COMPULSATOR
A HIGH POWER COMPENSATED PULSED ALTERNATOR

W. F. Weldon, M. D. Driga, W. L. Bird, K. M. Tolk,
H. H. Woodson, and H. G. Rylander

Second International Conference on
Energy Storage, Compression, and Switching
Venice, Italy
December 5-8, 1978

Publication No. PN-46
Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

COMPULSATOR -- A HIGH POWER COMPENSATED PULSED ALTERNATOR

W. F. Weldon, M. D. Driga, W. L. Bird, K. M. Tolk,
H. H. Woodson, H. G. Rylander

Center for Electromechanics
The University of Texas at Austin
Taylor Hall 167
Austin, Texas 78712

INTRODUCTION

The Center for Electromechanics (CEM) of The University of Texas at Austin has proposed a new pulsed power supply utilizing inertial energy storage as a possible replacement for large capacitor banks. The compensated pulsed alternator, or compulsator, overcomes many of the limitations of the pulsed homopolar generators previously developed by CEM and elsewhere in that it offers high voltage (10's of kV) and consequently higher pulse rise times, is self commutating, and offers the possibility of generating repetitive pulses.

The compulsator converts rotational inertial energy directly into electrical energy utilizing the principles of both magnetic induction and flux compression. Reduced to its simplest form, an alternator requires that a single turn coil of wire be spun in a magnetic field (Figure 1-A). Increasing the voltage of such an alternator requires increasing the magnetic field, spinning the coil faster or increasing the number of turns of wire in the coil. Since both the magnetic field strength and rotational speed of the coil are limited by physical properties of the materials used, one is ultimately faced with increasing the number of turns in the rotating coil (Figure 1-B). Unfortunately, as the number of turns (n) in the coil is increased, the coil inductance rises with n^2 while the alternator voltage only rises with n and the pulse rise time which the alternator is capable of producing consequently suffers. The CEM compulsator (Figure 1-C) solves this dilemma by including a series, stationary coil almost identical to the rotating one that, when the axes of the two coils coincide, almost completely compensates the inductance of the rotating coil allowing the generation of a very intense pulse. After the pulse peak, the inductance once again rises to its original high value, in effect, commutating the pulse and greatly reducing the performance required of the interrupting switch used with the compulsator.

The compulsator concept was originally intended to drive flashlamps for solid state lasers, requiring 12-15 kV pulses of 0.5 ms duration and most of the information in this paper deals with this application. However, more recent investigations indicate that the compulsator concept is applicable to the generation of much faster (<50 μs) pulses and this area will be discussed briefly.

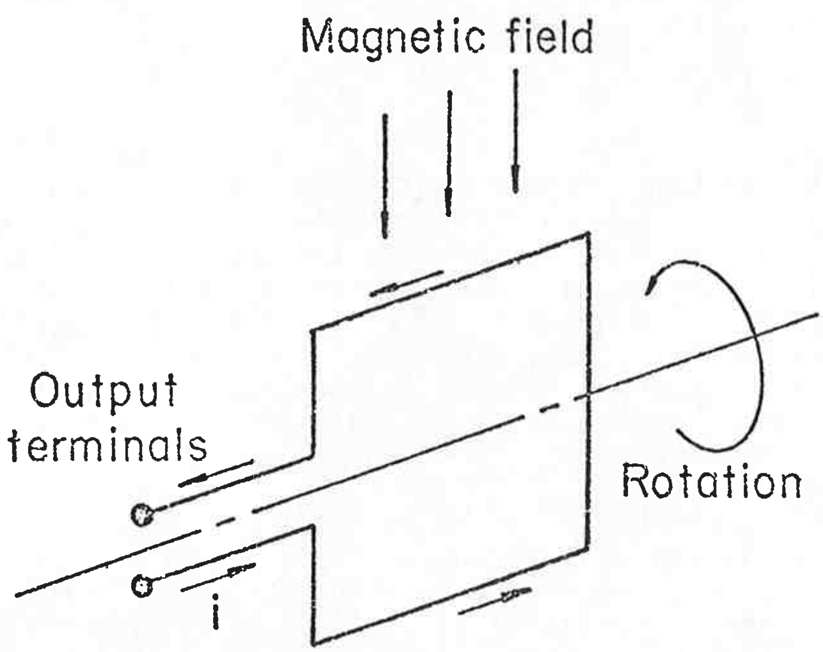

Figure 1-A: Simple Electrical Alternator.

