{pmatrix}$

The length of time required to power device.

$\mathrm{Radius}_{\mathrm{rotor}} := \mathrm{Radius}_{\mathrm{disk}}$

Radius of the flywheel rotor.

$\mathrm{Mass}_{\mathrm{rotor}} := \mathrm{Mass}_{\mathrm{disk}}$

Weight of flywheel rotor.

$\mathrm{Pulse}_{\mathrm{Repitition}} := \begin{pmatrix} 1 \\ 5 \\ 3 \end{pmatrix}$

How many times does the device need to be operated for the energy stored in the flywheel?

Calculations:

How much energy is needed to power the device for a given number of repetitions?

$\mathrm{W}_{\mathrm{Device\_required}} := \overrightarrow{\left(\mathrm{Pulse}_{\mathrm{Repitition}} \cdot \mathrm{P}_{\mathrm{Device\_required}} \cdot \mathrm{Pulse}_{\mathrm{length}}\right)}$

Energy required to be stored in flywheel in order to fully power device for required time for a set number of repititions.

$\mathrm{W}_{\mathrm{Device\_required}} = \begin{pmatrix} 120 \\ 2 \\ 60 \end{pmatrix} \mathrm{MJ}$

What is the max energy that can be stored in each system?

$\text{Energy}_{\text{system\_max}} := \text{Energy}_{\text{module\_max}} \cdot \text{Modules}_{\text{required}}$

$$\text{Energy}_{\text{system\_max}} = \begin{pmatrix} 222.366 \\ 889.463 \\ 5.559 \times 10^{4} \end{pmatrix} \text{MJ}$$

What is the power available from ship sources?

$P_{\text{in}} := 3V_{\text{in}} \cdot I_{\text{in}}$

Total powered provided to modules from shipboard source.

What are the electric to kinetic conversion losses?
What are the module losses?

Conversion Losses:

$P_{\text{electronics}} := 1\text{W}$

Dummy value. Not used in further calculations.

$P_{\text{loss\_due\_to\_power\_conversion\_in}} := .04 \cdot P_{\text{in}}$

The expected power lost in conversion is 96% efficiency.

$P_{\text{delivered\_to\_modules}} := P_{\text{in}} - P_{\text{loss\_due\_to\_power\_conversion\_in}}$

Resulting power delivered to the modules.

Parasitic Losses:

$P_{\text{windage}} := 1\text{W}$

These values are dummy values. The expected values are summarized to be 800kW per flywheel module with each module containing .5MWh of energy.

$P_{\text{bearing\_loss}} := 1\text{W}$

$P_{\text{thermal}} := 1\text{W}$

$P_{\text{Parasitic\_Loss}} := 800\text{kW} \cdot \text{Modules}_{\text{required}}$

Total power loss from windage, electronics, power conversion, bearing loss, and thermal losses.

$$P_{Parasitic\_Loss} = \begin{pmatrix} 3.2 \times 10^{3} \\ 1.28 \times 10^{4} \\ 8 \times 10^{5} \end{pmatrix} kW$$

Output power:

$$P_{delivered} := 10MW \cdot Modules_{required}$$

Max power deliverable to the load.

What is the power/energy loss in converting kinetic energy to em energy?

$$P_{loss\_due\_to\_power\_conversion\_out} := .04 \cdot P_{Device\_required}$$

Power loss from converting kinetic energy to em energy.

Power removed from module:

$$P_{loss\_for\_modules} := \left(P_{delivered} + P_{loss\_due\_to\_power\_conversion\_out}\right)$$

Total power departing module.

$$P_{loss\_for\_modules} = \begin{pmatrix} 41.6 \\ 166.4 \\ 1.04 \times 10^{4} \end{pmatrix} MW$$

What is the energy needed in the modules in order to provide the required energy to the device?

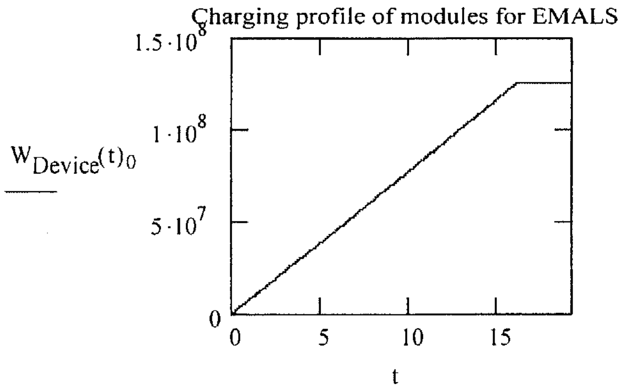
$$W_{Loss\_em\_conv} := \overrightarrow{\left(Pulse_{Repitition} \cdot P_{loss\_due\_to\_power\_conversion\_out} \cdot Pulse_{length}\right)}$$

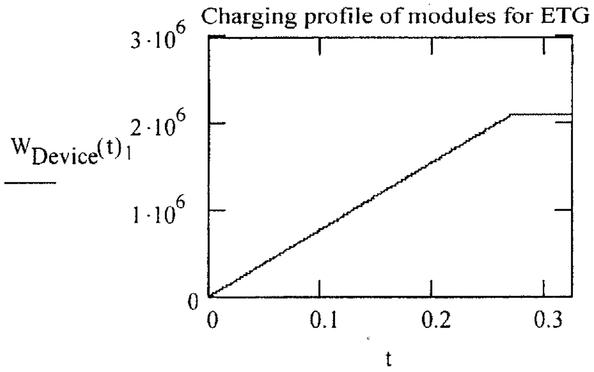
$$W_{modules\_required} := \overrightarrow{\left(W_{Device\_required} + W_{Loss\_em\_conv}\right)}$$

Resultant power required for the modules.

$$W_{Device}(t) := \begin{pmatrix} \left| \begin{array}{l} 0 \cdot t \;\; \text{if } t < 0 \\ P_{delivered\_to\_modules} \cdot t \;\; \text{if } 0 \le t \le time_{charge_0} \\ P_{delivered\_to\_modules} \cdot time_{charge_0} \;\; \text{if } t > time_{charge_0} \end{array} \right. \\ \left| \begin{array}{l} 0 \cdot t \;\; \text{if } t < 0 \\ P_{delivered\_to\_modules} \cdot t \;\; \text{if } 0 \le t \le time_{charge_1} \\ P_{delivered\_to\_modules} \cdot time_{charge_1} \;\; \text{if } t > time_{charge_1} \end{array} \right. \\ \left| \begin{array}{l} 0 \cdot t \;\; \text{if } t < 0 \\ P_{delivered\_to\_modules} \cdot t \;\; \text{if } 0 \le t \le time_{charge_2} \\ P_{delivered\_to\_modules} \cdot time_{charge_2} \;\; \text{if } t > time_{charge_2} \end{array} \right. \end{pmatrix}$$

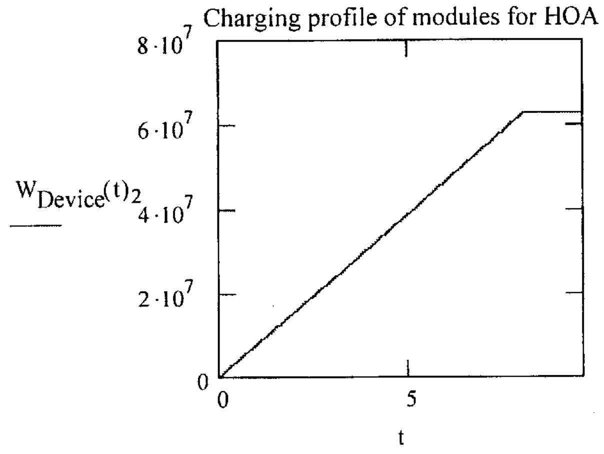
The graphs below show the charging profile of the flywheel from zero energy to the full energy required by the pulsed powered device.





$W_{Device}\left(time_{charge_0}\right)_0 = 124.805\mathrm{MJ}$

$W_{Device}\left(time_{charge_1}\right)_0 = 2.1\mathrm{MJ}$



$$time_{discharge} := \begin{pmatrix} \overrightarrow{\dfrac{W_{modules\_required_0}}{P_{loss\_for\_modules_0}}} \\ \overrightarrow{\dfrac{W_{modules\_required_1}}{P_{loss\_for\_modules_1}}} \\ \overrightarrow{\dfrac{W_{modules\_required_2}}{P_{loss\_for\_modules_2}}} \end{pmatrix}$$

$$W_{Device}\left(time_{charge_2}\right)_0 = 62.441 MJ$$

Discharge time: $$time_{discharge} = \begin{pmatrix} 3 \\ 0.013 \\ 6 \times 10^{-3} \end{pmatrix} s$$

$$Mass_{flywheel\_module\_system} := Mass_{flywheel\_module} \cdot Modules_{required}$$

$$Vol_{flywheel\_module\_system} := Vol_{flywheel\_module} \cdot Modules_{required}$$

$$\mathrm{Mass}_{\mathrm{flywheel\_module\_system}} = \begin{pmatrix} 120 \\ 480 \\ 3\times 10^{4} \end{pmatrix} \mathrm{LT} \qquad \mathrm{Vol}_{\mathrm{flywheel\_module\_system}} = \begin{pmatrix} 318.5 \\ 1.274\times 10^{3} \\ 7.963\times 10^{4} \end{pmatrix} \mathrm{m}^{3}$$

$$P_{\mathrm{flywheel\_system}} = \begin{pmatrix} 40 \\ 160 \\ 1\times 10^{4} \end{pmatrix} \mathrm{MW} \qquad \mathrm{time}_{\mathrm{charge}} = \begin{pmatrix} 0.267 \\ 4.5\times 10^{-3} \\ 0.134 \end{pmatrix} \mathrm{min}$$

$$\mathrm{time}_{\mathrm{discharge}} = \begin{pmatrix} 3 \\ 0.013 \\ 6\times 10^{-3} \end{pmatrix} \mathrm{s}$$

This is the discharge time for:. $\mathrm{Pulse}_{\mathrm{Repitition}} = \begin{pmatrix} 1 \\ 5 \\ 3 \end{pmatrix}$

$$P_{\mathrm{Parasitic\_Loss}} = \begin{pmatrix} 3.2\times 10^{3} \\ 1.28\times 10^{4} \\ 8\times 10^{5} \end{pmatrix} \mathrm{kW}$$

$$\mathrm{Specific}_{\mathrm{Power}} := \overrightarrow{\left(\frac{P_{\mathrm{flywheel\_system}}}{\mathrm{Mass}_{\mathrm{flywheel\_module\_system}}} \right)} \qquad \mathrm{Specific}_{\mathrm{Power}} = \begin{pmatrix} 328.069 \\ 328.069 \\ 328.069 \end{pmatrix} \frac{\mathrm{W}}{\mathrm{kg}}$$

$$\mathrm{Specific}_{\mathrm{Energy\_application}} := \overrightarrow{\left[\frac{\begin{pmatrix} W_{\mathrm{Device}}\left(\mathrm{time}_{\mathrm{charge}_0}\right)_0 \\ W_{\mathrm{Device}}\left(\mathrm{time}_{\mathrm{charge}_1}\right)_1 \\ W_{\mathrm{Device}}\left(\mathrm{time}_{\mathrm{charge}_2}\right)_2 \end{pmatrix}}{\mathrm{Mass}_{\mathrm{flywheel\_module\_system}}} \right]} \qquad \mathrm{Specific}_{\mathrm{Energy\_application}} = \begin{pmatrix} 1.024\times 10^{3} \\ 4.305 \\ 2.049 \end{pmatrix} \frac{\mathrm{J}}{\mathrm{kg}}$$

$$\text{Specific}_{\text{Energy\_storage\_device}} := \overrightarrow{\left(\frac{\text{Energy}_{\text{system\_max}}}{\text{Mass}_{\text{flywheel\_module\_system}}}\right)} \qquad \text{Specific}_{\text{Energy\_storage\_device}} = \begin{pmatrix}1.824\\1.824\\1.824\end{pmatrix}\frac{\text{kJ}}{\text{kg}}$$

$$\text{Power}_{\text{Density}} := \overrightarrow{\left(\frac{P_{\text{flywheel\_system}}}{\text{Vol}_{\text{flywheel\_module\_system}}}\right)} \qquad \text{Power}_{\text{Density}} = \begin{pmatrix}0.126\\0.126\\0.126\end{pmatrix}\frac{\text{MW}}{\text{m}^3}$$

$$\text{Energy}_{\text{Density\_application}} := \overrightarrow{\left[\frac{\begin{pmatrix}W_{\text{Device}}\left(\text{time}_{\text{charge}_0}\right)^{0}\\ W_{\text{Device}}\left(\text{time}_{\text{charge}_1}\right)^{1}\\ W_{\text{Device}}\left(\text{time}_{\text{charge}_2}\right)^{2}\end{pmatrix}}{\text{Vol}_{\text{flywheel\_module\_system}}}\right]} \qquad \text{Energy}_{\text{Density\_application}} = \begin{pmatrix}391.852\\1.648\\0.784\end{pmatrix}\frac{\text{kJ}}{\text{m}^3}$$

$$\text{Energy}_{\text{Density\_Storage\_device}} := \overrightarrow{\left(\frac{\text{Specific}_{\text{Energy\_storage\_device}}\cdot\text{Mass}_{\text{flywheel\_module\_system}}}{\text{Vol}_{\text{flywheel\_module\_system}}}\right)}$$

$$\text{Energy}_{\text{Density\_Storage\_device}} = \begin{pmatrix}0.698\\0.698\\0.698\end{pmatrix}\frac{\text{MJ}}{\text{m}^3}$$

Appendix B: Flywheels of Composite Material

Flywheel of composite material :
Flywheel technology is new and manufacturers are reluctant to publish some relative parameters which are proprietary. Therefore some assumptions are made and noted below.

Constants and conversions:

$MW := 1000000W$	Mega Watts	$rpm := 2 \cdot \frac{\pi}{min}$	Conversion from radians to RPM.
$GW := 1000MW$	Giga Watts	$LT := 2240lb$	LongTons
$kJ := 1000J$	kilo Joules	$USD := 1$	U.S. Dollars
$MJ := 1000000J$	Mega Joules	$MD := 1000000USD$	Million Dollars
$msec := \frac{sec}{1000}$	milli second	$BD := 1000MD$	Billion Dollars
$MWh := MW \cdot hr$	Mega Watt hour: A measurement of energy.	$MWh = 3.6 \times 10^{9} J$	

Inputs:

$V_{in} := 450V$		Voltage available to apply to flywheel from shipboard source.
$I_{in} := 6000A$		Total Current available to apply to flywheel.
$P_{in} := V_{in} \cdot I_{in}$	$P_{in} = 2.7MW$	Total Power deliverable to energy storage device.
$P_{Device\_required} := \begin{pmatrix} 40MW \\ 160MW \\ 10GW \end{pmatrix}$		Power required of flywheel to power device (EMALS, ETG, HOA).

