

FINAL DESIGN OF AN AIR CORE, COMPULSATOR DRIVEN, 60 CALIBER RAILGUN SYSTEM

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Abstract: The Center for Electromechanics at The University of Texas at Austin (CEM-UT), is currently in the manufacturing phase of a laboratory based small caliber electromagnetic (EM) launcher and compulsator power supply. The objective of the 29-month program is to develop a compact, lightweight test bed capable of accelerating 32-g masses to 2 km/s at a rate of 10 Hz. Both the power supply and launcher feature significant component design advances which will allow the system to operate at considerably higher energy and power densities than previously demonstrated. The 750-kg compulsator will generate 2.2 kV and the Silicon-controlled rectifier (SCR) switch will commutate 386-kA pulses into the 1.6-m long, 0.60 caliber augmented solid armature railgun.

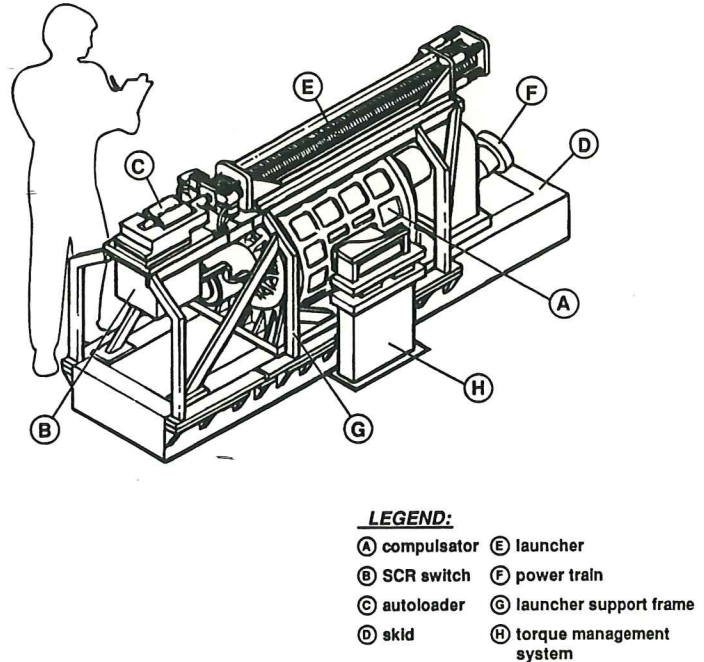
This paper describes the final design and predicted operating characteristics of the compulsator system. Overall system performance parameters are reported, including results from the optimization code used to aid in the design of the compulsator system. A system design overview is presented with emphasis on new materials and state-of-the-art machine components to be used for the first time in a compulsator.

Introduction

Patented by CEM-UT engineers in 1978 [1], compulsators can offer higher useable energy densities than either capacitors, homopolar generators, or batteries [2]. Along with higher obtainable energy storage densities, compulsators offer high voltage and peak current in a single element energy storage device, a smooth pulse profile, and naturally cycled current zeroes which allow for extremely low muzzle currents and simplified switching requirements. All of these factors combine to make the compulsator extremely attractive for driving EM launchers.

During the first phase of the contract, a computer code was developed to aid in determining the optimal configuration for the compulsator rotor [3]. Using this code, an optimum machine configuration composed of a self-excited two pole air-core compulsator was obtained which satisfied all of the design constraints placed on the system. In satisfying the design constraints of the optimized system, several new concepts and materials have been utilized throughout the system.

The small caliber compulsator (SCC) system is shown in figure 1. The compulsator is well into the manufacturing phase at this time and is predicted to begin commissioning in April, 1990. This paper describes the design and operation of the compulsator system.



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Figure 1. Small caliber compulsator system

System Operation

In this section, the general operation scenario of the compulsator is described for a full energy three-shot salvo. The experiment will begin with a projectile loaded in the railgun. The system controller will initiate all auxiliaries and stand-by until the system is ready to begin motoring. Motoring is accomplished using a hydrostatic drive system and a speed increasing gearbox. Once initiated, the rotor will be brought to about 25,200 rpm over a 3-min interval. At this time, the discharge sequence will be initiated. The entire three shot discharge sequence requires less than 1 s to complete.