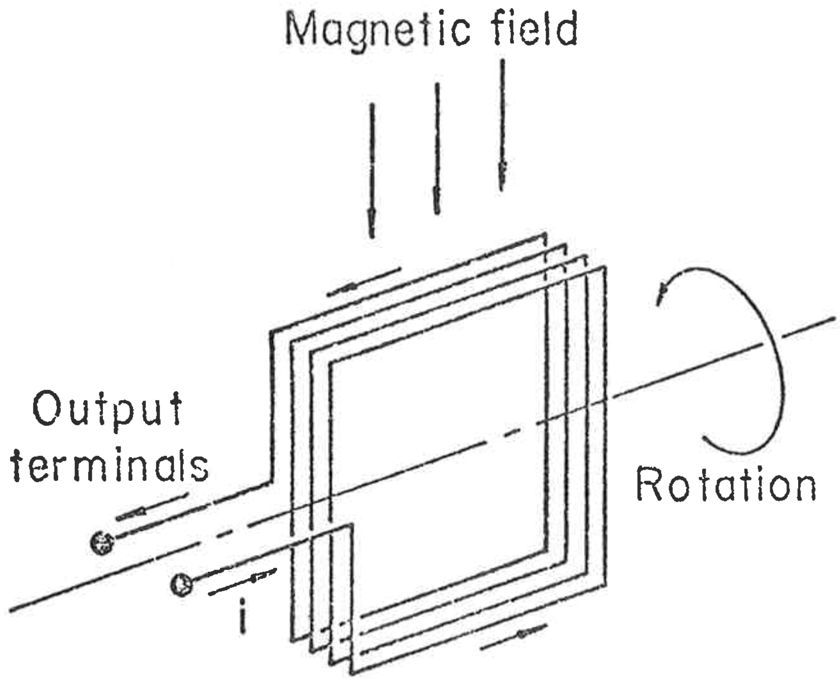

Figure 1-B: High Voltage Electrical Alternator.

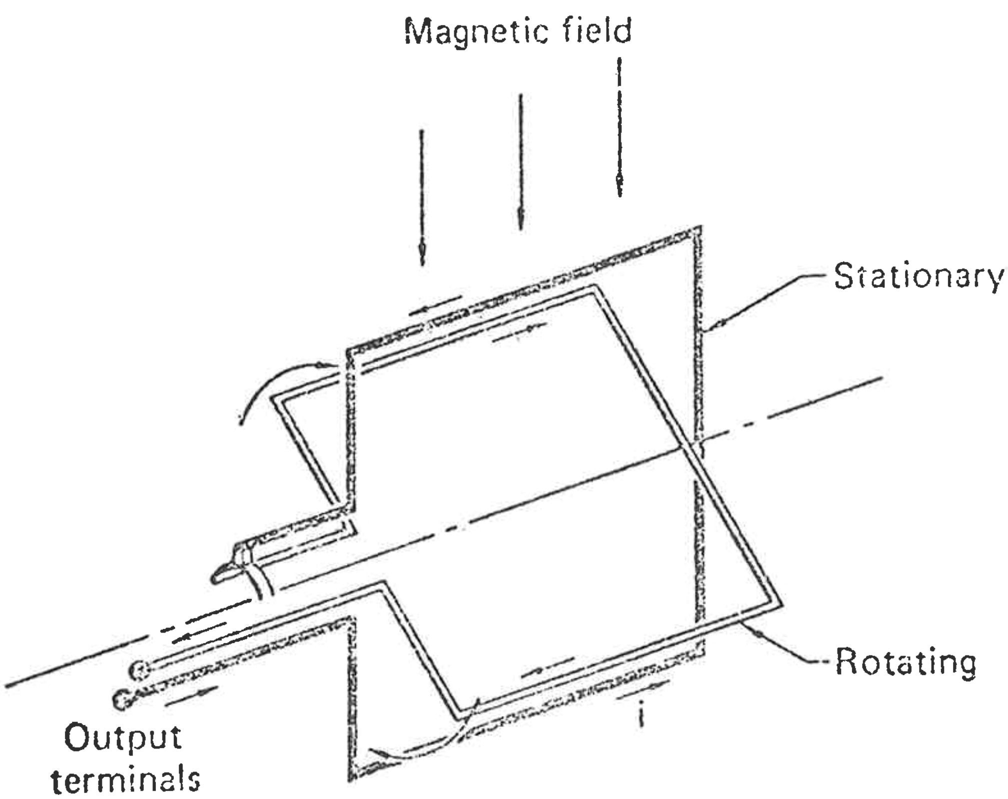

Figure 1-C: Compensated Pulsed Alternator.

THEORY OF OPERATION

The compensated pulsed alternator is an electromechanical device which combines rotary flux compression with conventional alternator energy conversion. A schematic diagram of the machine is shown in Figure 2. The circuit is represented by a sinusoidal voltage source V(t), a resistance R, and a variable inductance L. The resistance R is the sum of the generator resistance and the nonlinear resistance of the load (flashlamps, in this case). The circuit differential equation is given by

$$\frac{d}{dt}(Li) + \frac{R}{L}(Li) = V(t) \qquad (1)$$

or $$\frac{d\phi}{dt} + \frac{R}{L}(\phi) = V(t) \qquad (1a)$$

The solution to Equation (1a) is

$$\phi = \left[\phi_{initial} + \int_0^t V(t)\, e^{\int(R/L)dt}\, dt\right] e^{-\int(R/L)dt} \qquad (2)$$

where $\phi_{initial} = L_{max} i_{initial}$

The current may be expressed as

$$i = \frac{1}{L}\left[L_{max} i_{initial} + \int_0^t V(t)\, e^{\int(R/L)dt}\, dt\right] e^{-\int(R/L)dt} \qquad (3)$$

where R, L, and i are instantaneous values.