$P_{flywheel\_system\_max} := 40MW$

Power of system.

$$N_{Psystem} := \overrightarrow{\left(\frac{P_{Device\_required}}{P_{flywheel\_system\_max}}\right)}$$

$$N_{Psystem} = \begin{pmatrix} 1 \\ 4 \\ 250 \end{pmatrix}$$

$W_{flywheel\_system\_max} := 150MJ$

$Mass_{flywheel} := 4000kg$

Mass of each flywheel module.

$$Vol_{flywheel\_module} := 1.5m \cdot \pi \cdot 1m^2 \cdot \frac{150}{60}$$

Volume of flywheel system. Determined from "Flywheel Batteries come around again". Vol is paramaterized from a 1.5 meter high and 1m diameter flywheel system providing 60 MJ and 6 GW

$Speed_{max} := 10000rpm$

Max speed of flywheel in rotations per minute.

$$Pulse_{length} := \begin{pmatrix} 3s \\ 2.5msec \\ 2msec \end{pmatrix}$$

The length of time required to power device.

$Mass_{rotor} := Mass_{flywheel}$

Weight of flywheel rotor.

$$Pulse_{Repitition} := \begin{pmatrix} 1 \\ 5 \\ 3 \end{pmatrix}$$

How many times does the device need to be operated for the energy stored in the flywheel?

Calculations:

How much energy is needed to power the device for a given number of repetitions?

$$W_{Device\_required} := \overrightarrow{\left(Pulse_{Repitition} \cdot P_{Device\_required} \cdot Pulse_{length}\right)}$$

Energy required to be stored in flywheel in order to fully power device for required time for a set number of repititions.

$$W_{Device\_required} = \begin{pmatrix} 120 \\ 2 \\ 60 \end{pmatrix} MJ$$

$$N_{Wsystem} := \overrightarrow{\left(\frac{W_{Device\_required}}{W_{flywheel\_system\_max}}\right)}$$

$$N_{Wsystem} = \begin{pmatrix} 0.8 \\ 0.013 \\ 0.4 \end{pmatrix}$$

What is the power available from ship sources?

$$P_{in} := 3 \cdot V_{in} \cdot I_{in}$$

Total powered provided to modules from shipboard source.

What are the electric to kinetic conversion losses?
What are the module losses?

Conversion Losses:

$$P_{electronics} := 1W$$

Dummy value. Not used in further calculations.

$$P_{loss\_due\_to\_power\_conversion\_in} := .04 \cdot P_{in}$$

The expected power lost in conversion is 96% efficiency.

$$P_{delivered\_to\_modules} := P_{in} - P_{loss\_due\_to\_power\_conversion\_in}$$

Resulting power delivered to the system.

Parasitic Losses:

$$P_{standby} := \frac{500W}{7.2MJ}$$

$$W_{flywheel\_system\_max} = 150MJ$$

Parameterized iaw M4 DC Flywheel Power System of AFS TRINITY Power Corporation

$$P_{Parasitic\_Loss} := P_{standby} \cdot \overrightarrow{\left(W_{flywheel\_system\_max} \cdot N_{Psystem}\right)}$$

$$P_{Parasitic\_Loss} = \begin{pmatrix} 10.417 \\ 41.667 \\ 2.604 \times 10^{3} \end{pmatrix} \text{kW}$$

Total power loss from windage, electronics, power conversion, bearing loss, and thermal losses.

Parametrically assumed value from "Conceptual System Design of a 5 MWh/100 MW Superconducting Flywheel Energy Storage Plant for Power Utility Applications".

What is the power/energy loss in converting kinetic energy to em energy?

$$P_{loss\_due\_to\_power\_conversion\_out} := .022 \cdot P_{Device\_required}$$

Power loss from converting kinetic energy to em energy. Total efficiency (charge/discharge) is .937 iaw "Flywheel Batteries Come Around Again"

Power removed from module:

$$P_{loss\_for\_system} := \overrightarrow{\left(P_{Device\_required} + P_{loss\_due\_to\_power\_conversion\_out}\right)}$$

Total power departing system.

$$P_{loss\_for\_system} = \begin{pmatrix} 40.88 \\ 163.52 \\ 1.022 \times 10^{4} \end{pmatrix} \text{MW}$$

What is the energy needed in the modules in order to provide the required energy to the device?

$$W_{Loss\_em\_conv} := \overrightarrow{\left(Pulse_{Repitition} \cdot P_{loss\_due\_to\_power\_conversion\_out} \cdot Pulse_{length}\right)}$$

$$W_{modules\_required} := \overrightarrow{\left(W_{Device\_required} + W_{Loss\_em\_conv}\right)}$$

Resultant power required for the modules.

$$W_{modules\_required} = \begin{pmatrix} 122.64 \\ 2.044 \\ 61.32 \end{pmatrix} \text{MJ} \qquad W_{Loss\_em\_conv} = \begin{pmatrix} 2.64 \times 10^{6} \\ 4.4 \times 10^{4} \\ 1.32 \times 10^{6} \end{pmatrix} \text{J}$$

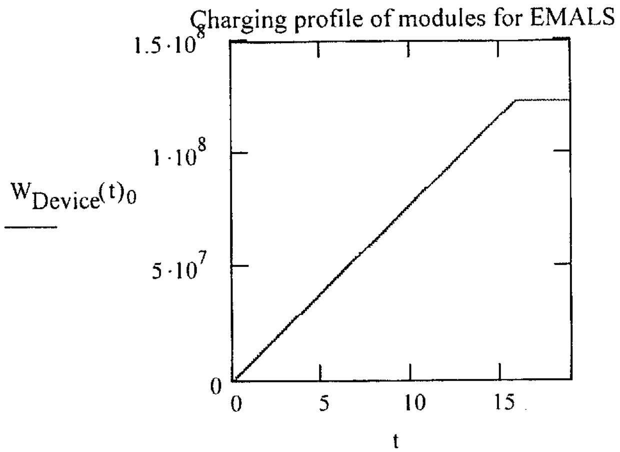
How much time does it take to charge the flywheel to the desired energy?

```
$\text{charge\_time}(P_{to\_rotor}, W_{rotor\_required}) :=$
    $est_{time} \leftarrow .01s$
    while $P_{to\_rotor} \cdot est_{time} < W_{rotor\_required}$
        $est_{time} \leftarrow est_{time} + .01s$
```

$$time_{charge} := \begin{pmatrix} \text{charge\_time}\left(P_{delivered\_to\_modules}, W_{modules\_required_0}\right) \\ \text{charge\_time}\left(P_{delivered\_to\_modules}, W_{modules\_required_1}\right) \\ \text{charge\_time}\left(P_{delivered\_to\_modules}, W_{modules\_required_2}\right) \end{pmatrix} \qquad time_{charge} = \begin{pmatrix} 0.263 \\ 4.5 \times 10^{-3} \\ 0.131 \end{pmatrix} \text{min}$$

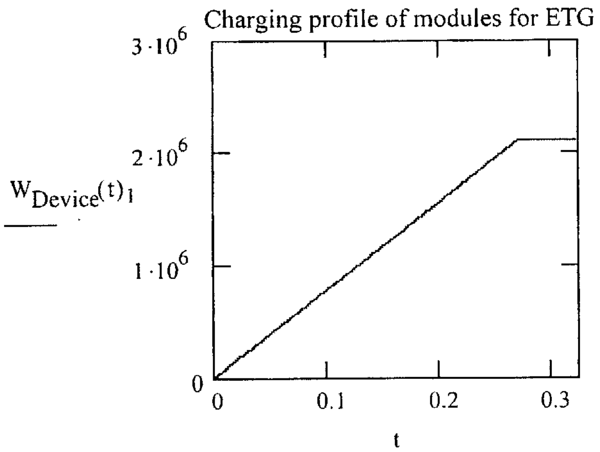
The length of time to charge flywheel to the desired energy level from zero.

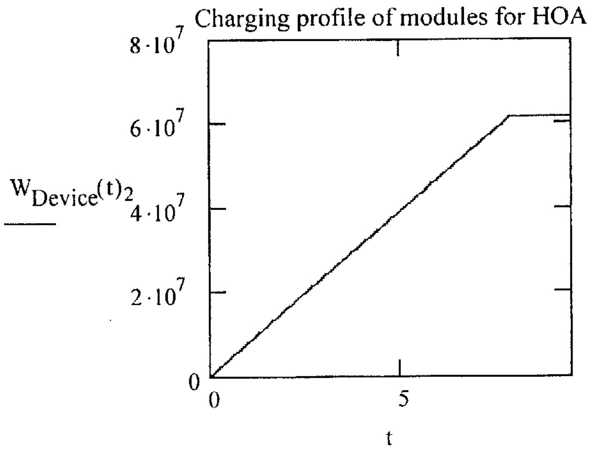
$$W_{Device}(t) := \begin{pmatrix} \begin{cases} 0 \cdot t & \text{if } t < 0 \\ P_{delivered\_to\_modules} \cdot t & \text{if } 0 \le t \le time_{charge_0} \\ P_{delivered\_to\_modules} \cdot time_{charge_0} & \text{if } t > time_{charge_0} \end{cases} \\ \begin{cases} 0 \cdot t & \text{if } t < 0 \\ P_{delivered\_to\_modules} \cdot t & \text{if } 0 \le t \le time_{charge_1} \\ P_{delivered\_to\_modules} \cdot time_{charge_1} & \text{if } t > time_{charge_1} \end{cases} \\ \begin{cases} 0 \cdot t & \text{if } t < 0 \\ P_{delivered\_to\_modules} \cdot t & \text{if } 0 \le t \le time_{charge_2} \\ P_{delivered\_to\_modules} \cdot time_{charge_2} & \text{if } t > time_{charge_2} \end{cases} \end{pmatrix}$$



$W_{Device}\left(time_{charge_0}\right)_0 = 122.705MJ$

These graphs shows the charging profile of the flywheels from no energy to the energy required to power the pulsed power device.





$W_{Device}\left(time_{charge_1}\right)_0 = 2.1MJ$

$W_{Device}\left(time_{charge_2}\right)_0 = 61.353MJ$

Discharge time:

$$\text{time}_{\text{discharge}} := \begin{pmatrix} \overrightarrow{\dfrac{W_{\text{modules\_required}_0}}{P_{\text{loss\_for\_system}_0}}} \\ \overrightarrow{\dfrac{W_{\text{modules\_required}_1}}{P_{\text{loss\_for\_system}_1}}} \\ \overrightarrow{\dfrac{W_{\text{modules\_required}_2}}{P_{\text{loss\_for\_system}_2}}} \end{pmatrix}$$

$$\text{time}_{\text{discharge}} = \begin{pmatrix} 3 \\ 0.013 \\ 6 \times 10^{-3} \end{pmatrix} \text{s}$$

$$\text{Specific}_{\text{energy}} := 120\frac{\text{kJ}}{\text{kg}}$$

$$\text{Specific}_{\text{power}} := 2.5\frac{\text{kW}}{\text{kg}}$$

These values are given for the actual rotating mass of a bus flywheel being tested in Texas. Assuming the electromagnetic and electronic components are equivalent in mass and that the containment vessel is of comparable mass, a factor of 4 (conservative?) is introduced.

$$\text{Assumed}_{\text{Specific\_energy}} := 4\cdot\text{Specific}_{\text{energy}}$$

$$\text{Assumed}_{\text{Specific\_power}} := 4\cdot\text{Specific}_{\text{power}}$$

$$\text{Mass}_{\text{flywheel\_module}} := \frac{P_{\text{Device\_required}}}{\text{Assumed}_{\text{Specific\_power}}}$$

$$\text{Capital}_{\text{expense}} := \frac{400\text{USD}}{\text{kW}}\cdot P_{\text{flywheel\_system\_max}}\cdot N_{\text{Psystem}}$$

$$\text{Vol}_{\text{flywheel\_module\_total}} := \text{Vol}_{\text{flywheel\_module}}\cdot N_{\text{Psystem}}$$

$\text{Mass}_{\text{flywheel\_module}} = \begin{pmatrix} 4 \\ 16 \\ 984 \end{pmatrix} \text{LT}$ $\text{Vol}_{\text{flywheel\_module\_total}} = \begin{pmatrix} 11.781 \\ 47.124 \\ 2.945 \times 10^{3} \end{pmatrix} \text{m}^{3}$

$\text{time}_{\text{discharge}} = \begin{pmatrix} 3 \\ 0.013 \\ 6 \times 10^{-3} \end{pmatrix} \text{s}$ This is the discharge time for:. $\text{Pulse}_{\text{Repitition}} = \begin{pmatrix} 1 \\ 5 \\ 3 \end{pmatrix}$

$\text{time}_{\text{charge}} = \begin{pmatrix} 15.78 \\ 0.27 \\ 7.89 \end{pmatrix} \text{sec}$ $\text{P}_{\text{Parasitic\_Loss}} = \begin{pmatrix} 10.417 \\ 41.667 \\ 2.604 \times 10^{3} \end{pmatrix} \text{kW}$ $\text{Capital}_{\text{expense}} = \begin{pmatrix} 16 \\ 64 \\ 4000 \end{pmatrix} \text{MD}$ Based on material costs only.

I am currently unable to take a quantitative approach to determine response time (the time lag from power demand to delivery). However, in a qualitative approach (fraught with peril!) one can argue that flywheels can respond in the msec range but not in the micro second range. Capacitive or inductive energy would be better suited to deliver power within the micro second time frame. The response time should not be confused with frequency. Response (rise) time is the time needed to deliver the power at full strength (which will probably be comprised of high frequency harmonics, but in an ideal world, may not). Ultra Capacitors cannot deliver high frequency power due to the physics of Ultra Capacitors (not to be confused with regular capacitors).