The discharge sequence begins with initiation of the self-excitation (SE) of the field coil (FC). At speed, the SE armature brushes are actuated onto the rotor slip rings to close the armature FC circuit. A capacitor is then discharged into the FC to initiate a starting excitation flux in the rotor. A half bridge control rectifier (discussed below) then charges the FC using stored rotor energy in about 0.5 s [5]. At this time, the main armature brushes will be actuated against separate rotor slip rings. At the desired firing angle, the controller will initiate a gating voltage to the main SCR switch which will launch the first projectile in the

railgun. Once the controller has confirmed that the main switch has reopened the circuit, the autoloader will be given the signal to reload the railgun and the above sequence is repeated two more times. After the third shot is complete, the field rectifier will open the SE charging circuit allowing the energy stored in the FC to decay passively. The braking valve is then energized on the hydrostatic drive system and the rotor brought to zero speed over about a 4-min interval.

System Design Overview

The SCC will be laboratory based, however, the system could readily be made field portable with some drive and auxiliary system modifications. At CEM-UT, the system will share hydrostatic drive auxiliaries and controls with the iron-core compulsator (ICC) [4] and receive site electrical power. Comprising the compulsator system are the following major components:

- (1) Two pole 9 MJ air-core compulsator
 - (a) composite flywheel
 - (b) ceramic shaft
 - (c) stator
 - (d) ceramic bearings, dampers, and seals
 - (e) SE system
 - (f) main SCR switch
- (2) Auxiliaries
- (3) Augmented EM launcher
- (4) Autoloader
- (5) Instrumentation and controls

Compulsator Design

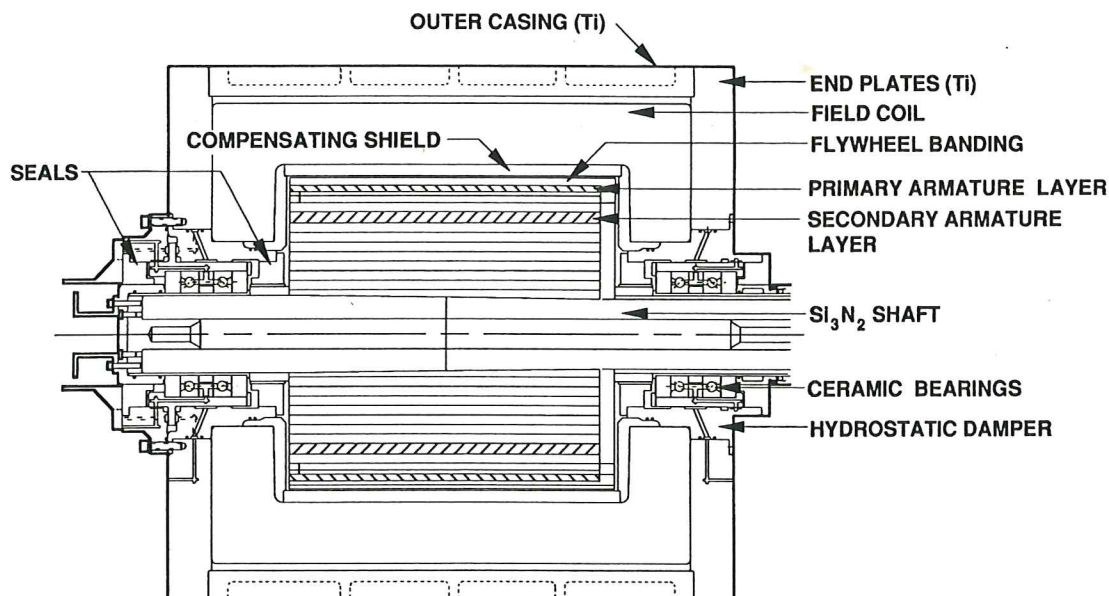
In satisfying the 910 kg weight limit, the optimization code settled on a two pole air-core rotor configuration for the SCC. In this configuration, the armature would be rotating and the FC would be self-excited. The rotor has two independent sets of armature windings; the primary and outermost winding operates the launcher, while the lower current secondary winding is used to self-excite the FC. The armature

windings are arranged 90° out-of-phase so as to avoid magnetic coupling between them.