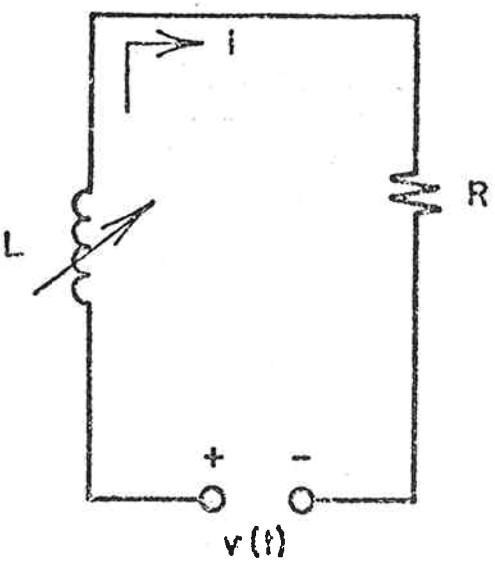

Figure 2: Rotating Flux Compressor Schematic.

Typical resistance, inductance, and current waveforms are shown in Figure 3.

It is important to note that the second term in Equation 3, $\int_0^t V(t)dt$, is the most important in determining the total energy transmitted to the load. The supplied alternator volt-seconds are approximately equal to the circuit resistive volt seconds. The inductance variation or flux compression, primarily affects the pulse shape (amplitude and half width) rather than delivered energy.

The armature inductance L is an intermediate quantity which relates flux linkage λ to armature current i.

$$L = \lambda / i$$

In a pulsed high current device such as the compensated pulsed alternator, non-linear time varying effects of magnetic saturation and diffusion make it useful, analytically, to consider the inductance in terms of magnetic energy rather than flux linkages. The inductance is calculated by

$$L = \frac{2}{i^2} \int_{vol} \frac{1}{2} \vec{B} \cdot \vec{H} \, d(vol) \qquad (4)$$

The inductance variation is calculated by determining the armature flux distribution as a function of rotor position, armature current, and time, using a transient finite element computer code. The magnetic energy W_m is calculated as

$$W_m = \sum_{i=1}^{N_{elements}} \left(1/2 \frac{B^2}{\mu_o \mu_r} \cdot vol\right)_i$$

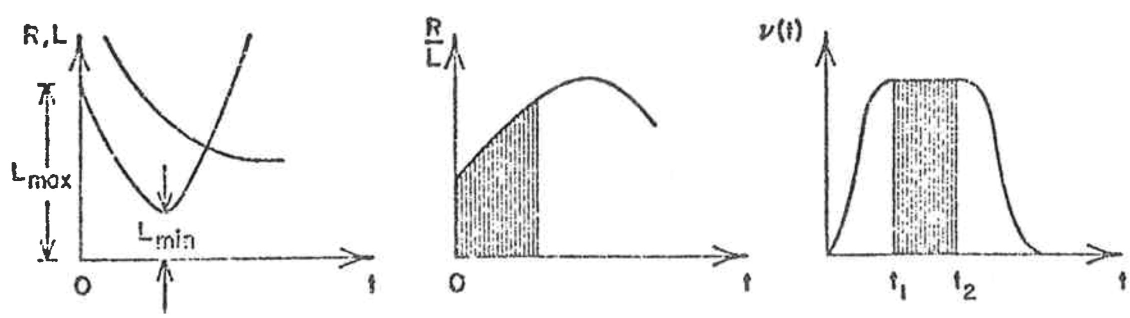

Figure 3: R, L, R/L and V as Functions of Time.