So what does all this mumbo jumbo mean? If you want is to push the button and have a quick response that cannot be differenticated by the naked eye, then flywheels can confidently be chosen. However, the same confidence cannot be enjoyed when selecting flywheels for applications for extremely fast response times (order of micro seconds). However, a large capacitor (or inductor) could provide the fast response time and the flywheels could provide the capacitor (or inductor) with a charge cycle and the subsequent dissipation losses for a short duration (dictated by the capacitor or inductor dissipation and the amount of energy available in the flywheels). But that combination will not be discussed in this thesis.

$$\text{Specific}_{\text{Power}} := \overrightarrow{\left(\frac{P_{\text{Device\_required}}}{\text{Mass}_{\text{flywheel\_module}}}\right)} \qquad \text{Specific}_{\text{Power}} = \begin{pmatrix}10\\10\\10\end{pmatrix}\frac{\text{kW}}{\text{kg}}$$

$$\text{Specific}_{\text{Energy\_application}} := \overrightarrow{\left[\frac{\begin{pmatrix}W_{\text{Device}}\left(\text{time}_{\text{charge}_0}\right)^{0}\\ W_{\text{Device}}\left(\text{time}_{\text{charge}_1}\right)^{1}\\ W_{\text{Device}}\left(\text{time}_{\text{charge}_2}\right)^{2}\end{pmatrix}}{\text{Mass}_{\text{flywheel\_module}}}\right]} \qquad \text{Specific}_{\text{Energy\_application}} = \begin{pmatrix}30.676\\0.131\\0.061\end{pmatrix}\frac{\text{kJ}}{\text{kg}}$$

$$\text{Specific}_{\text{Energy\_storage\_device}} := \overrightarrow{\left(\text{Specific}_{\text{energy}}\right)} \qquad \text{Specific}_{\text{Energy\_storage\_device}} = 120\frac{\text{kJ}}{\text{kg}}$$

$$\text{Power}_{\text{Density}} := \overrightarrow{\left(\frac{P_{\text{Device\_required}}}{\text{Vol}_{\text{flywheel\_module\_total}}}\right)} \qquad \text{Power}_{\text{Density}} = \begin{pmatrix}3.395\\3.395\\3.395\end{pmatrix}\frac{\text{MW}}{\text{m}^{3}}$$

$$\text{Energy}_{\text{Density\_application}} := \overrightarrow{\left[\frac{\begin{pmatrix}W_{\text{Device}}\left(\text{time}_{\text{charge}_0}\right)^{0}\\ W_{\text{Device}}\left(\text{time}_{\text{charge}_1}\right)^{1}\\ W_{\text{Device}}\left(\text{time}_{\text{charge}_2}\right)^{2}\end{pmatrix}}{\text{Vol}_{\text{flywheel\_module\_total}}}\right]} \qquad \text{Energy}_{\text{Density\_application}} = \begin{pmatrix}10.416\\0.045\\0.021\end{pmatrix}\frac{\text{MJ}}{\text{m}^{3}}$$

$$\text{Energy}_{\text{Density\_Storage\_device}} := \overrightarrow{\left(\frac{\text{Specific}_{\text{energy}}\cdot\text{Mass}_{\text{flywheel\_module}}}{\text{Vol}_{\text{flywheel\_module\_total}}}\right)} \qquad \text{Energy}_{\text{Density\_Storage\_device}} = \begin{pmatrix}40.744\\40.744\\40.744\end{pmatrix}\frac{\text{MJ}}{\text{m}^{3}}$$

Appendix C: SMES

SMES:

SMES technology is new and manufacturers are reluctant to publish some relative parameters, which are proprietary. Therefore some assumptions are made and noted below.

Constants and conversions:

$MW := 1000000W$	Mega Watts	$rpm := 2\cdot\frac{\pi}{min}$	Conversion from radians to RPM.
$GW := 1000MW$	Giga Watts	$LT := 2240lb$	LongTons
$kJ := 1000J$	kilo Joules	$USD := 1$	U.S. Dollars
$MJ := 1000000J$	Mega Joules	$MD := 1000000USD$	Million Dollars
$msec := \frac{sec}{1000}$	milli second	$BD := 1000MD$	Billion Dollars
$MWh := MW\cdot hr$	Mega Watt hour: A measurement of energy.	$MWh = 3.6\times 10^{9}J$	

Inputs:

$V_{in} := 450V$		Voltage available to apply to SMES from shipboard source.
$I_{in} := 6000A$		Total Current available to apply to SMES.
$P_{in} := V_{in}\cdot I_{in}$	$P_{in} = 2.7MW$	Total Power deliverable to energy storage device.
$P_{Device\_required} := \begin{pmatrix} 40MW \\ 160MW \\ 10GW \end{pmatrix}$		Power required of SMES to power device (EMALS, ETG, HOA).

$$\mathrm{Pulse}_{\mathrm{length}} := \begin{pmatrix} 3\mathrm{s} \\ 2.5\mathrm{msec} \\ 2\mathrm{msec} \end{pmatrix}$$

The length of time required to power device.

$$\mathrm{Pulse}_{\mathrm{Repitition}} := \begin{pmatrix} 1 \\ 5 \\ 3 \end{pmatrix}$$

How many times does the device need to be operated for the energy stored in the SMES?

Calculations:

How much energy is needed to power the device for a given number of repetitions?

$$W_{\mathrm{Device\_required}} := \overrightarrow{\left(\mathrm{Pulse}_{\mathrm{Repitition}} \cdot P_{\mathrm{Device\_required}} \cdot \mathrm{Pulse}_{\mathrm{length}}\right)}$$

Energy required to be stored in SMES in order to fully power device for required time for a set number of repitition s.

$$W_{\mathrm{Device\_required}} = \begin{pmatrix} 120 \\ 2 \\ 60 \end{pmatrix} \mathrm{MJ}$$

What is the power available from ship sources?

$$P_{\mathrm{in}} := V_{\mathrm{in}} \cdot I_{\mathrm{in}}$$

Total powered provided to modules from shipboard source.

What are the conversion losses?

What are the parasitic losses?

Conversion Losses:

$$P_{\mathrm{electronics}} := 1\mathrm{W}$$

Dummy value. Not used in further calculations.

The expected power lost in conversion is 96% efficiency.

$$P_{\mathrm{loss\_due\_to\_power\_conversion\_in}} := .01 \cdot P_{\mathrm{in}}$$

$$P_{\mathrm{delivered\_to\_modules}} := P_{\mathrm{in}} - P_{\mathrm{loss\_due\_to\_power\_conversion\_in}}$$

Resulting power delivered to the system.

Parasitic Losses:

$$P_{refrigerant} := \frac{217W}{6MJ} W_{Device\_required}$$

Parametric value of 217W/6MJ determined from "Micro Superconducting Magnetic Energy Storage (SMES) System for Protection of Critical Industrial and Military Loads"

$$P_{Parasitic\_Loss} := P_{refrigerant}$$

$$P_{refrigerant} = \begin{pmatrix} 4.34 \times 10^{3} \\ 72.333 \\ 2.17 \times 10^{3} \end{pmatrix} W \qquad P_{Parasitic\_Loss} = \begin{pmatrix} 4.34 \\ 0.072 \\ 2.17 \end{pmatrix} kW$$

What is the energy needed in the SMES in order to provide the required energy to the device?

$$W_{modules\_required} := W_{Device\_required} \cdot 1.01$$

I have assumed a 1% loss in power when converting the energy from the SMES into usable applied electrical power. This may not be accurate, however, I am unable to produce a better guess from my research.

$$W_{modules\_required} = \begin{pmatrix} 121.2 \\ 2.02 \\ 60.6 \end{pmatrix} MJ$$

How much time does it take to charge the SMES to the desired energy?

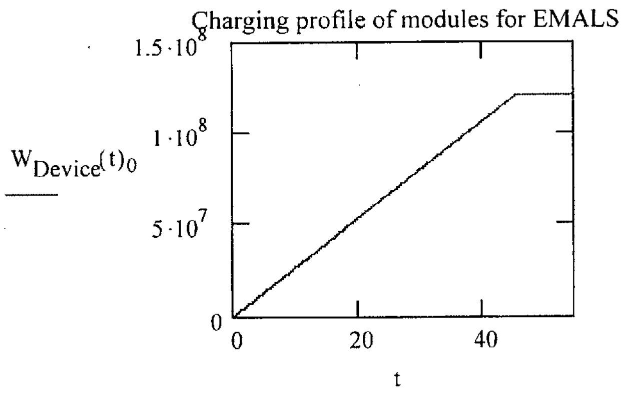
```
charge_time(P_to_SMES, W_rotor_required) :=
    est_time ← .01s
    while P_to_SMES · est_time < W_rotor_required
        est_time ← est_time + .01s
```

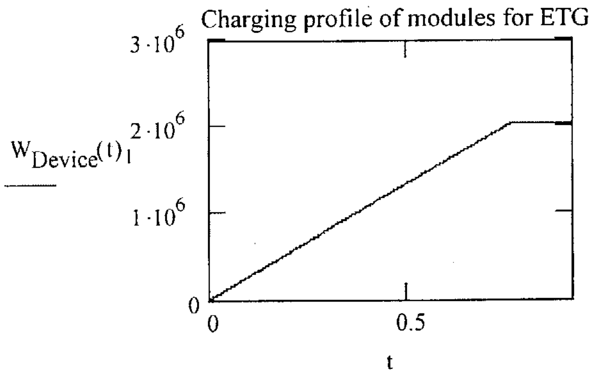
$$time_{charge} := \begin{pmatrix} charge\_time\left(P_{delivered\_to\_modules}, W_{modules\_required_{0}}\right) \\ charge\_time\left(P_{delivered\_to\_modules}, W_{modules\_required_{1}}\right) \\ charge\_time\left(P_{delivered\_to\_modules}, W_{modules\_required_{2}}\right) \end{pmatrix}$$

$$time_{charge} = \begin{pmatrix} 0.756 \\ 0.013 \\ 0.378 \end{pmatrix} min$$

The length of time to charge SMES to the desired energy level from zero.

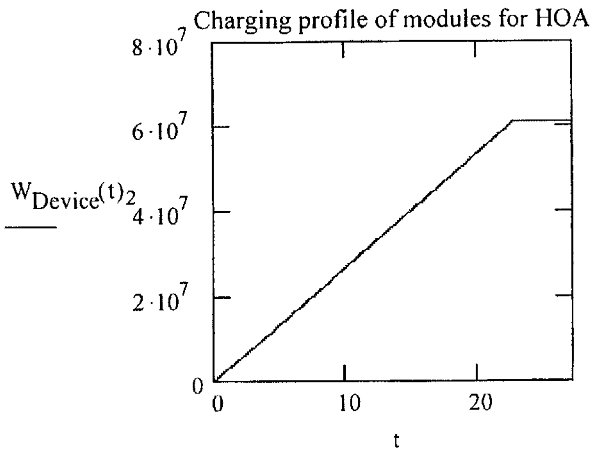
$$W_{Device}(t) := \begin{pmatrix} \left| \begin{array}{l} 0\cdot t \ \text{ if } \ t<0 \\ P_{delivered\_to\_modules}\cdot t \ \text{ if } \ 0 \le t \le time_{charge_0} \\ P_{delivered\_to\_modules}\cdot time_{charge_0} \ \text{ if } \ t > time_{charge_0} \end{array} \right. \\ \left| \begin{array}{l} 0\cdot t \ \text{ if } \ t<0 \\ P_{delivered\_to\_modules}\cdot t \ \text{ if } \ 0 \le t \le time_{charge_1} \\ P_{delivered\_to\_modules}\cdot time_{charge_1} \ \text{ if } \ t > time_{charge_1} \end{array} \right. \\ \left| \begin{array}{l} 0\cdot t \ \text{ if } \ t<0 \\ P_{delivered\_to\_modules}\cdot t \ \text{ if } \ 0 \le t \le time_{charge_2} \\ P_{delivered\_to\_modules}\cdot time_{charge_2} \ \text{ if } \ t > time_{charge_2} \end{array} \right. \end{pmatrix}$$





$W_{Device}\left(time_{charge_0}\right)_0 = 121.221\text{MJ}$

$W_{Device}\left(time_{charge_1}\right)_0 = 2.031\text{MJ}$



$$time_{discharge} := \begin{pmatrix} \overrightarrow{\dfrac{W_{modules\_required_0}}{\left(1.01P_{Device\_required}\right)_0}} \\ \overrightarrow{\dfrac{W_{modules\_required_1}}{1.01P_{Device\_required_1}}} \\ \overrightarrow{\dfrac{W_{modules\_required_2}}{\left(1.01P_{Device\_required}\right)_2}} \end{pmatrix}$$

$$W_{Device}\left(time_{charge_2}\right)_0 = 60.624MJ$$

$$time_{discharge} = \begin{pmatrix} 3 \\ 0.013 \\ 6\times 10^{-3} \end{pmatrix} s$$

$$P_{SMES\_max} := P_{Device\_required}$$

This is not truly accurate. SMES can provide much more power and is only limited by the power electronics channelling the power from the SMES to the load. The response time of delivering full power is also only limited by the electronics.

$$Energy_{to\_mass} := \frac{2045kg}{3MJ}$$

$$Mass_{SMES} := Energy_{to\_mass} \cdot W_{modules\_required}$$

$$Gauss_{radius} := 6.1m$$

The mass of the SMES is estimated here using values obtained by American Superconductor's data sheets on their SMES units. 10,000 lbs was subtracted to account for the mass of the trailer.