Table 1 presents the compulsator general specifications and operational descriptions. Figure 2 shows a sectioned view of the compulsator. In the following sections, the subsystems making up the compulsator are described.

Table 1. Compulsator general specifications

DESCRIPTION	VALUE
Compulsator Size:	
rotor length	0.425 m (16.7 in.)
rotor radius	0.199 m (7.8 in.)
structure length	0.864 m (34 in.)
structure radius	0.314 m (12.4 in.)
compulsator weight	750 kg (1,650 lb)
Primary Armature:	
number of poles	2
number of conductors per pole	10
Secondary Armature:	
number of poles	2
number of conductors per pole	26
Performance:	
rotational speed	25,115 rpm
tip speed	502 m/s (98,820 fpm)
banding peak hoop stress	1.477 GPa (214.2 ksi)
rotor energy	9.01 MJ
compulsator energy density	12 kJ/kg
compulsator peak power	660 MW
pulse width	1.87 m/s
discharge torque	292,000 N-m (215,368 lbf-ft)
primary peak voltage	2,252 V
primary peak current	386 kA
secondary peak voltage	4,510 V
secondary peak current	5.0 kA



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Figure 2. Sectioned view of the compulsator

Composite Flywheel

Overall dimensions for the flywheel were determined from the optimization code results. The nonmagnetic flywheel is built up of 15 composite material layers, of which fiberglass and graphite predominate. Two additional aluminum litz wire/epoxy layers make up the primary and secondary armature windings. The composite materials have the advantage of low density, high strength, and high specific stiffness. The rotor design was driven by several mechanical constraints including:

- (1) The need to maintain radial compression between flywheel layers at all times,
- (2) Supporting of the two armature layers at the required radii,
- (3) The ability to withstand high discharge torques, and
- (4) Operation free of any rotor bending frequencies.

Preliminary analysis of the flywheel layers was performed with a closed form solution for a series of nested rings made of transversely isotropic materials. This was followed up with an axisymmetric finite element analysis to study end effects and axial stresses not calculated with the nested ring analysis. All layers, excluding the two armature layers and the outer banding, will be preloaded using tapered interference fits. The banding is a straight fit over the primary armature. To avoid developing transverse bending stresses, the rings have to be supported at all times during assembly. Strain gauges are being used to monitor the amount of assembly interference in each ring.

Shaft

Due to the two pole air-core configuration, a non-conducting structural ceramic (Si_3N_2) is being used as the shaft material. Because of the brittle and statistical failure nature of the ceramic, the shaft design was closely coupled to the flywheel design with the magnitude of the tensile stresses being held to a minimum. Tensile stresses in the shaft develop due to several factors. These factors include shaft bending, pinch stresses at locations of radial pressure discontinuities, spin induced stresses, and stresses that develop during the assembly of the rotor. The fundamental criteria for the ceramic shaft design was to keep the tensile stresses less than one tenth of the modulus of rupture (MOR) values. The ceramic selection was based on MOR values, Weibull moduli, and fracture toughness values.

Stator

The stator was not originally incorporated into the mass optimization program that gave the basic dimensions for the rotor [3]. Initially it was assumed that the total machine mass would be directly proportional to the rotor volume. The optimization code used average radial flux density as an input parameter; the main step in sizing the stator was to design a FC that could deliver this average flux density and therefore meet the machine voltage requirements. A clamshell FC arrangement (fig. 3) was chosen because it yielded the most compact design. However, this arrangement has proved challenging due to the added complexity it introduces in handling compulsator discharge torques.

