POWER SUPPLIES FOR AIRBORNE LASER SYSTEMS

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Abstract

This paper investigates the power supply options for an airborne laser system (solid state laser diodes). The application demands a power supply capable of a high repetition rate (1,428 pulses per engagement over 2 s) and delivering total energy of 20 MJ (i.e. 14 kJ per pulse). The high repetition rate precludes the use of capacitors. Hence rotating machines storing inertial energy appear to be the most viable option.

In this paper the compensated pulsed alternator (compulsator) invented by the Center for Electromechanics at the University of Texas (CEM-UT) at Austin is examined as a possible power supply option for the above application. The laser system is characterized as a 1.25 mΩ resistive load. In the past the compulsator has been examined essentially for inductive loads like the railgun and hence the analysis presented here throws new light on the capabilities of the compulsator. Several configurations involving the compulsator are evaluated in this paper viz. two machines operating in parallel, a single machine storing all the energy and an external flywheel storing the required energy with compulsator serving as a energy conversion device. The paper explores the lower limits on the compulsator size and weight for the different configurations

I. INTRODUCTION

The compensated pulsed alternator or the compulsator, invented by the Center for Electromechanics at the University of Texas at Austin (CEM-UT) has been analyzed and utilized as a potential power supply for electromagnetic launchers (railguns) since 1978. The railgun is primarily an inductive load and therefore the use of a compulsator to supply a resistive load has not been received adequate attention. The compulsator is a device which utilizes compensation to reduce its internal impedance. There are several forms of compensation [1], passive compensation being the simplest. A passively compensated machine uses a continuous conducting shield which is at rest with respect to the field excitation of the machine. The static exciting field diffuses through the shield and induces a voltage in the spinning armature conductors. Passive compensation is achieved when compensating currents are induced in the shield during a discharge. Since the shield is continuous, compensation is provided equally in all rotor positions resulting in a constant low inductance. The passive machine will generate pulses which are basically sinusoidal in shape. Thus the passive compulsator is capable of maximizing power output by minimizing internal impedance.

This paper examines the use of a passive compulsator to supply a laser system load characterized as a 1.25 mΩ resistor. The ideal pulse shape for the application is square. This would suggest the use of a selective passive machine [2], which allows for the tailoring of a variety of pulse shapes. However, the load (1.25 mΩ) being highly resistive will dominate the circuit impedance and no pulse shaping can be realized. Therefore the passive machine is used as a power supply for this application. The application requires a pulse with a full width to half maximum (FWHM) requirement of 350 to 500 μs. The FWHM specification along with the requirement of 1,428 pulses over 2 s determines the electrical frequency of the compulsator for this application. The compulsator is required to have an electrical frequency of 714 Hz (with FWHM of 466 μs).

Each pulse delivers 14 kJ for energy resulting in a total energy of 20 MJ over 2 s to the load. The energy requirement specifies the load peak current to be 180 kA. The compulsator open circuit voltage is fixed at 300 V. Table 1 details the load requirements and the compulsator description. The different configurations and options available with the compulsator as the power supply are discussed below

Table 1. Load and compulsator descriptions

Load Specifications	
FWHM of current pulse	350 to 500 μ s
Energy per pulse to load	14 kJ
No. of pulses per engagement	1428
Time between pulses	1.4 ms
Duration of engagement	2.0 s
Total energy to load per engagement	20 MJ
Resistive load	1.25 mΩ
Compulsator Description	
Type of machine	Passive Compulsator
Type of excitation	Superconducting or Permanent Magnet
Pulse shape	Sinusoidal
Trigger point	Zero crossing
Electrical frequency	714 Hz
FWHM	466 μ s

II. CONFIGURATIONS FOR THE COMPULSATOR BASED POWER SUPPLY

The two main configurations evaluated for the compulsator are the single machine vs. two machines operating in parallel. Figure 1 indicates the prime mover options for the two machine configuration evaluated for the application detailed in this paper. The percentage change in speed is determined by the drive available for the compulsator. A turbine as the prime mover (with a gearbox drive) would allow only 5% drop in speed. The two machine option allows convenient operation (each machine can be located near the aircraft engines) of the 400 hp engines on the aircraft as the prime mover. The single machine configuration (fig. 2) however requires the use of a hydraulic pump (or electric generator) driving an hydraulic motor (or electric motor). The use of hydraulic pump-motor drive (or electric generator-motor drive) allows for a larger variation in speed during a discharge.