Gauss radius is the radius the SMES leakage field decreases to 5 Gauss.

$$h_{trailer} := 9ft$$

$$Vol_{3MJ\_SMES\_ratio} := \frac{\left(\pi \cdot Gauss_{radius}{}^{2} \cdot h_{trailer}\right)}{3MJ}$$

$$Vol_{SMES} := \overrightarrow{\left(W_{modules\_required} \cdot Vol_{3MJ\_SMES\_ratio}\right)} \qquad Vol_{SMES} = \begin{pmatrix} 1.296\times 10^{4} \\ 215.922 \\ 6.478\times 10^{3} \end{pmatrix} m^{3}$$

Secondary volume calculation based on "Systems Considerations in Capacitvive Storage" by Schempp, page 670.

$$Energy_{Density\_SMES} := .05\frac{J}{cm^{3}} \qquad Vol_{SMES2} := \frac{W_{modules\_required}}{Energy_{Density\_SMES}} \qquad Vol_{SMES2} = \begin{pmatrix} 2.424\times 10^{3} \\ 40.4 \\ 1.212\times 10^{3} \end{pmatrix} m^{3}$$

$$Mass_{SMES} = \begin{pmatrix} 8.262\times 10^{4} \\ 1.377\times 10^{3} \\ 4.131\times 10^{4} \end{pmatrix} kg \qquad time_{charge} = \begin{pmatrix} 0.756 \\ 0.013 \\ 0.378 \end{pmatrix} min$$

$$P_{SMES\_max} = \begin{pmatrix} 40 \\ 160 \\ 1\times 10^{4} \end{pmatrix} MW \qquad P_{Parasitic\_Loss} = \begin{pmatrix} 4.34 \\ 0.072 \\ 2.17 \end{pmatrix} kW$$

$$time_{discharge} = \begin{pmatrix} 3 \\ 0.013 \\ 6\times 10^{-3} \end{pmatrix} s \qquad Pulse_{Repitition} = \begin{pmatrix} 1 \\ 5 \\ 3 \end{pmatrix}$$

$$\text{Specific}_{\text{Power}} := \overrightarrow{\left(\frac{P_{\text{SMES\_max}}}{\text{Mass}_{\text{SMES}}}\right)}$$

$$\text{Specific}_{\text{Power}} = \begin{pmatrix}0.484\\116.197\\242.078\end{pmatrix}\frac{\text{kW}}{\text{kg}}$$

$$\text{Specific}_{\text{Energy\_application}} := \overrightarrow{\left[\frac{\begin{pmatrix}W_{\text{Device}}\left(\text{time}_{\text{charge}_0}\right)^{0}\\ W_{\text{Device}}\left(\text{time}_{\text{charge}_1}\right)^{1}\\ W_{\text{Device}}\left(\text{time}_{\text{charge}_2}\right)^{2}\end{pmatrix}}{\text{Mass}_{\text{SMES}}}\right]}$$

$$\text{Specific}_{\text{Energy\_application}} = \begin{pmatrix}1.467\\1.475\\1.468\end{pmatrix}\frac{\text{kJ}}{\text{kg}}$$

$$\text{Specific}_{\text{Energy\_storage\_device}} := \overrightarrow{\left(\frac{1}{\text{Energy}_{\text{to\_mass}}}\right)}$$

$$\text{Specific}_{\text{Energy\_storage\_device}} = 1.467\frac{\text{kJ}}{\text{kg}}$$

$$\text{Power}_{\text{Density}} := \overrightarrow{\left(\frac{P_{\text{SMES\_max}}}{\text{Vol}_{\text{SMES2}}}\right)}$$

$$\text{Power}_{\text{Density}} = \begin{pmatrix}16.502\\3.96\times 10^{3}\\8.251\times 10^{3}\end{pmatrix}\frac{\text{kW}}{\text{m}^{3}}$$

$$\text{Energy}_{\text{Density\_application}} := \text{Energy}_{\text{Density\_SMES}}$$

$$\text{Energy}_{\text{Density\_application}} = 50\frac{\text{kJ}}{\text{m}^{3}}$$

$$\text{Energy}_{\text{Density\_Storage\_device}} := \overrightarrow{\left(\frac{\text{Specific}_{\text{Energy\_storage\_device}}\cdot\text{Mass}_{\text{SMES}}}{\text{Vol}_{\text{SMES2}}}\right)}$$

$$\text{Energy}_{\text{Density\_Storage\_device}} = \begin{pmatrix}0.05\\0.05\\0.05\end{pmatrix}\frac{\text{MJ}}{\text{m}^{3}}$$

Appendix D: Metalized Electrode Capacitors

Metalized Electrode Capacitors:

This model is mainly based on the metalized electrode capacitor outlined in "High Energy Density Capacitors for ETC Gun Applications".

Constants and conversions:

$MW := 1000000W$	Mega Watts	$rpm := 2 \cdot \frac{\pi}{min}$	Conversion from radians to RPM.
$GW := 1000MW$	Giga Watts	$LT := 2240lb$	LongTons
$kJ := 1000J$	kilo Joules	$USD := 1$	U.S. Dollars
$MJ := 1000000J$	Mega Joules	$MD := 1000000USD$	Million Dollars
$msec := \frac{sec}{1000}$	milli second	$BD := 1000MD$	Billion Dollars
$MWh := MW \cdot hr$	Mega Watt hour: A measurement of energy.	$MWh = 3.6 \times 10^{9} J$	

Inputs:

$V_{in} := 450V$	Voltage available to apply to Ultra Capacitors from shipboard source.
$I_{in} := 2000A$	Total Current available to apply to Ultra Capacitors.
$P_{Device\_required} := \begin{pmatrix} 40MW \\ 160MW \\ 10GW \end{pmatrix}$	Power required of Ultra Capacitors to power device (EMALS, ETG, Higher Order Applications).

$$\mathrm{Pulse}_{\mathrm{length}} := \begin{pmatrix} 3\mathrm{sec} \\ 2\mathrm{msec} \\ 2.5\mathrm{msec} \end{pmatrix}$$

The length of time required to power device.

$$\mathrm{Pulse}_{\mathrm{Repitition}} := \begin{pmatrix} 1 \\ 5 \\ 3 \end{pmatrix}$$

How many times does the device need to be operated for the energy stored in the Ultra Capacitors?

Calculations:

How much energy is needed to power the device for a given number of repititions?

$$W_{\mathrm{Device\_required}} := \overrightarrow{\left(\mathrm{Pulse}_{\mathrm{Repitition}} \cdot P_{\mathrm{Device\_required}} \cdot \mathrm{Pulse}_{\mathrm{length}}\right)}$$

Energy required to be stored in Ultra Capacitors in order to fully power device for required time for a set number of repititions.

What is the power available from ship sources?

$$P_{\mathrm{in}} := 3V_{\mathrm{in}} \cdot I_{\mathrm{in}}$$

Total powered provided to Ultra Capacitors from shipboard source.

$$C_{\mathrm{MEC}} := \begin{pmatrix} 206\mu\mathrm{F} & 192.5\mu\mathrm{F} \end{pmatrix}$$

Capacitance of the Ultra Capacitors

$$dt_{\mathrm{MEC}} := \begin{pmatrix} 8\mathrm{msec} & 4\mathrm{msec} \end{pmatrix}$$

The capacitors being analyzed can fully discharge within these times. The power is averaged over this time for the amount of energy in the capacitor. Although the power would be much greater in the initial discharge of the capacitor, the energy capacity of the capacitor is the driving factor to determine the number of capacitors in the bank.

$$V_0 := \begin{pmatrix} 22\mathrm{kV} & 35\mathrm{kV} \end{pmatrix}$$

$$W_{\mathrm{MEC}} := \overrightarrow{\left(.5 \cdot C_{\mathrm{MEC}} \cdot {V_0}^2\right)} \qquad W_{\mathrm{MEC}} = \begin{pmatrix} 0.05 & 0.118 \end{pmatrix} \mathrm{MJ}$$

$$P_{MEC} := \overrightarrow{\frac{W_{MEC}}{dt_{MEC}}} \qquad P_{MEC} = (6.231\ \ 29.477)\ \text{MW}$$

$$I_{MEC} := \overrightarrow{\left(\frac{P_{MEC}}{V_0}\right)} \qquad I_{MEC} = (283.25\ \ 842.188)\ \text{A}$$

The rise time of the second capacitor is 750 μsec to maximum discharge current of 11.5 kA. The first analyzed capacitor has a peak current of 150 kA

The capacitor can be fully discharged (crowbar) within 1 msec. Well within the ETG and Higher Order Applications pulse lengths being considered in this thesis. Typical discharge time for pulse power can be as short as 2-2.5 msec.

How many capacitors are needed to meet the power and energy demands of the power pulse devices?

$$N_{MEC\_1st} := \overrightarrow{\left(\text{ceil}\left(\frac{P_{Device\_required} \cdot Pulse_{length} \cdot Pulse_{Repitition}}{W_{MEC_{0,0}}}\right)\right)}$$

$$N_{MEC\_2nd} := \overrightarrow{\left(\text{ceil}\left(\frac{P_{Device\_required} \cdot Pulse_{length} \cdot Pulse_{Repitition}}{W_{MEC_{0,1}}}\right)\right)}$$

$$N_{MEC\_1st} = \begin{pmatrix} 2.408 \times 10^{3} \\ 33 \\ 1.505 \times 10^{3} \end{pmatrix} \qquad N_{MEC\_2nd} = \begin{pmatrix} 1.018 \times 10^{3} \\ 14 \\ 637 \end{pmatrix}$$

$$W_{MEC\_bank\_1st} := \overrightarrow{\left(N_{MEC\_1st} \cdot W_{MEC_{0,0}}\right)} \qquad W_{MEC\_bank\_1st} = \begin{pmatrix} 120.044 \\ 1.645 \\ 75.027 \end{pmatrix} \mathrm{MJ}$$

$$W_{MEC\_bank\_2nd} := \overrightarrow{\left(N_{MEC\_2nd} \cdot W_{MEC_{0,1}}\right)} \qquad W_{MEC\_bank\_2nd} = \begin{pmatrix} 120.029 \\ 1.651 \\ 75.106 \end{pmatrix} \mathrm{MJ}$$

$$P_{MEC\_bank\_1st} := \overrightarrow{\left(N_{MEC\_1st} \cdot P_{MEC_{0,0}}\right)} \qquad P_{MEC\_bank\_1st} = \begin{pmatrix} 1.501 \times 10^{4} \\ 205.639 \\ 9.378 \times 10^{3} \end{pmatrix} \mathrm{MW}$$

$$P_{MEC\_bank\_2nd} := \overrightarrow{\left(N_{MEC\_2nd} \cdot P_{MEC_{0,1}}\right)} \qquad P_{MEC\_bank\_2nd} = \begin{pmatrix} 3.001 \times 10^{4} \\ 412.672 \\ 1.878 \times 10^{4} \end{pmatrix} \mathrm{MW}$$

$$\mathrm{Weight}_{MEC} := \left(145.2\mathrm{kg} \quad 70\mathrm{kg}\right)$$

$$\mathrm{Volume}_{MEC} := \left(.086397\mathrm{m}^3 \quad .059\mathrm{m}^3\right)$$

$$\mathrm{Weight}_{MEC\_bank\_1st} := \overrightarrow{\left(N_{MEC\_1st} \cdot \mathrm{Weight}_{MEC_{0,0}}\right)} \qquad \mathrm{Weight}_{MEC\_bank\_1st} = \begin{pmatrix} 385.414 \\ 5.282 \\ 240.884 \end{pmatrix} \mathrm{ton}$$

$$\mathrm{Weight}_{MEC\_bank\_2nd} := \overrightarrow{\left(N_{MEC\_1st} \cdot \mathrm{Weight}_{MEC_{0,1}}\right)} \qquad \mathrm{Weight}_{MEC\_bank\_2nd} = \begin{pmatrix} 185.806 \\ 2.546 \\ 116.128 \end{pmatrix} \mathrm{ton}$$

$$\mathrm{Volume}_{\mathrm{MEC\_bank\_1st}} := \overrightarrow{\left(N_{\mathrm{MEC\_1st}} \cdot \mathrm{Volume}_{\mathrm{MEC}_{0,0}}\right)} \qquad \mathrm{Volume}_{\mathrm{MEC\_bank\_1st}} = \begin{pmatrix} 208.044 \\ 2.851 \\ 130.027 \end{pmatrix} \mathrm{m}^3$$

$$\mathrm{Volume}_{\mathrm{MEC\_bank\_2nd}} := \overrightarrow{\left(N_{\mathrm{MEC\_1st}} \cdot \mathrm{Volume}_{\mathrm{MEC}_{0,1}}\right)} \qquad \mathrm{Volume}_{\mathrm{MEC\_bank\_2nd}} = \begin{pmatrix} 142.072 \\ 1.947 \\ 88.795 \end{pmatrix} \mathrm{m}^3$$

Time to recharge capacitor bank:

$$\mathrm{Time}_{\mathrm{from\_zero\_1st}} := \overrightarrow{\left(\frac{W_{\mathrm{MEC\_bank\_1st}}}{P_{\mathrm{in}}}\right)} \qquad \mathrm{Time}_{\mathrm{from\_zero\_1st}} = \begin{pmatrix} 0.741 \\ 0.01 \\ 0.463 \end{pmatrix} \mathrm{min}$$

$$\mathrm{Time}_{\mathrm{from\_zero\_2nd}} := \overrightarrow{\left(\frac{W_{\mathrm{MEC\_bank\_2nd}}}{P_{\mathrm{in}}}\right)} \qquad \mathrm{Time}_{\mathrm{from\_zero\_2nd}} = \begin{pmatrix} 0.741 \\ 0.01 \\ 0.464 \end{pmatrix} \mathrm{min}$$

$$\mathrm{Specific}_{\mathrm{Power}} := \overrightarrow{\left(\frac{P_{\mathrm{MEC\_bank\_2nd}}}{\mathrm{Weight}_{\mathrm{MEC\_bank\_2nd}}}\right)} \qquad \mathrm{Specific}_{\mathrm{Power}} = \begin{pmatrix} 0.178 \\ 0.179 \\ 0.178 \end{pmatrix} \frac{\mathrm{MW}}{\mathrm{kg}}$$

$$\mathrm{Specific}_{\mathrm{Energy\_application}} := \overrightarrow{\left(\frac{W_{\mathrm{Device\_required}}}{\mathrm{Weight}_{\mathrm{MEC\_bank\_2nd}}}\right)} \qquad \mathrm{Specific}_{\mathrm{Energy\_application}} = \begin{pmatrix} 0.712 \\ 0.693 \\ 0.712 \end{pmatrix} \frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$\mathrm{Specific}_{\mathrm{Energy\_storage\_device}} := \overrightarrow{\left(\frac{W_{\mathrm{MEC\_bank\_2nd}}}{\mathrm{Weight}_{\mathrm{MEC\_bank\_2nd}}}\right)} \qquad \mathrm{Specific}_{\mathrm{Energy\_storage\_device}} = \begin{pmatrix} 0.712 \\ 0.715 \\ 0.713 \end{pmatrix} \frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$\mathrm{Power}_{\mathrm{Density}} := \overrightarrow{\left(\frac{P_{\mathrm{MEC\_bank\_2nd}}}{\mathrm{Volume}_{\mathrm{MEC\_bank\_2nd}}}\right)} \qquad \mathrm{Power}_{\mathrm{Density}} = \begin{pmatrix} 211.211 \\ 211.953 \\ 211.46 \end{pmatrix} \frac{\mathrm{MW}}{\mathrm{m}^3}$$

$$\mathrm{Energy}_{\mathrm{Density\_application}} := \overrightarrow{\left(\frac{W_{\mathrm{Device\_required}}}{\mathrm{Volume}_{\mathrm{MEC\_bank\_2nd}}}\right)} \qquad \mathrm{Energy}_{\mathrm{Density\_application}} = \begin{pmatrix} 0.845 \\ 0.822 \\ 0.845 \end{pmatrix} \frac{\mathrm{MJ}}{\mathrm{m}^3}$$

$$\mathrm{Energy}_{\mathrm{Density\_Storage\_device}} := \overrightarrow{\left(\frac{W_{\mathrm{MEC\_bank\_2nd}}}{\mathrm{Volume}_{\mathrm{MEC\_bank\_2nd}}}\right)} \qquad \mathrm{Energy}_{\mathrm{Density\_Storage\_device}} = \begin{pmatrix} 0.845 \\ 0.848 \\ 0.846 \end{pmatrix} \frac{\mathrm{MJ}}{\mathrm{m}^3}$$

$$\mathrm{Cost}_{\mathrm{MEC\_2nd}} := 3800\mathrm{USD}$$

$$\mathrm{Capital}_{\mathrm{expense}} := N_{\mathrm{MEC\_2nd}} \cdot \mathrm{Cost}_{\mathrm{MEC\_2nd}} \qquad \mathrm{Capital}_{\mathrm{expense}} = \begin{pmatrix} 3.868 \\ 0.053 \\ 2.421 \end{pmatrix} \mathrm{MD}$$

Appendix E: Ultra Capacitors

Ultra Capacitor 2700: 2700F capacitors are being produced by Maxwell Technologies

This model is mainly based on the numerical procedures outlined by "Analysis of Double Layered Capacitors Supplying Constant Power Loads" using the classical equivalent circuit for a double layered capacitor. The capacitance is in parallel with the EPR (Equivalent Parallel Resistance) to model the leakage current. The capacitance and the EPR are together in series with the ESR (Equivalent Series Resistance) to model the heat dissapation.