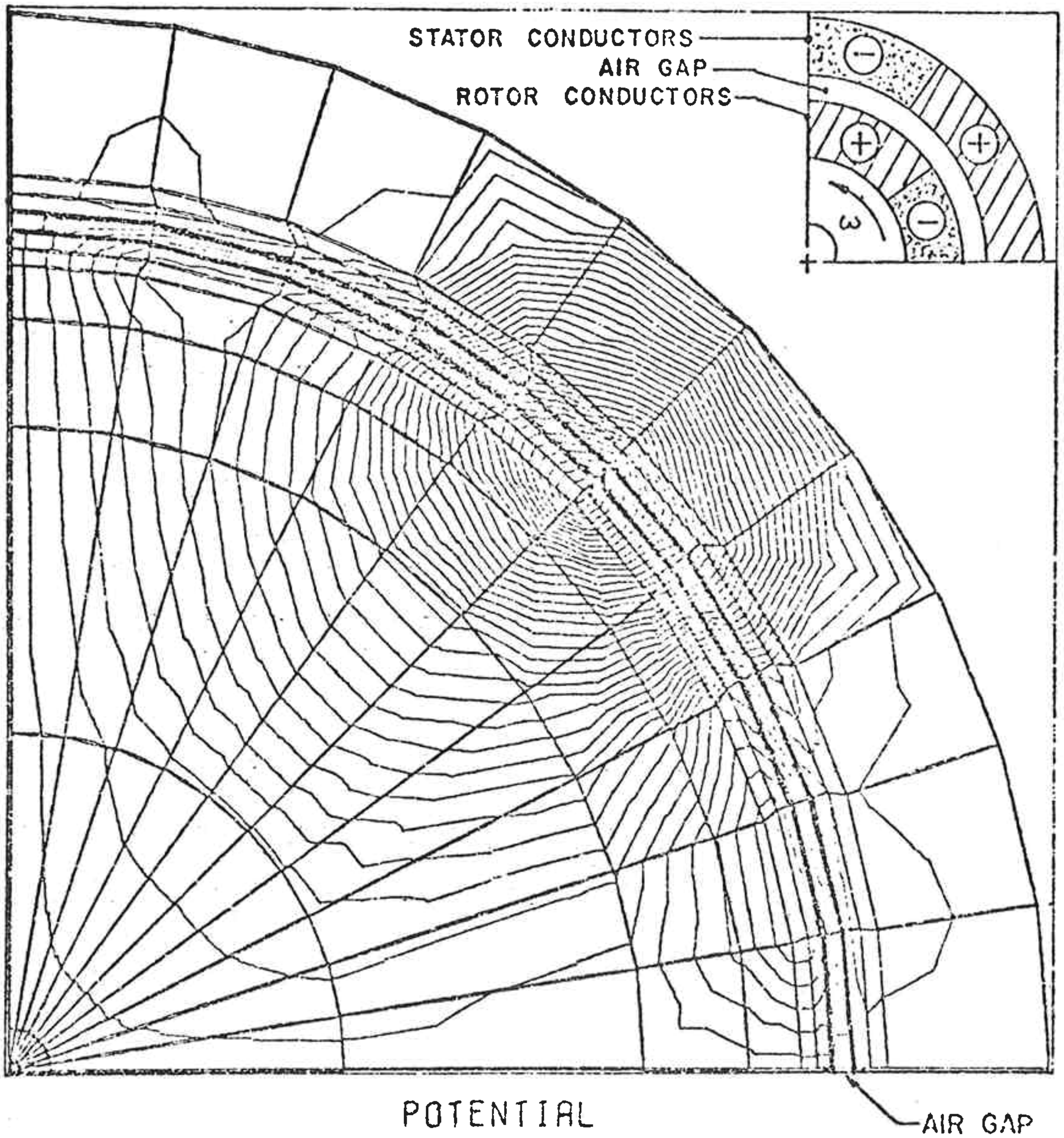

FIGURE 4: Flux Plot -- Coil Systems Displaced 32° (Electrical)

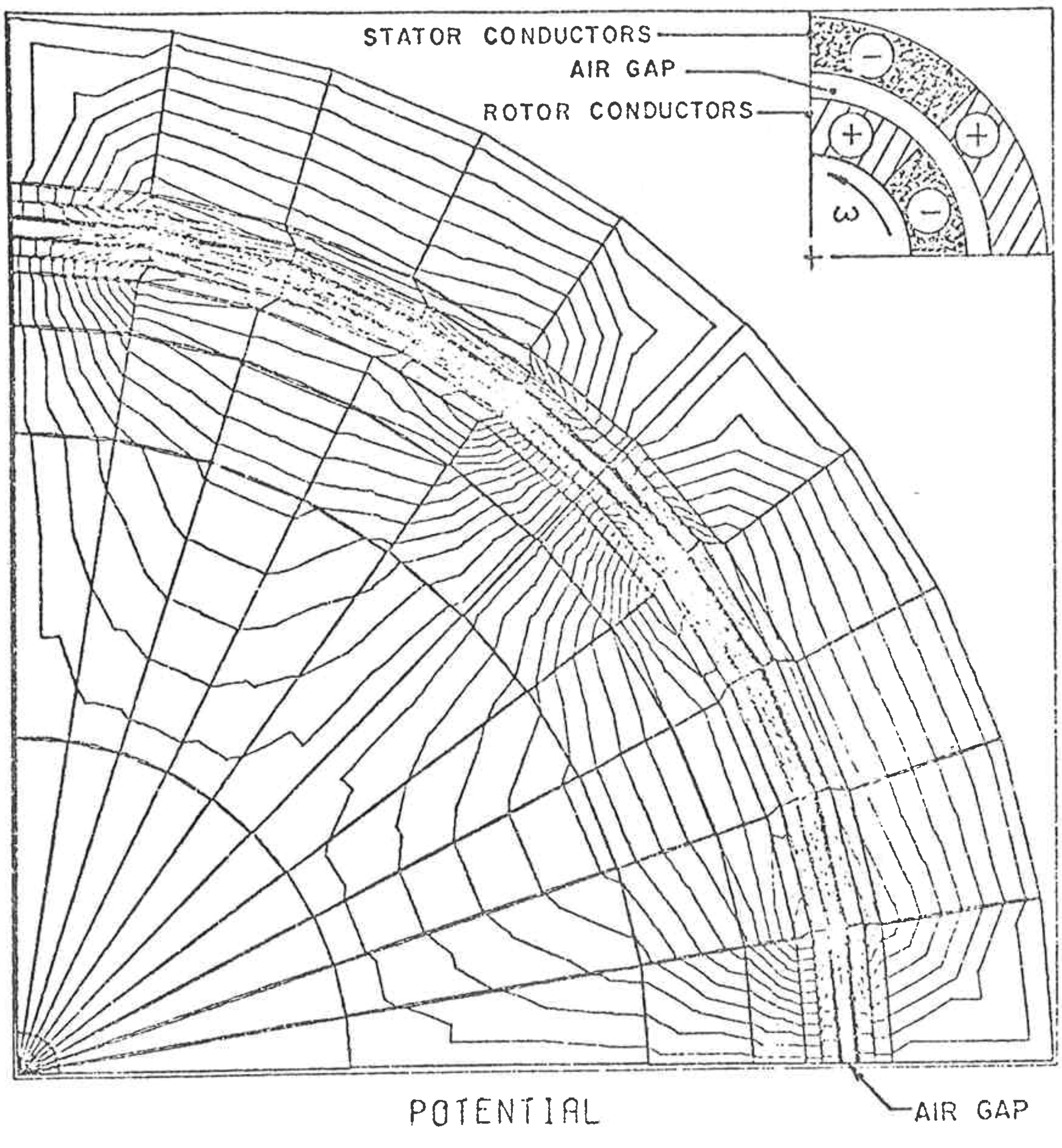

Figure 5: Flux Plot -- Coil Systems Displaced 0° (Electrical)

The initial armature current is established during the startup period during which the flashlamps are also preionized. At some time t_0 the lamps are switched across the alternator terminals. At the moment of switching the rotor and stator (compensating) coils are displaced approximately 32 electrical degrees, and the armature flux is as shown in Figure 4.