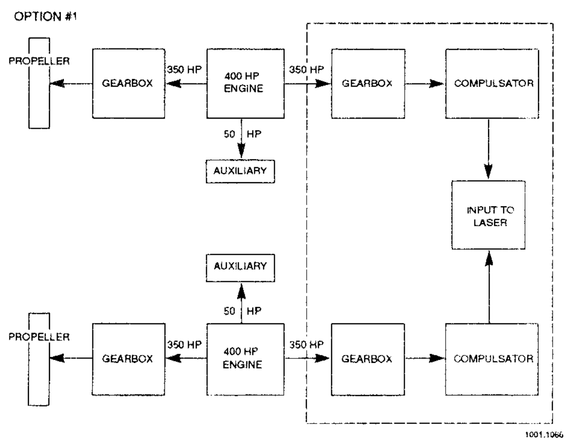

Figure 1. Motoring option for two compulsator configuration

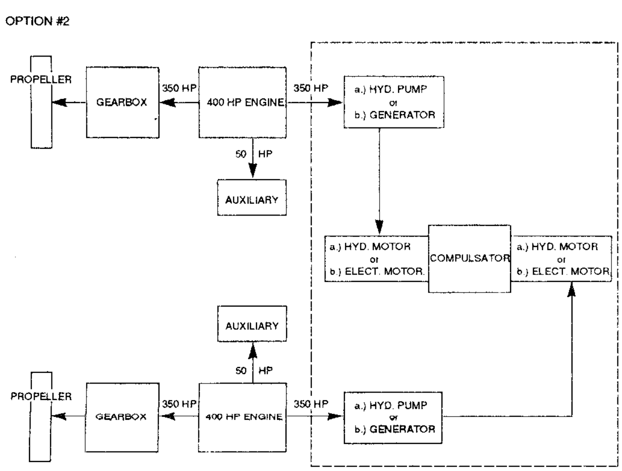

Figure 2. Motoring options for one compulsator configuration

Figure 3 shows the different compulsator options investigated in this paper. The change in speed indicated in the figure is over the entire engagement (1,428 pulses). The 25 % change in speed with the single machine configuration was analyzed to arrive at an estimate for the lowest weight possible with a single compulsator.

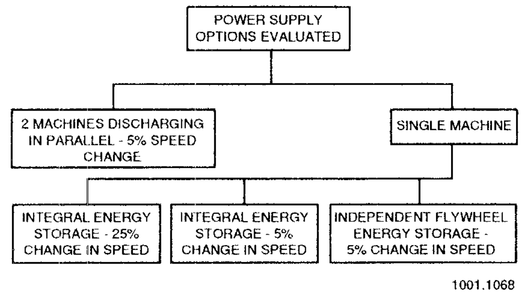

Figure 3. Power supply options evaluated for laser application

The high electrical frequency (714 Hz) of operation precludes the possibility of a two pole compulsator, which would be the most attractive configuration with respect to minimizing the mass of the power supply. The high tip speeds in a two pole configuration result in stress management problems (especially armature winding banding) and the two pole design also has a high magnetic signature. The four, six etc. pole configurations have the advantages of lower magnetic signature but have more mass because of lower rotor tip speeds. All compulsators examined in this paper are of the external rotor (shell) machine type.

A) Two Machines Discharging in Parallel

The stored energy requirement for this option can be calculated based on a speed change of 5 % over one engagement and the total energy (20 MJ) to be delivered to the load. A discharge efficiency of 95% was assumed. Each machine stores 100 MJ. The four and six pole options were evaluated. The results of the evaluation are presented in table 2. The machines represent the minimum mass choices. The compulsators were designed for high tip speeds (not exceeding 1,000 m/s) to maximize energy density. Also the machines are of the shell (external) rotor type. The design allows for a temperature rise of 95°C over one complete engagement. The six pole option is heavier as it spins at a lower tip speed but has the advantage of lower magnetic signature.