Constants and conversions:

$MW := 1000000W$	Mega Watts	$rpm := 2\cdot\frac{\pi}{min}$	Conversion from radians to RPM.
$GW := 1000MW$	Giga Watts	$LT := 2240lb$	LongTons
$kJ := 1000J$	kilo Joules	$USD := 1$	U.S. Dollars
$MJ := 1000000J$	Mega Joules	$MD := 1000000USD$	Million Dollars
$msec := \frac{sec}{1000}$	milli second	$BD := 1000MD$	Billion Dollars
$MWh := MW\cdot hr$	Mega Watt hour: A measurement of energy.	$MWh = 3.6\times 10^{9}\,J$	
$gram := \frac{kg}{1000}$	gram		

Inputs:

$V_{in} := 450V$ Voltage available to apply to Ultra Capacitors from shipboard source.

$I_{in} := 2000A$ Total Current available to apply to Ultra Capacitors.

$$P_{Device\_required} := \begin{pmatrix} 40MW \\ 160MW \\ 10GW \end{pmatrix}$$

Power required of Ultra Capacitors to power device (EMALS, ETG, Higher Order Applications).

$$Pulse_{length} := \begin{pmatrix} 3sec \\ 2msec \\ 2.5msec \end{pmatrix}$$

The length of time required to power device.

$$Pulse_{Repitition} := \begin{pmatrix} 1 \\ 5 \\ 3 \end{pmatrix}$$

How many times does the device need to be operated for the energy stored in the Ultra Capacitors?

Calculations:

How much energy is needed to power the device for a given number of repititions?

$$W_{Device\_required} := \overrightarrow{\left(Pulse_{Repitition} \cdot P_{Device\_required} \cdot Pulse_{length}\right)}$$

Energy required to be stored in Ultra Capacitors in order to fully power device for required time for a set number of repititions.

What is the power available from ship sources?

$$P_{in} := 3V_{in} \cdot I_{in}$$

Total powered provided to Ultra Capacitors from shipboard source.

$$C_{2700} := 2700F$$

Capacitance of the Ultra Capacitors

$$Vol_{2700} := .6liter$$

$$Weight_{2700} := 600gram$$

$ESR := .001ohm$ $EPR := .001ohm$

ESR is the equivalent series resistance. EPR is the equivalent parallel resistance.

$$n_S := \begin{pmatrix} 40 \\ 40 \\ 40 \end{pmatrix}$$

The number of capacitors connected in series.

$$n_P := \begin{pmatrix} 2800 \\ 11200 \\ 700000 \end{pmatrix}$$

The number of capacitors connected in parallel.

$V_0 := 2.5V$

The voltage of the capacitor bank to be applied to the DC to DC converter which will power the load. This is in order to provide a constant voltage to the load instead of the decreasing voltage of the Ultra Capacitor as the energy is depleted.

$$R_{bank} := \overrightarrow{\left(n_S \cdot \frac{ESR}{n_P}\right)} \qquad R_{bank} = \begin{pmatrix} 1.429 \times 10^{-5} \\ 3.571 \times 10^{-6} \\ 5.714 \times 10^{-8} \end{pmatrix} \Omega$$

Equivalent resistance for the bank of Ultra Capacitors.

$$C_{bank} := \overrightarrow{\left(n_P \cdot \frac{C_{2700}}{n_S}\right)} \qquad C_{bank} = \begin{pmatrix} 1.89 \times 10^{5} \\ 7.56 \times 10^{5} \\ 4.725 \times 10^{7} \end{pmatrix} F$$

Equivalent capacitance for the bank of Ultra Capacitors.

$$V_{cap\_initial} := V_0 \cdot n_S \qquad V_{cap\_initial} = \begin{pmatrix} 100 \\ 100 \\ 100 \end{pmatrix} V$$

We will assume that the capacitor is initially charged to a full 2.5 volts per capacitor in the capacitor bank.

$$\eta_{DC\_DC\_converter} := .915$$

Assumed efficiency of DC to DC converter.

$$P_{cap\_bank\_reqd} := \overrightarrow{\frac{P_{Device\_required}}{\eta_{DC\_DC\_converter}}}$$

Power of capacitor bank needed to overcome the power loss in the DC to DC converter.

$$I_{cap\_initial} := \overrightarrow{\frac{\left(V_{cap\_initial} - \sqrt{V_{cap\_initial}^{\;2} - 4 \cdot R_{bank} \cdot P_{Device\_required}}\right)}{2 \cdot R_{bank}}}$$

Initial current needed with the given voltage of the capacitor bank in order to provide the power needed by the device.

$$V_{cap\_final} := \overrightarrow{\left(2 \cdot \sqrt{R_{bank} \cdot P_{cap\_bank\_reqd}}\right)} \qquad V_{cap\_final} = \begin{pmatrix} 49.98 \\ 49.98 \\ 49.98 \end{pmatrix} V$$

The voltage will diminish as the capacitor releases energy.

$$I_{cap\_final} := \overrightarrow{\frac{V_{cap\_final}}{2 \cdot R_{bank}}} \qquad I_{cap\_final} := \overrightarrow{\sqrt{\frac{P_{cap\_bank\_reqd}}{R_{bank}}}} \qquad \overrightarrow{\left(I_{cap\_initial}^{\;2} \cdot R_{bank}\right)} = \begin{pmatrix} 2.591 \\ 10.366 \\ 647.869 \end{pmatrix} MW$$

$$I_{cap\_final} = \begin{pmatrix} 1.749 \times 10^{6} \\ 6.997 \times 10^{6} \\ 4.373 \times 10^{8} \end{pmatrix} A$$

Final current needed with the given voltage of the capacitor bank in order to provide the power needed by the device.

$$P_{cap\_initial} := \overrightarrow{\left(V_{cap\_initial} \cdot I_{cap\_initial}\right)}$$

$$P_{cap\_initial} = \begin{pmatrix} 42.591 \\ 170.366 \\ 1.065 \times 10^{4} \end{pmatrix} \mathrm{MW}$$

As the current increases to compensate for the votage dimishing, the heat loss will increase.

$$P_{cap\_final} := \overrightarrow{\left(V_{cap\_final} \cdot I_{cap\_final}\right)}$$

$$P_{cap\_final} = \begin{pmatrix} 87.432 \\ 349.727 \\ 2.186 \times 10^{4} \end{pmatrix} \mathrm{MW}$$

$$I_{cap\_individual} := \overrightarrow{\frac{I_{cap\_final}}{n_P}}$$

$$I_{cap\_individual} = \begin{pmatrix} 624.756 \\ 624.756 \\ 624.756 \end{pmatrix} \mathrm{A}$$

This value cannot exceed 625 amps for the 2700F capacitor of Maxwell Technologies. Adjust the number of capacitors in series and in parallel to adjust this value.

Determine behavior and discharge time of Ultra Capacitor

$j := 1000000 \qquad p := 5000 \quad k := 170 \qquad l := 100 \qquad n := 1..k$

Number of increments.

$$I_{increment} := \begin{bmatrix} \dfrac{\left(I_{cap\_final_0} - I_{cap\_initial_0}\right)}{p} \\ \dfrac{\left(I_{cap\_final_1} - I_{cap\_initial_1}\right)}{j} \\ \dfrac{\left(I_{cap\_final_2} - I_{cap\_initial_2}\right)}{j} \end{bmatrix} \qquad I_{increment} = \begin{pmatrix} 264.68 \\ 5.294 \\ 330.851 \end{pmatrix} \mathrm{A}$$

Current increments for calculations.

$$I_{incremental}(n) := \left|\begin{array}{l} \left(\overrightarrow{\left(I_{cap\_initial} + n \cdot I_{increment}\right)}\right) \text{ if } n > 0 \\ 0 \text{ if } n \le 0 \end{array}\right.$$

The current at each instant in time.

$$V_{incremental}(n) := \left|\begin{array}{l} \overrightarrow{\left(\frac{P_{Device\_required}}{I_{incremental}(n)} + I_{incremental}(n) \cdot R_{bank}\right)} \text{ if } n > 0 \\ V_{cap\_initial} \text{ if } n \le 0 \end{array}\right.$$

The voltage at each instant in time.

$$time_{delta}(n) := \frac{\overrightarrow{\left[C_{bank} \cdot \left(V_{incremental}(n-1) - V_{incremental}(n+1)\right)\right]}}{2 I_{incremental}(n)}$$

time increments

$$time_{discharge}(k) := \sum_{n=1}^{k} \overrightarrow{time_{delta}(n)}$$

$$time_{discharge}(10) = \begin{pmatrix} 0.24 \\ 1.211 \times 10^{-3} \\ 1.211 \times 10^{-3} \end{pmatrix} s$$

$$m_{EMALS}(k) := \left|\begin{array}{l} m_{EMALS} \leftarrow 0 \\ \text{for } i \in 1..k \\ \quad m_{EMALS} \leftarrow m_{EMALS} + 1 \text{ if } time_{discharge}(i)_0 < Pulse_{length_0} \end{array}\right.$$

$$m_{EMALS}(k) = 141$$

This computes the number of time intervals of the computation such that it can be used later to compute the energy dissipated from the capacitor.

$$m_{ETG}(m) := \left|\begin{array}{l} m_{ETG} \leftarrow 0 \\ \text{for } i \in 1..m \\ \quad m_{ETG} \leftarrow m_{ETG} + 1 \text{ if } time_{discharge}(i)_1 < Pulse_{length_1} \end{array}\right.$$

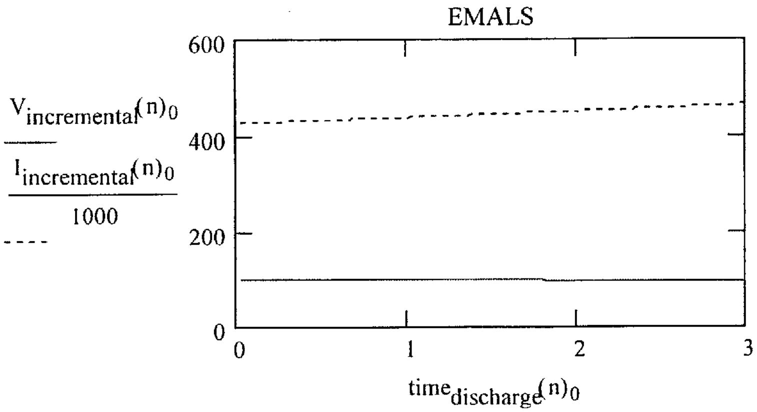
$$m_{ETG}(l) = 16$$

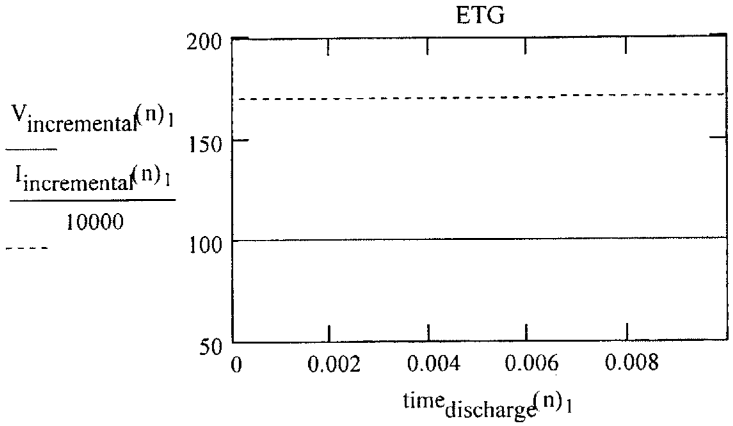
This computes the number of time intervals of the computation such that it can be used later to compute the energy dissipated from the capacitor.