Note that the direction of the flux lines in the air gap is radial. The ampere turns which generate the flux are located at the four uncompensated sectors, 32 electrical degrees each, which are distributed 180 electrical degrees apart. Since the flux lines are radial, the magnetic circuit has a relatively low reluctance and, therefore, a high inductance. Approximately 80 percent of the magnetic energy is stored in the air gap. The remaining 20 percent is stored in the rotor. The relative permeability of the rotor laminations is determined by the main field flux density and is approximately equal to 40. Since the volume of the rotor iron is much greater than the air gap, the energy stored in the rotor does influence the inductance calculation somewhat.

As the rotor spins during the pulse the angular displacement between the coils decreases and when the displacement reaches zero, the inductance is minimized. The armature flux distribution at the point of minimum inductance (maximum-compensation) is shown in Figure 5. In this case the flux lines in the air gap are tangential to the periphery of the rotor, the length of the magnetic path being proportional to the polar pitch τ. Since the reluctance of this circuit is greater, the corresponding inductance is smaller.

The variation of inductance of the point design pulsed alternator is shown in Figure 6. The variation in the inductance over the main pulse is approximately twenty to one.

To determine the ratio of L_{max}/L_{min} for another machine configuration, it is best to run the finite element code for that particular case. However, for comparing a large number of machines, this is not practical and a simple scaling law is required. The approximate scaling factor can be obtained by comparing the ratio of the magnetic flux density in the air gap at the maximum and minimum inductance positions. The magnetic flux density is inversely proportional to the air gap flux path length. Therefore, to determine (L_{max}/L_{min}) for machine A given (L_{max}/L_{min}) for machine B

$$(L_{max}/L_{min})_A \sim (\tau/g)_A^2 \,/\, (\tau/g)_B^2 \cdot (L_{max}/L_{min})_B \qquad (5)$$

Since the width of the air gap does not increase linearly with diameter, the inductance variation increases with diameter. The pole