Table 2. Two machines discharging in parallel; 5% change in speed over one engagement

Machine Parameters	Units	Value	
		4 pole	6 pole
Outer diameter	m	0.88	1.16
Length	m	0.83	0.9
Stored energy	MJ	100	100
Machine Speed	rpm	21,420	14,280
Tip Speed	m/s	992	866
Peak open circuit voltage	V	300	300
Discharge efficiency	%	95.6	94.7
Mass	kg	750	1014

In general, the two machine option is always heavier than the single machine. But each of the two machines is smaller in size

B) A Single Machine

1) Integral energy storage and 5% change in speed over one engagement: table 3 depicts the results of storing all the required energy (200 MJ) in one machine for a 5% change in speed over one engagement. Again the four and six pole configurations are explored. Again the designs (table 3) represent the minimum mass options. The temperature rise and tip speed limitations are as mentioned above.

Table 3. Single machine (integral energy storage); 5% change in speed over one engagement

Machine Parameters	Units	Value	
		4 pole	6 pole
Outer diameter	m	0.90	1.3
Length	m	1.10	1.0
Stored energy	MJ	200	200
Machine Speed	rpm	21,420	14,280
Tip Speed	m/s	1,031	968
Peak open circuit voltage	V	300	300
Discharge efficiency	%	96.3	97.1
Mass	kg	1,078	1,327

2) Integral energy storage and 25 % change in speed over one engagement: table 4 shows the four and six pole options each storing 50 MJ. These machines are designed to discharge almost 50% of the stored energy over one engagement. The mass of these machines are lower than the other options explored above.

Table 4. Single machine (integral energy storage); 25% change in speed over one engagement

Machine Parameters	Units	Value	
		4 pole	6 pole
Outer diameter	m	0.70	0.90
Length	m	0.62	0.67
Stored energy	MJ	50	50
Machine Speed	rpm	21,420	14,280
Tip Speed	m/s	782	680
Peak open circuit voltage	V	300	300
Discharge efficiency	%	96.7	96
Mass	kg	540	720

All the designs presented previously are energy limited designs i.e. the machine mass is driven by energy storage requirements. A study was to conduct to appraise the effect of storing energy, independently, in a flywheel attached to the rotor of the compulsator. The size and mass of the compulsator was determined as a function of the energy stored in the rotor. Table 5 shows the minimum mass options. Two flywheels are used to store the required energy. The flywheels are also limited to a maximum of 1,000 m/s in tip speed.

Table 5. Single machine- independent flywheel energy storage; 5% change in speed over one engagement

Machine Parameters	**Units**	**Value**	
		4 pole	**6 pole**
Outer diameter	m	0.48	0.56
Length	m	0.58	0.53
Stored energy	MJ	13	10
Machine Speed	rpm	21,420	14,280
Tip Speed	m/s	548	417
Peak open circuit voltage	V	300	300
Discharge efficiency	%	96.2	94
Mass	kg	393	460
FLYWHEEL (1 OF 2)			
Outer diameter	m	0.9	1.34
Length	m	0.35	0.158
Stored energy	MJ	93.5	95
Tip Speed	m/s	1,000	1,000
Mass	kg	353	370
Total Mass (machine+2 flywheels)	**kg**	**1,100**	**1,200**

Figures 4 to 7 summarize the results of the study. Figure 4 reflects the effect of the stored energy on the mass of the machine. As the energy stored in the machine decreases so does the size and the mass of the machine. However at energy levels below 10 MJ the returns diminish. This is because as the size of the machine decreases the coupling between the armature and the field windings becomes poor (fig. 5), resulting in higher field ampere-turn requirement and consequently higher field coil mass (fig. 6). The designs evaluated in figure 4 were for a maximum field density 0.5 T at the armature winding. These designs also revealed that the internal impedance of the machine was insignificant in comparison to the 1.25 mΩ load. Lowering the peak field to 0.25 T resulted in an increase in the armature conductors per pole and the internal impedance of the machine, thus affecting the performance of the machine. Increasing the peak flux density above 0.5 T increased the field coil mass and the mass of the machine indicating that the optimum value of the maximum flux density was between the two values. Figure 7 shows the component mass and total power supply mass vs. energy stored in the compulsator rotor.