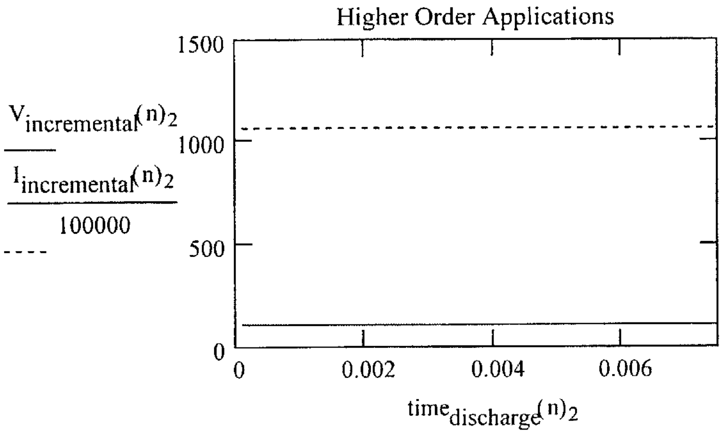
```
mHOA(m) := | mHOA ← 0
           | for i ∈ 1..m
           |   mHOA ← mHOA + 1  if timedischarge(i)2 < Pulselength2
```

$m_{HOA}(l) = 20$

This computes the number of time intervals of the computation such that it can be used later to compute the energy dissipated from the capacitor.







$$P_{incremental\_out\_of\_cap}(n) := \overrightarrow{\left(V_{incremental}(n) \cdot I_{incremental}(n)\right)}$$

The power out of the capacitor at time n is multiplied by the delta time (n-1) and summed until the discharge time determined above is reached (m.EMALS(m).

$$W_{out\_of\_cap\_EMALS} := \sum_{n=1}^{m_{EMALS}(k)} \overrightarrow{\left(P_{incremental\_out\_of\_cap}(n)_0 \cdot time_{delta}(n)_0\right)}$$

$$W_{out\_of\_cap\_EMALS} = 128.135MJ$$

$$W_{out\_of\_cap\_ETG} := \sum_{n=1}^{m_{ETG}(l)} P_{incremental\_out\_of\_cap}(n)_1 \cdot time_{delta}(n)_1$$

$$W_{out\_of\_cap\_ETG} = 0.33MJ$$

$$W_{out\_of\_cap\_HOA} := \sum_{n=1}^{m_{HOA}(l)} P_{incremental\_out\_of\_cap}(n)_2 \cdot time_{delta}(n)_2$$

$$W_{out\_of\_cap\_HOA} = 25.787MJ$$

$$W_{out\_of\_cap} := \begin{pmatrix} W_{out\_of\_cap\_EMALS} \\ W_{out\_of\_cap\_ETG} \\ W_{out\_of\_cap\_HOA} \end{pmatrix}$$

$$P_{incremental\_out\_of\_cap\_after\_ht\_loss}(n) := \overrightarrow{\left(V_{incremental}(n) \cdot I_{incremental}(n) - I_{incremental}(n)^2 \cdot R_{bank}\right)}$$

$$P_{incremental\_out\_of\_cap\_after\_ht\_loss}(10) = \begin{pmatrix} 40 \\ 160 \\ 1 \times 10^4 \end{pmatrix} MW$$

Double check that the power out after heat dissipation is of the required energy above.

$$W_{avail\_for\_device} := \begin{pmatrix} \displaystyle\sum_{n=1}^{m_{EMALS}(k)} \overrightarrow{\left(P_{incremental\_out\_of\_cap\_after\_ht\_loss}(n)_0 \cdot time_{delta}(n)_0\right)} \\ \displaystyle\sum_{n=1}^{m_{ETG}(l)} \overrightarrow{\left(P_{incremental\_out\_of\_cap\_after\_ht\_loss}(n)_1 \cdot time_{delta}(n)_1\right)} \\ \displaystyle\sum_{n=1}^{m_{HOA}(l)} \overrightarrow{\left(P_{incremental\_out\_of\_cap\_after\_ht\_loss}(n)_2 \cdot time_{delta}(n)_2\right)} \end{pmatrix}$$

$$W_{avail\_for\_device} = \begin{pmatrix} 119.706 \\ 0.31 \\ 24.218 \end{pmatrix} MJ$$

How much time does it take to charge the Ultra Capacitors to the desired energy?

$$I_{single\_unit\_cap\_max} := 625A$$

$$I_{bank\_cap\_max} := \overrightarrow{\left(I_{single\_unit\_cap\_max} \cdot n_P\right)}$$

$$I_{bank\_cap\_max} = \begin{pmatrix} 1.75 \times 10^{6} \\ 7 \times 10^{6} \\ 4.375 \times 10^{8} \end{pmatrix} A$$

$$V_{bank\_cap\_max} := V_0 \cdot n_S$$

$$V_{bank\_cap\_max} = \begin{pmatrix} 100 \\ 100 \\ 100 \end{pmatrix} V$$

$$P_{bank\_charge\_max} := \overrightarrow{\left(V_{bank\_cap\_max} \cdot I_{bank\_cap\_max}\right)}$$

$$P_{bank\_charge\_max} = \begin{pmatrix} 175 \\ 700 \\ 4.375 \times 10^{4} \end{pmatrix} MW$$

$$W_{bank\_charge\_max} := \overrightarrow{\left(.5 \cdot C_{bank} \cdot V_{bank\_cap\_max}^{\;2}\right)}$$

$$W_{bank\_charge\_max} := \overrightarrow{\left(.5 \cdot C_{2700} \cdot V_0^{\,2} \cdot n_P \cdot n_S\right)}$$

$$W_{bank\_charge\_max} = \begin{pmatrix} 945 \\ 3.78\times 10^{3} \\ 2.362\times 10^{5} \end{pmatrix} \mathrm{MJ}$$

$$P_{to\_cap\_bank} := P_{in}$$

$$I_{to\_cap\_bank} := \overrightarrow{\frac{P_{to\_cap\_bank}}{V_{bank\_cap\_max}}}$$

$$P_{in} = 2.7\mathrm{MW}$$

Power from ship source.

$$P_{bank\_charge} := \overrightarrow{\left(P_{to\_cap\_bank} \cdot \eta_{DC\_DC\_converter} - I_{to\_cap\_bank}^{\,2} \cdot R_{bank}\right)}$$

$$P_{bank\_charge} = \begin{pmatrix} 2.46 \\ 2.468 \\ 2.47 \end{pmatrix} \mathrm{MW}$$

Power applied to capacitor bank after losses in capacitor bank and 91.5% efficiency assumed for the DC to DC converter.

Time to charge capacitor bank from no energy to full energy:

$$Time_{from\_zero} := \overrightarrow{\left(\frac{W_{bank\_charge\_max}}{P_{bank\_charge}}\right)}$$

$$Time_{from\_zero} = \begin{pmatrix} 6.402 \\ 25.528 \\ 1.594\times 10^{3} \end{pmatrix} \mathrm{min}$$

$$Time_{to\_recharge} := \overrightarrow{\frac{W_{out\_of\_cap}}{P_{bank\_charge}}}$$

$$Time_{to\_recharge} = \begin{pmatrix} 52.085 \\ 0.134 \\ 10.438 \end{pmatrix} \mathrm{sec}$$

$$Vol_{bank} := \overrightarrow{\left(Vol_{2700} \cdot n_S \cdot n_P\right)}$$

$$Vol_{bank} = \begin{pmatrix} 67.2 \\ 268.8 \\ 1.68\times 10^{4} \end{pmatrix} \mathrm{m}^{3}$$

$$\text{Weight}_{\text{bank}} := \overrightarrow{\left(\text{Weight}_{2700} n_S \cdot n_P\right)}$$

$$\text{Weight}_{\text{bank}} = \begin{pmatrix} 66.139 \\ 264.555 \\ 1.653\times 10^{4} \end{pmatrix} \text{LT}$$

Cost:

$$\text{Cost}_{2700} := 27\text{USD} \qquad \text{Cost}_{2700} = 27\text{USD}$$

$$\text{Cost}_{\text{bank}} := \overrightarrow{\left(n_S \cdot n_P \cdot \text{Cost}_{2700}\right)}$$

$$\text{Cost}_{\text{bank}} = \begin{pmatrix} 3.024 \\ 12.096 \\ 756 \end{pmatrix} \text{MD}$$

$$\text{Specific}_{\text{Power}} := \overrightarrow{\left(\frac{P_{\text{Device\_required}}}{\text{Weight}_{\text{bank}}}\right)} \qquad \text{Specific}_{\text{Power}} = \begin{pmatrix} 0.595 \\ 0.595 \\ 0.595 \end{pmatrix} \frac{\text{kW}}{\text{kg}}$$

$$\text{Specific}_{\text{Energy\_application}} := \overrightarrow{\left(\frac{W_{\text{Device\_required}}}{\text{Weight}_{\text{bank}}}\right)} \qquad \text{Specific}_{\text{Energy\_application}} = \begin{pmatrix} 1.786\times 10^{3} \\ 5.952 \\ 4.464 \end{pmatrix} \frac{\text{J}}{\text{kg}}$$

$$\text{Specific}_{\text{Energy\_storage\_device}} := \overrightarrow{\left(\frac{W_{\text{bank\_charge\_max}}}{\text{Weight}_{\text{bank}}}\right)} \qquad \text{Specific}_{\text{Energy\_storage\_device}} = \begin{pmatrix} 14.063 \\ 14.063 \\ 14.063 \end{pmatrix} \frac{\text{kJ}}{\text{kg}}$$

$$\text{Power}_{\text{Density}} := \overrightarrow{\left(\frac{P_{\text{Device\_required}}}{\text{Vol}_{\text{bank}}}\right)} \qquad \text{Power}_{\text{Density}} = \begin{pmatrix} 0.595 \\ 0.595 \\ 0.595 \end{pmatrix} \frac{\text{MW}}{\text{m}^{3}}$$

$$\text{Energy}_{\text{Density\_application}} := \overrightarrow{\left(\frac{W_{\text{Device\_required}}}{\text{Vol}_{\text{bank}}}\right)} \qquad \text{Energy}_{\text{Density\_application}} = \begin{pmatrix} 1.786\times 10^{3} \\ 5.952 \\ 4.464 \end{pmatrix} \frac{\text{kJ}}{\text{m}^{3}}$$

$$\text{Energy}_{\text{Density\_Storage\_device}} := \overrightarrow{\left(\frac{W_{\text{bank\_charge\_max}}}{\text{Vol}_{\text{bank}}}\right)} \qquad \text{Energy}_{\text{Density\_Storage\_device}} = \begin{pmatrix} 14.063 \\ 14.063 \\ 14.063 \end{pmatrix} \frac{\text{MJ}}{\text{m}^{3}}$$

Appendix F: Compulsators

CCEMG parameters			
Power Required	400000	W	
Energy Required	40000000	J	
Power Duration	3	sec	
PRR	3	sec	Best guess using picture. Supporting structure taken into account
Weight	2045	kg	
Volume (ft^3)	432	ft^3	

Application Parameters	EMALS	ETG	Higher Order Applications
Power Required	40 MW	160 MW	10 GW
Energy Required	121 MJ	400 kJ	20 MJ
Power Duration	3 sec	2.5 msec	2 msec
PRR	45 sec	5 sec	.1 sec

Using a parametric comparison, how many compulsators are required to meet the demands of the above application parameters?

Equivalently, what would be the size of a compulsator which is enlarged to provide the demands of the above application parameters?

	Power (W)	Energy (J)	Duration (sec)	Weight (kg)	Volume (m^3)
CCEMG	400000	40000000	3	2045	12.2328576
EMALS	40000000	120000000	3		
# of CCEMGs	100	3	1	204500	1223.28576
ETG	160000000	400000	0.0025		
# of CCEMGs	400	0.01	8.33333E-04	818000	4893.14304
Higher Order Applications	10000000000	20000000	0.002		
# of CCEMGs	25000	0.5	6.66667E-04	51125000	305821.44

	Specific Power	Specific Energy per pulse power application	Specific Energy per energy storage device	Power Density	Energy Density per pulse power application	Energy Density per energy storage device
CCEMG	W/kg	J/kg	J/kg	W/m^3	J/m^3	J/m^3
EMALS						
# of CCEMGs	195.599022	586.797066	19559.9022	32698.8192	98096.45785	3269881.928
ETG						
# of CCEMGs	195.599022	0.488997555	19559.9022	32698.8192	81.74704821	0.002452411
Higher Order Applications						
# of CCEMGs	195.599022	0.391198044	19559.9022	32698.8192	65.39763857	2.04368E-06

Appendix G: Batteries

Batteries:

Battery technology is a mature technology and great improvements should not be expected. The calculations below quickly show the futility of considering batteries for military power pulse applications. All parameters of the battery analyzed below will be assumed at the value to benefit the battery for consideration. In the end, the recharge rate is far too slow. Commercial pulse power applications may still be feasible if the recharge time is not an issue.

Constants and conversions:

$MW := 1000000W$	Mega Watts	$rpm := 2 \cdot \frac{\pi}{min}$	Conversion from radians to RPM.
$GW := 1000MW$	Giga Watts	$LT := 2240lb$	LongTons
$kJ := 1000J$	kilo Joules	$USD := 1$	U.S. Dollars
$MJ := 1000000J$	Mega Joules	$MD := 1000000USD$	Million Dollars
$msec := \frac{sec}{1000}$	milli second	$BD := 1000MD$	Billion Dollars
$MWh := MW \cdot hr$	Mega Watt hour: A measurement of energy.	$MWh = 3.6 \times 10^{9} J$	
$MT := 1000000kg$	Metric Ton		

Inputs:

$V_{in} := 450V$		Voltage available to apply to Battery Bank from shipboard source.
$I_{in} := 6000A$		Total Current available to apply to batteries.
$P_{in} := V_{in} \cdot I_{in}$	$P_{in} = 2.7MW$	Total Power deliverable to energy storage device.

$$P_{Device\_required} := \begin{pmatrix} 40MW \\ 160MW \\ 10GW \end{pmatrix}$$

Power required of batteries to power device (EMALS,ETG, Higher Order Applications).

$$Pulse_{length} := \begin{pmatrix} 3sec \\ 2msec \\ 2.5msec \end{pmatrix}$$

The length of time required to power device (EMALS,ETG, Higher Order Applications).

$$Pulse_{Repitition} := \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

How many times does the device need to be operated for the energy stored in the batteries?

Calculations:

How much energy is needed to power the device for a given number of repititions?

$$W_{Device\_required} := \overrightarrow{\left(Pulse_{Repitition} \cdot Pulse_{length} \cdot P_{Device\_required}\right)}$$

Energy required to be stored in batteries in order to fully power device for required time for a set number of repititions.

$$W_{Device\_required} = \begin{pmatrix} 120 \\ 0.32 \\ 25 \end{pmatrix} MJ$$

How many batteries are needed in the bank (type: SBH920 Ni-Cd battery from SAFT)? The best case scenario will be assumed for all parameters

$$V_{battery\_cell} := 1.14V$$

Voltage of each battery (cell)

$$A_{battery\_cell\_5sec} := 3130A$$

Discharge rate of each battery (cell) assuming the battery is fully charged. When the battery is not fully charged, the discharge rate is significantly reduced.

$P_{battery\_cell} := V_{battery\_cell} \cdot A_{battery\_cell\_5sec}$ $P_{battery\_cell} = 3.568\times 10^{3}\,W$ Power of the battery (cell)

$$Np_{batteries} := \overrightarrow{\frac{P_{Device\_required}}{P_{battery\_cell}}} \qquad Np_{batteries} = \begin{pmatrix} 1.121\times 10^{4} \\ 4.484\times 10^{4} \\ 2.803\times 10^{6} \end{pmatrix}$$

Number of batteries required to provide the required power.