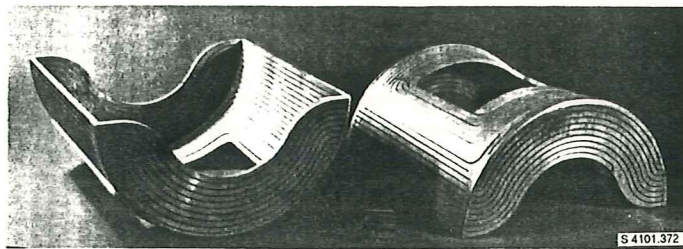


Figure 3. One of seven layers comprising the small caliber compulsator field coil

To determine ampere-turn requirements, a two-dimensional (2-D) flux distribution code, based on space harmonic analysis, was coupled to the armature geometry in order to calculate armature voltage. Field coil geometry could then be adjusted until this voltage matched the output of the optimization code. Results were then confirmed for the complex FC shape using a full three-dimensional (3-D) finite element analysis (FEA). The 3-D analysis also provided flux densities for regions of interest outside the immediate rotor cavity, namely the bearing regions.

The overall FC size was limited so that its power loss would be less than 4.5 kW. A larger coil would lower the energy consumption, but naturally results in a heavier machine. A smaller coil has a deleterious effect on the system salvo performance. This is because more energy is taken out of the rotor between shots, with a subsequent lengthening of the compulsator pulse width. The 4.5-kW coil limits the muzzle current to about 60 kA on the last shot.

The FC is being fabricated from electrical grade aluminum to save weight and retain good electrical conductivity. Current is limited to under 5 kA from switch requirements. This yields 350 turns for the 1.6 MA turn magnetomotive force. The coil is formed by cutting the conductor pattern into series of concentric cylinders with a waterjet cutting tool. Cylinders are then split in half to form the clamshell, wrapped with glass tape, and welded together to form layers. The two layered halves will then be vacuum impregnated with epoxy for structural strength and insulating integrity.

Compensating Shield Assembly

The SCC is passively compensated using a high strength aluminum tube located a short distance from the flywheel banding. A 2-D FEA of the shield structure was carried out based on loadings determined from a 3-D FEA of the armature during a full power discharge. Results showed that a shield of about 0.6-in. thick would carry the discharge forces when properly supported. Compulsator discharge torque is transmitted from the compensating shield to two large titanium side lugs rigidly fixed to the shield. The 180° spaced lugs protrude through the pole spacers of the FC and are attached to the compulsator skid through rigid support structures.

The titanium outer casing and end plates form the outside structure of the compulsator. Both elements were designed to have a stiffness on the order of 10 Milb/in. in bending to minimize deflection from FC forces and potential discharge thrust loads. The casing

is cast as a webbed cylindrical shell with two holes for the shield lugs, while the end plates are machined from wrought material.

Bearings and Seals

High rotational speeds and the presence of magnetic fields outside the rotor cavity in the air-core design lead to the selection of ceramic rolling element bearings for rotor support. Specifically, a hybrid ceramic bearing consisting of a ceramic inner race, ceramic balls or rollers, a tool steel stationary outer race, and a silver plated brass cage was selected. The bearings will operate at a severe 2,640,000 DN. Two angular contact duplex sets will support the rotor and a single cylindrical roller bearing is used to support the outer end of the current collector shaft. Bearings are being solicited through the American Koyo Corporation.

To aid in maintaining dynamic stability, the rolling element bearings are mounted in stationary full hydrostatic bearings. The hydrostatic bearings will provide for a tunable support stiffness and a near optimum amount of damping for the rotor-bearing system. Each radial bearing provides for a support stiffness of 0.5 Mlb/in and a damping rate of approximately 1,000 lb-s/in. Three, four pocket radial bearings and one, three pocket opposed pad thrust bearing will be used in the system. The hydrostatic bearings will operate at 350 psig supply pressure and use the same lubricant as specified by the ceramic rolling element bearing manufacturer. This bearing combination will allow the rotor to operate below its first bending frequency.