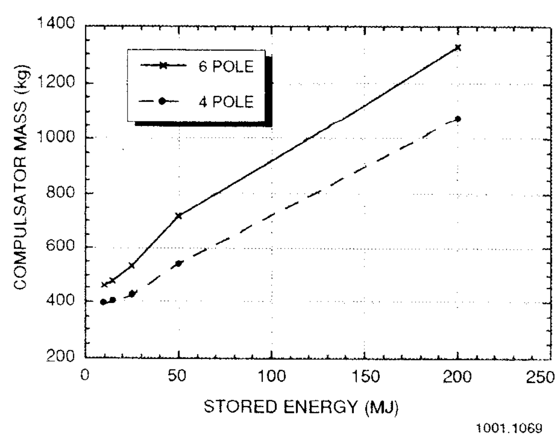

Figure 4. Mass of compulsator vs. stored inertial energy

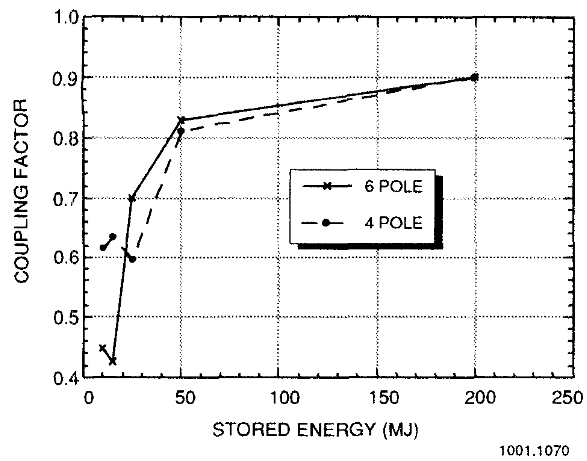

Figure 5. Coupling between field and armature windings vs. stored inertial energy

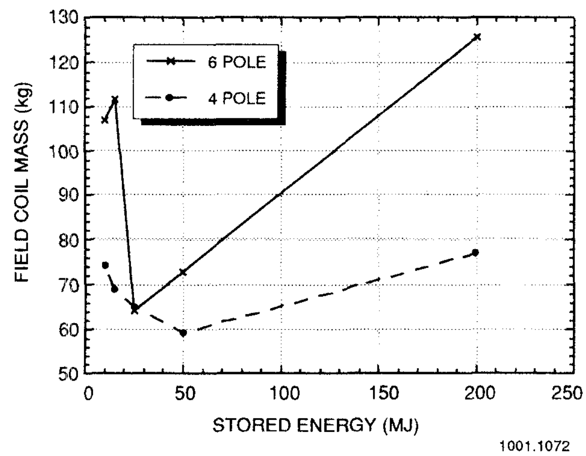

Figure 6. Field coil mass of compulsator vs. stored energy (inertial)

III. CONCLUSIONS

The paper sheds new light on the capabilities of the compulsator. It shows that the compulsator has potential to be used as a power supply for solid state laser diodes. The different configurations examined in the paper reveal the different factors which control the weight of the compulsator as the inertial energy stored is varied.

To conclude, the compulsator has several attractive features and further optimization of the design could lead to reducing the mass of the system. The external rotor (shell) machine is an interesting concept and requires detailed engineering.

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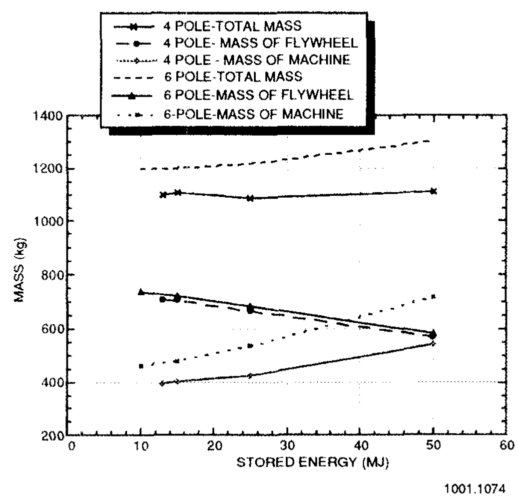

Figure 7. Component and total mass for independent energy storage