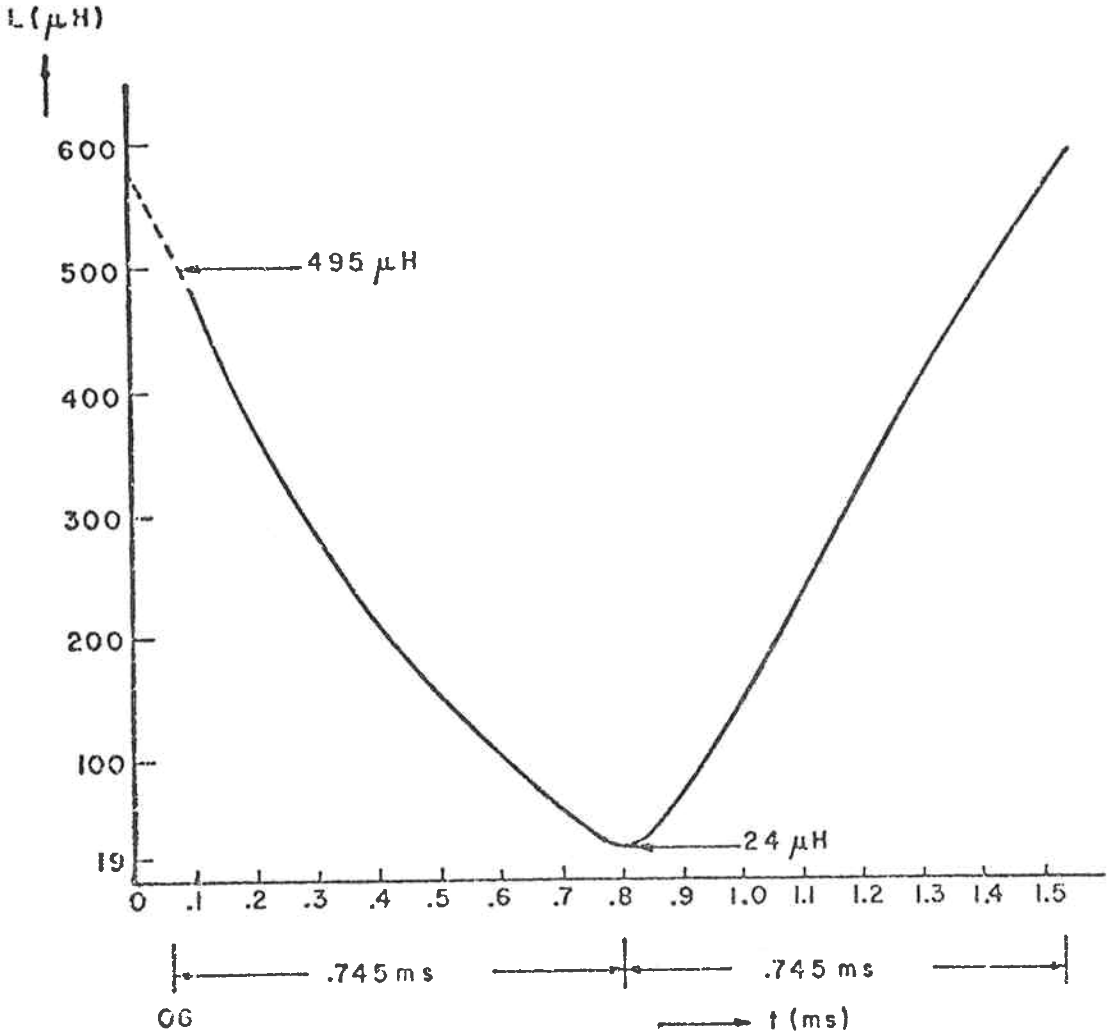

Figure 6: Armature Circuit Inductance Variation

pitch τ is inversely proportional to the number of poles. Therefore, for a given diameter, the inductance variation is greatest for the machine with the fewest number of poles.

PROTOTYPE COMPULSATOR DESIGN

A 1/2 scale engineering prototype of the compulsator design intended to power flashlamps for Lawrence Livermore Laboratories NOVA solid state laser fusion experiment (Figure 7) is under construction at CEM and is scheduled for completion in late spring of 1979. The performance parameters for the prototype are given in Table I.

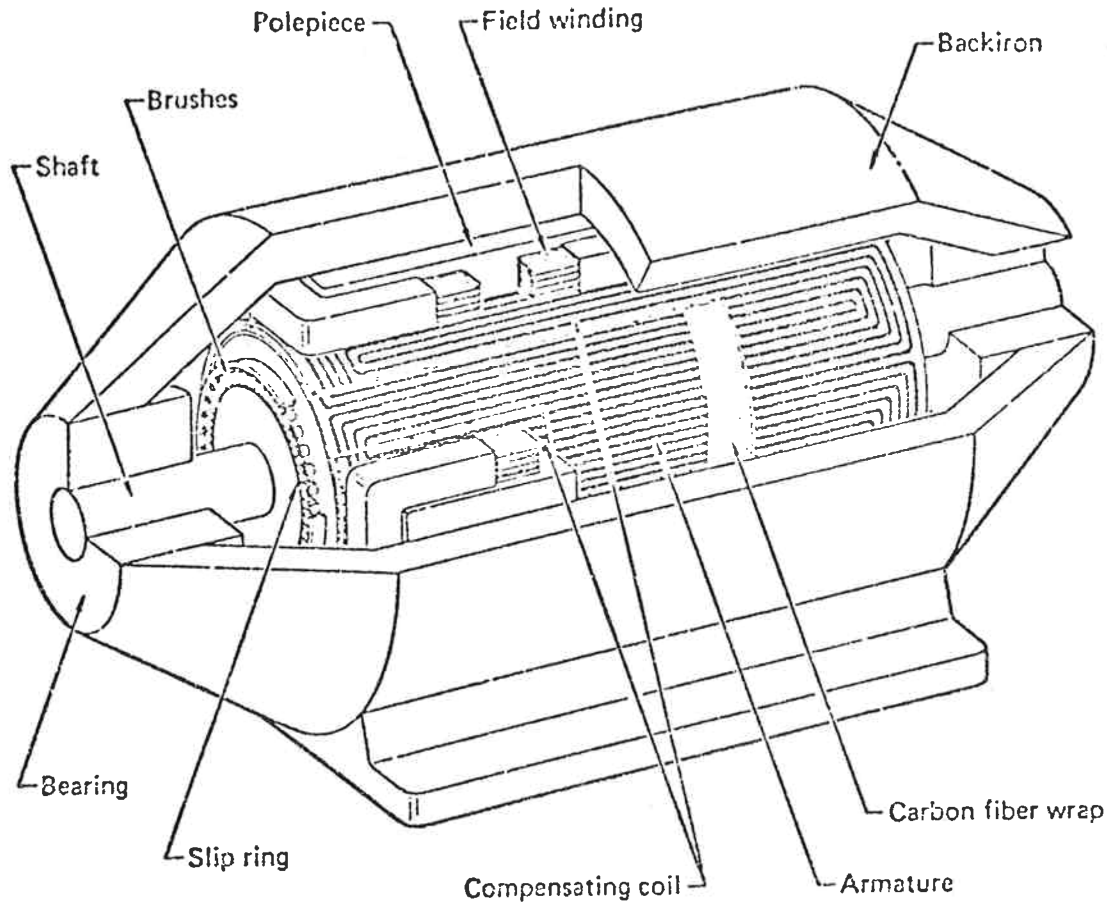

Figure 7: LLL Compulsator

Table I. Engineering Prototype Compulsator Performance Parameters

Open Circuit Voltage	5.8	kV
Voltage Under Load	7.2	kV
Delivered Energy	200	kJ
Peak Current Into Load	70	kA
Peak Output Power	0.48	GW
Output Pulse Width	500	μsec
Peak Short Circuit Current	160	kA
Peak Short Circuit Mechanical Power	1.45	GW

The armature circuit consists of two air gap windings connected in series opposing. The rotor winding is connected to the compensating (stator) winding and the alternator terminals via slip rings located at each end of the rotor. The windings provide a variable armature inductance with angular position, with the minimum inductance occurring when the axes of the coils are aligned with the quadrature axes of the main field windings (point of maximum voltage). The rotor and compensating winding conductors are wound in a continuous serpentine fashion as shown in Figure 8. The serpentine winding scheme was chosen to simplify the construction of the end turns by eliminating connections and crossovers. Note that the end turns are supported by the rotor laminations and do not overhang the ends of the rotor. The end turns of the compensating winding are supported similarly.