$A_{battery\_5Ah} := 920A\cdot hr$

Battery discharge rate over 5 hours. This value is also used to determine the charging rate.

$W_{battery\_5Ah} := V_{battery\_cell} \cdot A_{battery\_5Ah}$

Giving the battery bank the best voltage available even though the voltage will drop as the battery is discharged.

$W_{battery\_5Ah} = 3.776MJ$

Energy of each battery.

$$Nw_{batteries} := \overrightarrow{\left(\frac{W_{Device\_required}}{W_{battery\_5Ah}}\right)} \qquad Nw_{batteries} = \begin{pmatrix} 31.782 \\ 0.085 \\ 6.621 \end{pmatrix}$$

Number of batteries required if the energy was the only consideration.

$N_{batteries} := Np_{batteries}$

The number of batteries will always depend on the power required assuming the power requirements are high.

$Height_{920} := 405mm$ Height of model SBH920 of SAFT

$Width_{920} := 195mm$ Width of model SBH920 of SAFT

$Length_{920} := 522mm$ Length of model SBH920 of SAFT

$Volume_{920} := Height_{920} \cdot Width_{920} \cdot Length_{920}$ Volume of model SBH920 of SAFT

$Volume_{920} = 0.041m^{3}$

$$Volume_{bank} := \overrightarrow{\left(Volume_{920} \cdot N_{batteries}\right)} \qquad Volume_{bank} = \begin{pmatrix} 462.137 \\ 1.849 \times 10^{3} \\ 1.155 \times 10^{5} \end{pmatrix} m^{3}$$

Volume of the battery bank

$$C_{5A} := 920A$$

Charge/discharge rate of the 920 battery over a 5 hour period

$$Weight_{920} := 72kg + 5.95kg$$

$$Weight_{bank} := \overrightarrow{\left(Weight_{920} \cdot N_{batteries}\right)} \qquad Weight_{bank} = \begin{pmatrix} 0.874 \\ 3.495 \\ 218.457 \end{pmatrix} MT$$

Full weight of the battery bank

Using the recharge rate for the battery bank and the amount of power which needs to be replaced, the time of recharge is determined.

$$Normal_{charging\_rate} := .2 \cdot C_{5A}$$

$$Power_{into\_battery\_normal} := Normal_{charging\_rate} \cdot V_{battery\_cell}$$

$$Power_{into\_battery\_normal} = 209.76W$$

$$time_{to\_replace\_discharge} := \overrightarrow{\frac{P_{Device\_required} \cdot Pulse_{length}}{Power_{into\_battery\_normal}}}$$

$$time_{to\_replace\_discharge} = \begin{pmatrix} 158.912 \\ 0.424 \\ 33.107 \end{pmatrix} hr$$

At the normal recharging rate.

$\text{Fast}_{\text{charging\_rate}} := .4 \cdot C_{5A}$

$\text{Power}_{\text{into\_battery\_normal}} := \text{Fast}_{\text{charging\_rate}} \cdot V_{\text{battery\_cell}}$

$\text{Power}_{\text{into\_battery\_normal}} = 419.52\text{W}$

$$\text{time}_{\text{to\_replace\_discharge}} := \overrightarrow{\frac{P_{\text{Device\_required}} \cdot \text{Pulse}_{\text{length}}}{\text{Power}_{\text{into\_battery\_normal}}}}$$

$$\text{time}_{\text{to\_replace\_discharge}} = \begin{pmatrix} 79.456 \\ 0.212 \\ 16.553 \end{pmatrix} \text{hr} \qquad \text{time}_{\text{to\_replace\_discharge}} = \begin{pmatrix} 4.767 \times 10^3 \\ 12.713 \\ 993.199 \end{pmatrix} \text{min}$$

At the fast recharge rate.

$$\text{Specific}_{\text{Power}} := \overrightarrow{\frac{P_{\text{battery\_cell}} \cdot N_{\text{batteries}}}{\text{Weight}_{\text{bank}}}} \qquad \text{Specific}_{\text{Power}} = \begin{pmatrix} 45.775 \\ 45.775 \\ 45.775 \end{pmatrix} \frac{\text{W}}{\text{kg}}$$

$$\text{Specific}_{\text{Energy\_application}} := \overrightarrow{\left(\frac{W_{\text{Device\_required}}}{\text{Weight}_{\text{bank}}}\right)} \qquad \text{Specific}_{\text{Energy\_application}} = \begin{pmatrix} 137.326 \\ 0.092 \\ 0.114 \end{pmatrix} \text{Sv}$$

$$\text{Specific}_{\text{Energy\_storage\_device}} := \overrightarrow{\frac{W_{\text{battery\_5Ah}} \cdot N_{\text{batteries}}}{\text{Weight}_{\text{bank}}}} \qquad \text{Specific}_{\text{Energy\_storage\_device}} = \begin{pmatrix} 4.844 \times 10^4 \\ 4.844 \times 10^4 \\ 4.844 \times 10^4 \end{pmatrix} \text{Sv}$$

$$\mathrm{Power}_{\mathrm{Density}} := \overrightarrow{\frac{P_{\mathrm{battery\_cell}} \cdot N_{\mathrm{batteries}}}{\mathrm{Volume}_{\mathrm{bank}}}} \qquad \mathrm{Power}_{\mathrm{Density}} = \begin{pmatrix} 8.655\times 10^{4} \\ 8.655\times 10^{4} \\ 8.655\times 10^{4} \end{pmatrix} \frac{\mathrm{kg}}{\mathrm{ms}^{3}}$$

$$\mathrm{Energy}_{\mathrm{Density\_application}} := \overrightarrow{\left(\frac{W_{\mathrm{Device\_required}}}{\mathrm{Volume}_{\mathrm{bank}}}\right)} \qquad \mathrm{Energy}_{\mathrm{Density\_application}} = \begin{pmatrix} 259.663 \\ 0.173 \\ 0.216 \end{pmatrix} \frac{\mathrm{kJ}}{\mathrm{m}^{3}}$$

$$\mathrm{Energy}_{\mathrm{Density\_Storage\_device}} := \overrightarrow{\frac{W_{\mathrm{battery\_5Ah}} \cdot N_{\mathrm{batteries}}}{\mathrm{Volume}_{\mathrm{bank}}}} \qquad \mathrm{Energy}_{\mathrm{Density\_Storage\_device}} = \begin{pmatrix} 91.587 \\ 91.587 \\ 91.587 \end{pmatrix} \frac{\mathrm{MJ}}{\mathrm{m}^{3}}$$

Bibliography

1. Radzykewycz, D. T., J. L. Fausz and W. R. James, "Energy Storage Technology Development at the Air Force Research Laboratory Space Vehicles Directorate", AIAA 99-4503.
2. Hebner, Robert, Joeseph Beno, "Flywheel Batteries Come Around Again", IEEE Spectrum, April 2002: 46-51.
3. Taylor, Paula, Laura Johnson, Kim Reichart, Phil DiPietro, Joseph Philip, and Paul Butler, "A Summary of the State of the Art of Super Conducting Magnetic Energy Storage Systems, Flywheel Energy Storage Systems, and Compressed Air Energy Storage Systems" Sandia National Laboratories, Albuquerque, NM.
4. Clelland, Ian W., and Rick A. Price, "Recent Advances in Capacitor Technology with Application to High Frequency Power Electronics and Voltage Conversion" Reprint from the proceedings of the 14th Annual Applied Power Electronics Conference & Exposition (APEC), March 1999, Illinois Tool Works, 1999.
5. Tripp, Scot, and Arieh Meitav "Bestcap: A New Dimension in "Fast" Supercapacitors", AVX Ltd, Fleet, UK.
6. Clelland, Ian W., and Rick A. Price, "Requirement for Robust Capacitors in High Density Power Converters", ITW Paktron Illinois Tool Works Inc. 2001.
7. Plater, Bryan B., and James A. Andrews, "Advances in Flywheel Energy Storage Systems" Active Power, Inc. 2001.
8. S. M. Schoenung and W. R. Meier, J. R. Hull, R. L. Fagaly, M. Heiberger, R. B. Stephens, J. A. Leuer, and R. A. Guzman, "Design Aspects of Mid-Size SMES Using High Temperature Superconductors", IEEE Transactions on Applied Superconductivity, Vol. 3, No. 1, March 1993
9. Jerome L. Brown, "Electric Energy Weapon Implementation on an Airborne Platform", IEEE Transactions on magnetics, Vol. 29, N0. 1 January 1993
10. Doyle, Michael R., Douglas J. Samuel, Thomas Conway, Robert R. Klimowski, "Electromagnetic Aircraft Launch System – EMALS", IEEE Transactions on Magnetics, Vol. 31, No. 1, January 1995
11. Holger G. Wisken, Frank Podeyn, and Thomas H. G. G. Weise, "High Energy Density Capacitors for ETC Gun Applications", IEEE Transaction on Magnetics, Vol. 37, No. 1, January 2001
12. J. H. Beno, R. C. Thompson, M. D. Werst, S. M. Manifold, and J. J. Zierer, "End-of-Life Design for Composite Rotors", IEEE Transactions on Magnetics, Vol. 37, No. 1, January 2001
13. Thomas D. Hordubay, Owen R. Christianson, Donald T. Hackworth and David W. Scherbarth, "Winding of the Navy SMES Background Coil", IEEE Transaction on Applied Superconductivity, Vol 9, No. 2, June 1999
14. Xiaohua Jiang, Jinfeng Tian, Yingming Dai and Yunjia Yu, "Considerations for Reducting Stray Field of SMES Magnets", IEEE Transaction on Applied Superconductivity", Vol. 10, No. 1, March 2000

15. F. P. Emad, J. P. Borraccini, D. J. Waltman, T. H. Fikse, W. R. Ruby, M. J. Superczynski, R. C. Whitestone, E. V. Thomas, "DTRC Electromagnetic Launcher with Feedback Control", IEEE Transactions on Magnetics, Vol 29, No. 1, January 1993

16. Grater, Guy F., Timothy J. Doyle, "Propulsion Powered Electric Guns – A Comparison of Power System Architectures", IEEE Transactions on Magnetics, Vol. 29, No. 1, January 1993

17. "Superconducting magnetic Energy Storage:SMES", written in French http:\\circwww.epfl.ch/studinfo/courses/cors_supra/smes/, American Superconductors.

18. D. G. Akopyan, Yu. P. Batakov, A. M. Dedjurin, et al, "Magnet Energy Storage", IEEE Transactions on Magnetics, Vol. 28, No. 1, January 1992

19. J. Biebach, P. Ehrhart, A. Muller, G. Reiner, and W. Weck, "Compact Modular Power Supplies for Superconducting Inductive Storage and for Capacitor Charging", IEEE Transaction on Magnetics, Vol. 37, No. 1, January 2001

20. K. P. Juengst and H. Salbert, "Fast SMES for Generation of High Power Pulses", IEEE Transactions on Magnetics, Vol. 32, No. 4, July 1996

21. E. P. Polulyakh, L. A. Plotnikova, V. A. Afanas'ev, M. I. Kharinov and A. K. Kondratenco, E. Yu. Klimenco, and V. I. Novicov, "Development of Toroidal Superconducting Magnetic Energy Storages (SMES) for High-Current Pulsed Power Supplies", IEEE, 1999

22. Xianrui Huang, Stephen F. Kral, Gregory A. Lehmann, Yury M. Lvovsky and Minfeng Xu, "30 MW Babcock and Wilcox SMES Program for Utility Applications" IEEE Transactions on Applied Superconductivity, Vol. 5, No. 2, June 1995

23. T. Ise and T. Murakami, "Modular Based Design for a Small to Medium Scale Toroidal Type SMES", IEEE Transactions on Applied Superconductivity, Vol. 4, No. 2, June 1994

24. S. M. Schoenung, R. L. Bieri, T. C. Bickel, "The Advantages of Using High-Temperature Superconductors in High-Duty-Cycle Applications of SMES", IEEE Transaction on Applied Superconductivity, Vol. 5, No. 2, June 1995

25. Ibrahim D. Hassan, Richard M. Bucci, and Khin T. Swe, "400 MW SMES Power Conditioning System Development and Simulation", IEEE Transactions on Power Electronics, Vol. 8, No. 3, July 1993

26. Nomura, Shinichi, Dabide Ajiki, Chisato Suzuki, Naruaki Watanabe, Etsuko Koizumi, Hiroaki Tsutsui, Shunji Tsuji-Iio, Ryuichi Shimada, "Design Considerations for Force-Balanced Coil Applied to SMES", IEEE Transactions on Applied Superconductivity, Vol 11, No. 1, March 2001.

27. Nomura, S., T. Osaki, J. Kondoh, H. Tsutsui, S. Tsuji-Iio, Y. Sato and R. Shimada, "Force Balanced Coil for Large SMES", IEEE Transactions on Applied Superconductivity, Vol 9, No. 2, June 1999.

28. Nomura, S., K. Yamagata, N. Watanabe, D. Ajiki, H. Ajikawa, E. Koizumi, R. Shimada, "Experiment of HTS Stress-Balanced Helical Coil", IEEE Transactions on Applied Superconductivity, Vol 10, No. 1, March 2000.

29. Korpela, A., J. Lehtonen, R. Mikkonen, J. Paasi, "Optimization of SMES Magnet Volume with Electromagnetic and Mechanical Constraints", IEEE Transactions on Applied Superconductivity, Vol 10, No. 1, March 2000.