Generator shaft seals are being manufactured by Stein Seal, Inc. The rotor side seals have the additional duty of functioning against a roughing vacuum within the rotor cavity. The vacuum is necessary so large windage losses are not incurred during high speed operation. The five shaft seals are of similar design; each has two multisegment carbon circumferential contacting seals with a pressurized buffer between them.

Brush Mechanisms

Two separate sets of brushes carry the two armature currents produced by the compulsator. Both slip rings are contained on the removable current collector shaft extension which is attached to the ceramic shaft. The brush mechanisms are very similar to those developed for use in homopolar generators at CEM-UT. The main brushes carry a peak 386 kA during the 1.87 ms discharge pulse. Each brush terminal is made up of 50 Morganite CM1S™ brush pads which are pneumatically actuated against the shaft. The brush slip ring speed is 165 m/s. Special attention has been paid in insulating the brush terminals to prevent arcing.

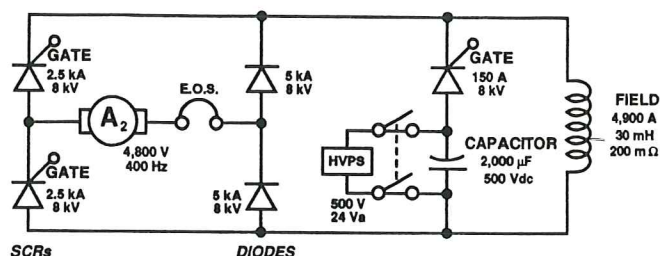
The excitation brush duty is less severe as five brushes per terminal carry a peak 5 kA during FC charge and hold periods. Again special attention is being given to insulation practices between the brush terminals which are at a 4.5 kV potential.

Self-Excitation System

The air-core compulsator generates no voltage without field current, so an external device must be provided to initiate the field excitation. A conveniently

sized package is realized by using electrolytic capacitors totaling 2,000 μF with an operating voltage of 500 V dc. The resultant injection energy (250 J) delivers a time-to-peak field charge of less than 0.2 s (for constant rotor speed).

The exciter winding rectifier bridge (schematic shown in fig. 4) is half-control as the field is not regenerated back into the rotor after firing. Instead, its energy (360 kJ) is allowed to dissipate in freewheeling resistive losses after the salvo firing. The current in the excitation circuit has three phases after field initiation: the charge-up lasting about 0.33 s (allowing for speed droop), the holding period lasting 0.3 s, and the field decay period of 0.15 s. To design in a factor of safety, a third of a second for each period was used as a performance specification for the rectifier components. The SCR's carry current with a 50% duty (square-wave) during the charge-up and during ON-periods of the holding period. The diodes compliment the duty cycle of the SCR's, but carry full current during the OFF-periods of holding and during the field decay period.



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Figure 4. Small caliber compulsator field charging circuit schematic