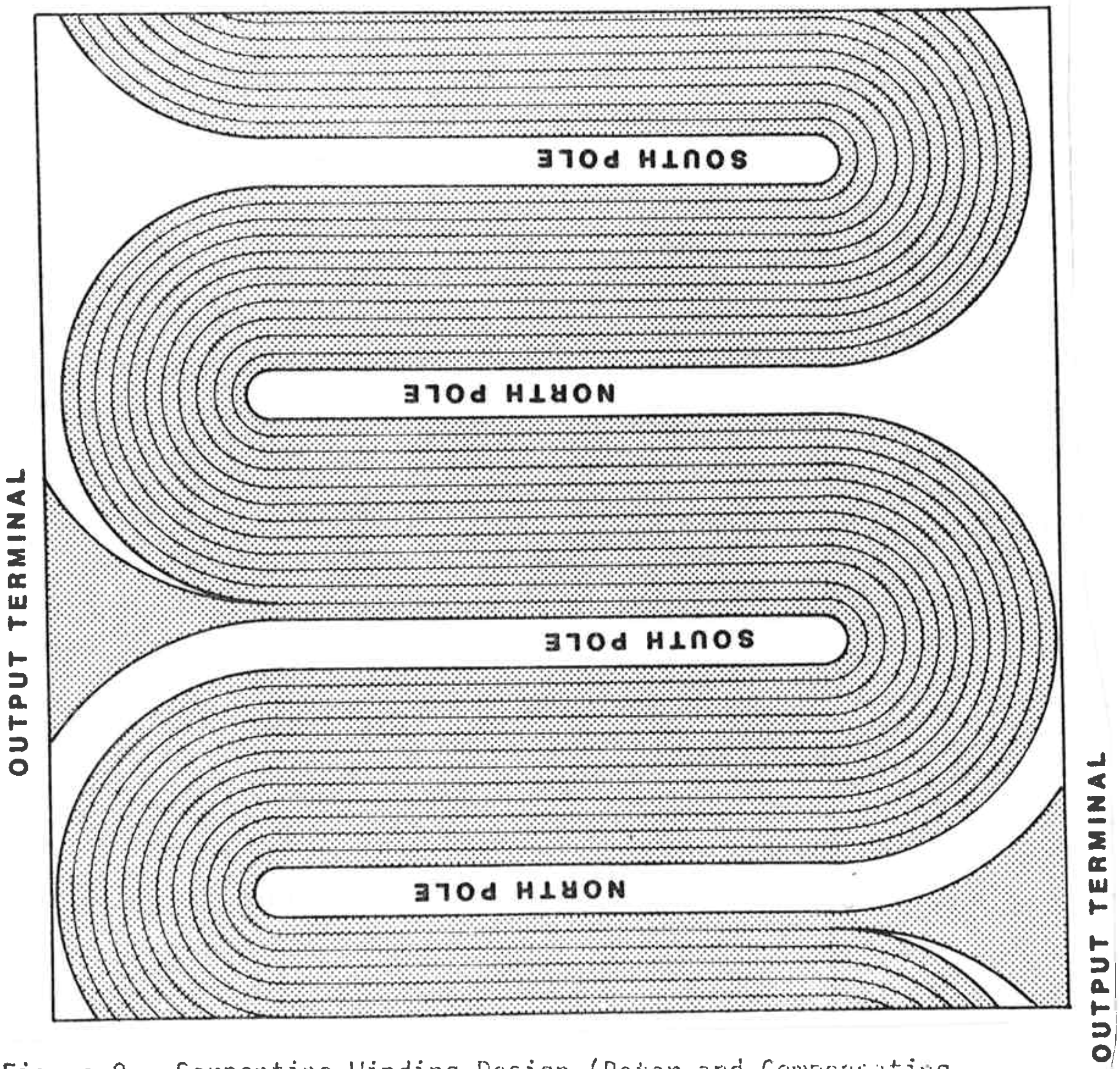

Figure 8: Serpentine Winding Design (Rotor and Compensating Conductors)

In an air gap winding the rotor conductors are exposed to a high density (1.9 Tesla) relatively high frequency (120-180 Hz) magnetic field. Therefore, the rotor conductors must be constructed from an assembly of small diameter wires to reduce eddy current losses and to prevent a significant temperature rise in the conductors during the time that the main field windings are excited. Based on the fundamental time constant of the field, it is anticipated that the field of the point design generator would be ramped to the peak level in 30 seconds, held constant for 60 to 120 seconds, and ramped down in 30 seconds. Since it is doubtful that any significant heat transfer will occur during the field pulse, an adiabatic heating process can be assumed to size the conductors. Assuming that the field is energized for 60 seconds and the open circuit frequency is 180 Hz, the temperature rise of a #20 AWG copper wire is 96°C at a peak field level of 1.9 Tesla. Similarly a #30 AWG copper wire experiences a 9.4°C temperature rise. A #30 AWG basic wire size is being used for the engineering prototype.