30. Boyes, John D., Nancy H. Clark, "Technologies for Energy Storage Flywheels and Super Conducting Magnetic Energy Storage", Sandia National Laboratories, IEEE 2000.
31. Schottler, R., R. G. Coney, "Commericial application experiences with SMES", Power Engineering Journal, Special Feature: Electrical energy storage, June 1999.
32. Miyagawa, Y., H. Kameno, R. Takahata and H. Ueyama, "A 0.5 kWh Flywheel Energy Storage System using A High-Tc Superconducting Magnetic Bearing", IEEE Transactions on Applied Superconductivity, Vol 9, No. 2, June 1999.
33. Kameno, Hironori, Yasukata Miyagawa, Ryouichi Takahata, Hirochika Ueyama, "A Measurement of Rotation Loss Characteristics of High-Tc Superconducting Magnetic Bearing and Active Magnetic Bearings", IEEE Transactions on Applied Superconductivity, Vol 9, No. 2, June 1999.
34. Fang, J. R., L. Z. Lin, L. G. Yan, and L. Y. Xiao, "A New Flywheel Energy Storage System Using Hybrid Superconducting Magnetic Bearings", IEEE Transactions on Applied Superconductivity, Vol 11, No. 1, March 1999.
35. Bornemann, Hans J., "Conceptual System Design of a 5 MWh/100 MW Superconducting Flywheel Energy Storage Plant for Power Utility Applications", IEEE Transactions on Applied Superconductivity, Vol 7, No. 2, June 1997.
36. Mulcahy, Thomas M., John R. H87ll, Kenneth L. Uherka, and Ralph C. Niemann, "Flywheel Energy Storage Advances Using HTS Bearings", IEEE Transactions on Applied Superconductivity, Vol 9, No. 2, June 1999.
37. Nagaya, Shigeo, and Naoki Hirano, "Fundamental Study on High Tc Superconducting Magnetic Bearings for Flywheel System", IEEE Transactions on Applied Superconductivity, Vol 5, No. 2, June 1995.
38. Hull, J. R., T. M. Mulcahy, K. L. Uherka, "Low Rotational Drag In High-Temperature Superconducting Bearings", IEEE Transactions on Applied Superconductivity, Vol 5, No. 2, June 1995.
39. Okano, Makoto, Noriharu Tamada, Shuichiro Fuchino, Itaru Ishii and Toshio Iwamoto, "Numerical Analysis of a Superconducting Bearing", IEEE Transactions on Applied Superconductivity, Vol 10, No. 1, March 2000.
40. Coombs, T., A. M. Cambell, R. Storey, R Weller, "Superconducting Magnetic Bearings for Energy Storage Flywheels", IEEE Transactions on Applied Superconductivity, Vol 9, No. 2, June 1999.
41. Hassenzahl, William V., "Superconductivity, An Enabling Technology for 21st Century Power Systems?", IEEE Transactions on Applied Superconductivity, Vol 11, No. 1, March 2001.
42. Sarjeant, W. J., Ian W. Clelland, and Rick A. Price, "Capacitive Components for Power Electronics", Proceedings of the IEEE, Vol. 89, No. 6, June 2001
43. Slenes, Kirk M., Paul Winsor, Tim Scholz, and Martin Hudis, "Pulse Power Capability of High Energy Density Capacitors Based on a New Dielectric Material", IEEE Transactions on Magnetics, Vol 37, No. 1, January 2001.
44. Weissbach, Robert S., George G. Karady, Richard G. Farmer, "A Combined Uninterruptible Power Supply and Dynamic Voltage Compensator Using a Flywheel Energy Storage System", IEEE Transactions on Power Delivery, Vol 16, No. 2, April 2001.

45. Biebach, J., P. Ehrhart, A. Muller, G. Reiner, and W. Weck, "Compact Modular Power Supplies for Superconducting Inductive Storage and for Capacitor Charging", IEEE Transactions on Magnetics, Vol 37, No. 1, January 2001.

46. Sels, T., C. Dragu, T. Van Craenenbroeck, R. Belmans, "Overview of New Energy Storage Systems for an Improved Power Quality and Load Managing on Distribution Level", CIRED2001, 18-21 June 2001, Conference Publication No. 482 IEE 2001.

47. Duran-Gomez, Jose Luis, Prasad N. Enjeti, Annette von Jouanne, "An Approach to Achieve Ride-Through ofan Adjustable Speed Drive with Flyback Converter Modules Powered by Super Capacitors", IEEE 1999.

48. Kapali, V., O. Prasad, G. M. Parthasarathy, K. B. Sarangapani, S. Muralidharan and A. Mani, "Comparison of the Origin of High Capacitance at Nickel and/or Carbon-Aqueous Electrolyte Interfaces and Its Uses in the Development of Potassium Ion Intercalation Based Super Capacitor", IEEE 1998.

49. Jin, Yun-Sik, Hong-Sik Lee, Geun-Hee Rim, Jong-Soo Kim, Jin-Sung Kim, Jeung-Ho Chu, Jae-Won Jung, and Dong-Won Hwang, "Design and Performance of a 300 kJ Pulsed Power Module for ETC Application", IEEE Transactions on Magnetics, Vol 37, No. 1, Junc 1999.

50. .Lawless, W. N., C. F. Clarck, Jr., "Energy Storage at 77K in Multilayer Ceramic Capacitors", IEEE 1996.

51. Cornette, James B., Richard A. Marshall, "Optimal Simulation Techniques for Distributed Energy Store Railguns with Solid State Switches", University of Texas at Austin.

52. Dick, Warren, J., Edward B. Goldman, "Analysis of Components in Advanced Capacitive Pulse Forming Networks for Electric Guns", IEEE Transactions on Magnetics, Vol 31, No. 1, January 1995.

53. McNab, Ian R., "Pulsed Power for Electric Guns", IEEE Transactions on Magnetics, Vol 33, No. 1, January 1997.

54. Musolino, Antonino, Marco Raugi, Bernado Tellini, "Pulse Forming Network Optimal Design for the Power Supply of Eml Launchers", IEEE Transactions on Magnetics, Vol 33, No. 1, Januray 1997.

55. Novac, B. M., I. R. Smith, P. Senior, M. C. Enache and K. Gregory, "Can the Efficiency of an Electrostatic to Kinetic Energy Conversion Process Exceed 50%?", IEEE 1997.

56. Hammon, J., K. Nielsen, R. Ford of Physics Interational Company, Th. H. G. G. Weise, S. Jungblut, of Federal Republic of Germany, "A 30 MJ Modular 22kV/44kV Capacitor Bank", not dated.

57. Hammon J. of Physics INterational Company, USA, S. Gilbert, G. Savell of Defence Research Agency, UK, "The Kirkcudbright EML Facility Pulsed Power System as a Driver for Electrothermal Guns", not dated.

58. Gully, J. H., S. B. Pratap, and R. N. Headifen, "Investigation of an Alternator Chraged Pulse Forming Network with Flywheel Energy Storage", IEEE Transactions on Magnetics, Vol 29, No. 1, January 1993.

59. Turnbull, S. M., J. M. Koutsoubis and S. J. MacGregor, "Development of a High Voltage, High PRF PFN Marx Generator", IEEE 1998.

60. Lassalle, F. G. Avrillaud, F. Bayol, B. Cassany, A. Foussat, F. Kovacs, R. Lample, J. F. Leon, P. Monjaux, A. Morell, B. Roques, R. Vezinet, "Syrinx Project First Results on a 160kJ, 700ns Fast Marx Module", IEEE 1997

61. Graham, J. D., D. G. Gale, W. E. Sommars, and S. E. Calico, "Compact 400kV Marx Generator with Common Switch Housing", IEEE 1997.

62. Turnbull, S. M., S. J. MacGregor, J. harrower and F. A. Tuema, "A PFN High Voltage Marx Generator", IEEE.

63. MacGregor, S. J., S. M. Turnbull, F. A. Tuema and J. Harrower, "The Performance of a Simple PFN Marx Generator", IEEE 1996.

64. Harada, Koosuke, Eiji Sakai, Hiroki Hyakutake, Goichi Ariyoshi, and Kiyomi Yamasaki, "Power Systems with Cold Stand-by Using Ultra Capacitors", IEEE 1998.

65. Bose, Bimal K., M. David Kankam, "Power and Energy Storage Devices for Next Generations Hybrid Electric Vehcile", IEEE 1996.

66. Wisken, Holger G., Frank Podeyn, and Thomas H. G. G. Weise, "High Energy Density Capacitors for ETC Gun Applications", IEEE Transactions on Magnetics, Vol 37, No. 1, January 2001.

67. Kalafala, A. K., J. Bascunan, D. D. Bell, L. Blecher, F. S. Murray, M. B. Parizh, M. W. Sampson, and R. E. Wilcox, "Micro Superconducting Magnetic Energy Storage (SMES) System for Protection of Critical Industrial and Military Loads", IEEE Transactions on Magnetics, Vol 32, No 4, July 1996.

68. McDowall, Jim, "Nickel-Cadmium Batteries for Energy Storage Applications", IEEE 1999.

69. Yang, Z., C. Shen, L. Zhang, M. L. Crow, , and S. Atcitty, "Integration of a StatCom and Battery Energy Storage", IEEE Transactions on Power Systems, Vol. 16, No. 2, May 2001.

70. Bruce, Gregg C., Lynn Marcoux, "Large Lithium Ion Batteries for Aerospace and Aircraft Applications", IEEE AESS Systems Magazine, September 2001.

71. Mills, Randell, Ethirajula Dayalan, "Novel Alkali and Alkaline Earth Hydride for High Voltage and High Energy Density Batteries", IEEE 2002.

72. Zahner, Ryan, Kitty Rodden, Bill Warf, Ruth MacDougall, "Lab Testing of NiMH Battery Packs on Four Different Hybrid Control Strategies to Evaluate Life and Performance", IEEE 2002

73. Kelly, Kenneth J., Mark Mihalie, Matthew Zolot, "Battery Usage and Thermal Performance of the Toyota Prius and Honda Insight During Chasis Dynometer Testing", XVII: Seventeenth Annual Battery Conference on Applications and Advances, IEEE 2002

74. Hansen, E., L. Wilhelm, N. Karditsas, I. Menjak, D. Corrigan, S. Dahr, S. Ovshinsky, "Full System Nickel-Metal Hydride Battery Packs for Hybrid Electrical Vehicle Applications", IEEE 2002.

75. Bramoulle, M., J-P Marret, P. Michalczyk, D. Rubin de Cervens, "Ultimate Properties of the Polypropylene Film for Energy Storage Capacitors", IEEE 2002.

76. Clelland I., R. Price, and W. J. Sarjeant, "Advances in Capacitor Technology for Modern Technology", IEEE 2000.

77. Schempp, Ellery, William D. Jackson, "Systems Consideration in Capacitive Energy Storage", IEEE 1996.

78. Spyker, R. L., R. M. Nelms, "Analysis of Double-Capacitors Supplying Constant Loads", IEEE Transactions on Aerospace and Electronic Systems Vol 36, No 4, October 2000.

79. Hase, Shin-ichi, Takeshi Konishi, Akinobu Okui, Yoshinobu Nakamichi, Hidetaka Nara, and Tadashi Uemura, "Fundamental Study on Energy Storage System for DC Electric Railway System", IEEE 2002.

80. Takahara, Eimei, Tomohiro Wakasa, and Jun Yamada, "A Study for Electric Double Layer Capacitor (EDLC) Application to Railway Traction Energy Saving including Changeover Between Series and Parallel Modes", IEEE 2002.

81. Sarjeant, Walter J., Jennifer Zirnheld, and Fredrick W. MacDougall, "Capacitors", IEEE Transaction on Plasma Science, Vol 26, No 5, October 1998.

82. Lomonova, E. A., S. R. Miziurin, "The Theoretical Investigations and Mathematical Models of the Compulsators", 'Electric Machines and Drives', 11-13 September 1995, Conference Publication No 412, IEEE 1995.

83. Kitzmiller, J. R., S. B. Pratap, M. D. Werst, C. E. Penny, T. J. Hotz, and B. T. Murphy, "Laboratory Testing of the Pulse Power System for the Cannon Caliber Electromagnetic Gun System (CCEGS)", IEEE Transactions on Magnetics, Vol 33 No 1, January 1997.

84. McNab, Ian R., "Homopolar Generators for Electric Guns", IEEE Transactions on Magnetics, Vol 33, No 1, January 1997.

85. Murphy, B. T., S. M. Manifold, and J. R. Kitzmiller, "Compulsator Rotordynamics and Suspension Design", IEEE Transactions on Magnetics, Vol 33, No 1, January 1997.

86. Pratap, S. B., J. P. Kajs, W. A Walls, W. F. Weldon, and J. R. Kitzmiller, "A Study of Operating Modes for Compulsator Based on EM Launcher Sytems", IEEE Transactions on Magnetics, Vol 33, No 1, January 1997.

87. Werst, M. D., J. R. Kitzmiller, and Alexander E. Zielinsky, "Rapid Fire Railgun for the Cannon Caliber Electromagnetic Gun System".

88. Pratap, S. B., J. P. Kajs, W. A Walls, W. F. Weldon, J. R. Kitzmiller and S. K. Murthy, "Operating Modes for Compulsator Based Electromagnetic Launcher System".

89. Thelen, R. F., "Field Excitation and Discharge Switching for Air Core Compulsators", University of Texas at Austin.

90. Driga, M. D., M. Ozdemir, "Compulsators as Pulsed Power Supplies for High-Power, High-Energy Powder Spraying", IEEE 1997.

91. Hahne, J. J., C. A. Graf, J. R. Kitzmiller, W. A. Walls, and W. G. Brinkman, "High Strain Insulation Systems for Compulsator Rotors", IEEE Transactions on Magnetics, Vol 35, No 1, January 1999.

92. Werst M. D., C. E. Penny, T. J. Hotz, and J. R. Kitzmiller, "Continued Testing of the Cannon Caliber Electromagnetic Gun System (CCEMG)", IEEE Transactions on Magnetics, Vol 35, No 1, January 1999.

93. McCorkle, William C., "Compensated Pulsed Alternators to Power Electromagnetic Guns", IEEE 1999.

94. Giesselmann, Michael, and Don Eccleshall, "Modeling of a Compulsator and Railgun System", IEEE Transactions on Magnetics, Vol 37, No 1, January 2001.

95. Driga, M. D., S. B. Pratap, A. W. Walls, and J. R. Kitzmiller, "The Self-Excitation Process in Electrical Rotating Machines Operating in Pulsed Power Regime", IEEE Transactions on Magnetics, Vol 37, No 1, January 2001.

96. Brian T. Murphy, Jon R. Kitzmiller, Ray Zowarka, Jon Hahne, and Alan Walls, "Rotordynamics Design and Test Results for a Model Scale Compulsator Rotor", IEEE Transactions on Magnetics, Vol 37, No 1, January 2001.

97. Nagy, Geza and Stuart Rosenwasser, "The Evaluation of Advanced Composite Material Performance in High Speed Pulsed Power Rotor Applications", IEEE Transactions on Magnetics, Vol 37, No 1, January 2001.

98. Kitzmiller, J. R., K. G. Cook, J. J. Hahne, et al, "Predicted versus Actual Performance of the Model Scale Compulsator System", IEEE Transactions on Magnetics, Vol 37, No 1, January 2001.

99. Kitzmiller, Jonathan R., John A. Pappas, Siddharta B. Pratap, and Mircea D. Driga, "Single and Multiphase Compulsator System Architectures: A Practical Comparison", IEEE Transactions on Magnetics, Vol 37, No 1, January 2001.