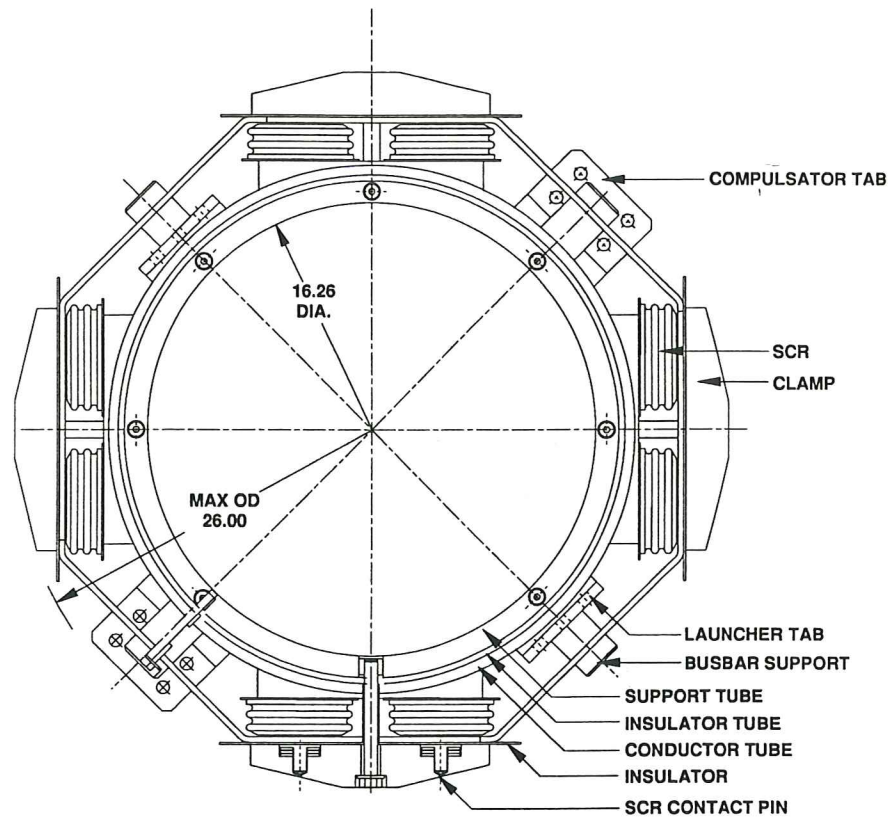
The holding period is an ON-OFF control that cycles between field charging and decay across the field resistance and four series diodes. The field charging rate in the neighborhood of 4,900 A is 90 kA/s, while the field decay rate is 33 kA/s. Consequently, the cycle time for a $\pm 1\%$ variation around 4,900 A is 54 ms (21.5 cycles @ 400 Hz) ON and 153 ms (61 cycles @ 400 Hz) OFF.

Main SCR Switch

Although compulsator-driven railguns can operate without external switching, the addition of an SCR switch provides several distinct advantages. In particular, the requirements placed upon the railgun and autoloading components are alleviated. The requirements of the railgun switch include;

- (1) AC voltage hold-off: $\pm 2,300 \text{ V}_{\text{pk}}$; max. $\text{dv/dt} = 1 \text{ V}/\mu\text{s}$
- (2) zero voltage turn-on; max. $\text{di/dt} = 11.6 \text{ A}/\mu\text{s}$
- (3) transmit $400 \text{ kA}_{\text{pk}}$; $255 \text{ kA}_{\text{avg}}$ /shot; $6.5 \text{ kA}_{\text{avg}}$ /salvo
- (4) recover -2,300 V stand-off at current zero and forward voltage recovery by 0.6 ms later.

A fairly conservative switch design has been specified which uses 16 International Rectifier Corp. #S52R34A components in parallel. This results in 25 kA per device and a 3,400 V recovered rating. To minimize



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Figure 5. Preliminary main SCR switch design-end on view

material, weight, and size, the self-contained package has been developed to encircle the brushbox of the compulsator, similar to the configuration seen in figure 5.

Auxiliaries

Auxiliary systems for the SCC/railgun system include the rolling element bearing and hydrostatic damper lubrication system, the compulsator motoring system, nitrogen supply for brush operation, and the vacuum system used to reduce rotor windage losses.

The bearing lubrication system consists of a 7-hp motor powering tandem supply pumps drawing lubricant from a common sump. One pump supplies the hydrostatic bearings, while the other supplies the rolling element bearings. Total bearing system flow requirements are under 23 g/m. Machine sumps are actively scavenged at approximately 1.15 times the displacement of the supply pumps. Lubricant is actively cooled with a small chilled water heat exchanger and stored in a low profile 25 gal baffled sump located beneath the machine skid.

The compulsator motoring system includes a bent axis hydraulic motor developing 200 hp output at 5,000 rpm. This proportional control motor is connected to a 5.02:1 speed increasing gearbox. A high-speed coupling connects the gearbox output shaft to the compulsator. The hydraulic motor is powered by a 400 hp hydraulic skid which is used to power the ICC at CEM-UT. The gearbox is lubricated by an independent system which

operates at 6 g/m and 35 psi.

The nitrogen supply is used to actuate the brushes and also to clean brush debris away from the brush contact surfaces. The system operates off of an accumulator which is charged each time for an experiment from a 2,200 psi storage bottle.

The vacuum system is used to reduce the pressure inside the compulsator cavity to approximately 0.5 torr. This vacuum is necessary to negate the rotor windage losses.

Railgun/Autoloader

The EM gun is a specifically tailored load for the compulsator. The solid armature augmented launcher features an extremely stiff and light design using molybdenum primary rails and copper augmenting rails encased in stainless steel laminations spanning 1.6 m in length. L' of the launcher has been experimentally determined at 1.25 mH/m. Details of the launcher can be found in a paper by R. L. Fuller, et al. [6].

The SCC autoloader uses high-pressure nitrogen to operate a single ended, double acting pneumatic cylinder. The cylinder is oscillated using two Marotta MV100 solenoid actuated valves and a system of check valves. A circuit diagram can be seen in figure 6. A 285 cu. in. cylinder is used to store the nitrogen working fluid at 3,000 psi. A clip of three projectiles are

sequenced using a loading spring. The loader is designed to operate comfortably at 10 Hz.

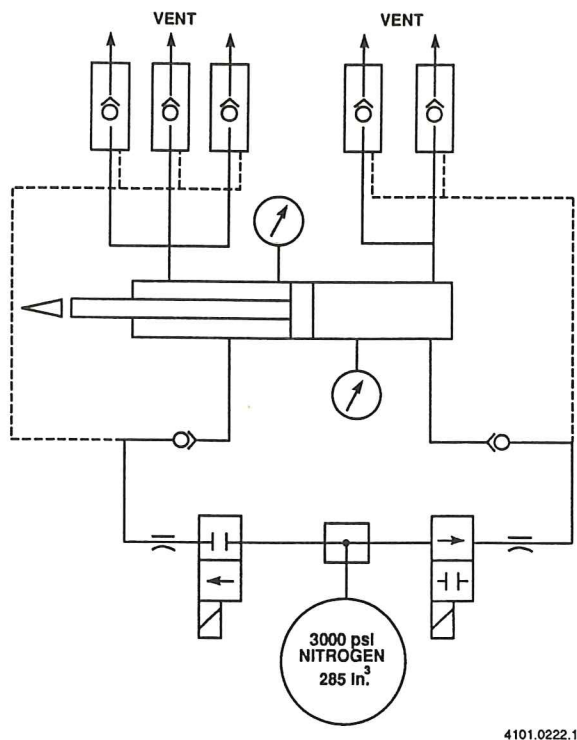


Figure 6. Autoloader circuit schematic

Instrumentation and Diagnostics

The SCC system will be instrumented to provide design corroboration data, fault analysis information, and necessary control input data. The compulsator itself will be instrumented for vibration and rotor spin growth in two planes radially and axial growth will be monitored opposite the thrust bearing. Because the flywheel is composite and the readings are to be made within the machine excitation field, photonic gap sensors have been selected to make these measurements. The instruments use the reflectance vs. gap curves of light off a solid surface to indicate gaps on the order of 10 to 80 mils with an accuracy of 50 μ m. Signal filtering will be employed to differentiate between surface contours (> 100 x rpm), vibrations (1 to 5 x rpm), and rotor growth (< 0.01 x rpm).

Conclusions

The need for an extremely high power density pulsed power supply has lead to several novel features and materials to be used for the first time in the SCC. The resulting design is one which promises a high probability of success. The SCC is well into the fabrication phase at this time, with a planned commissioning date of April, 1990.

In parallel with the fabrication effort, the SCC augmented railgun and pneumatic autoloader are being prepared for testing using the ICC power supply. This experiment will prove the augmented railgun and projectile package designs, the autoloader design, and the 400 kA SCR closing switch design. The goal of the

experiments is to demonstrate the full energy three shot salvo performance of the launcher. This testing is scheduled to begin in February, 1990.

Acknowledgment

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