To prevent the buildup of circulating currents within a conductor, the assembly of small diameter insulated wires must be transposed so that each wire links the same flux. The windings are formed of an array of type 8 Litz wire as manufactured by New England Electric Wire Company. The type 8 Litz wire is a spiral flattened tube which is rolled into a rectangular cross section. The tube consists of multiple bundles of seven strand (six around one) insulated magnet wire. A sketch of one rotor conductor consisting of 13 type 8 Litz wires is shown in Figure 9.

Since the Litz wires are connected in parallel at the slip rings, it is important that each cut the same flux. Note that the serpentine winding forms a natural transposition: a wire that occupies the inside position of the main conductor width under the North poles, occupies the outside position under the South poles. Conceivably, each Litz wire could be terminated with its own slip ring and brush, providing a natural division for supplying multiple circuits from one compulsator.

ADVANCED COMPULSATOR DESIGNS

Studies are now underway at CEM to investigate the application of the compulsator concept to pulsed power applications requiring pulse times much shorted than the half millisecond regime of the first compulsator. Modifications being investigated include counter-rotating the two armature windings to double the voltage available from a given machine size as well as doubling the base frequency of the machine, cup type rotors with stationary central ferromagnetic cores to reduce rotor inertia and thus reduce the shear stress on the conductor/insulation bond during discharge and, of course,

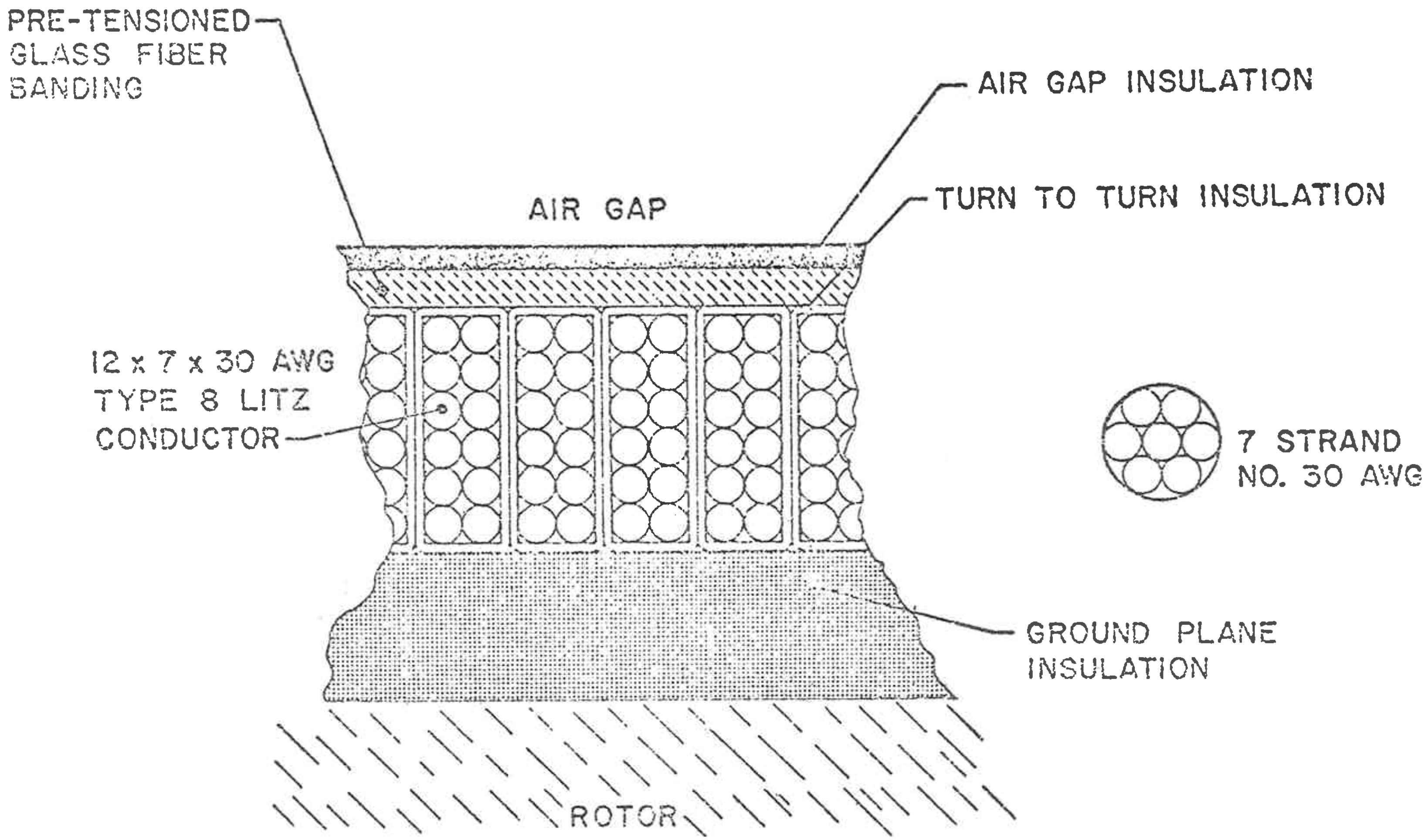

Figure 9: Rotor Conductor Detail

operating the machines at higher frequencies, voltages and surface current densities. Initial results indicate that pulse times below 50 μsec are feasible for such machines. The final results of these preliminary studies on second generation compulsators should be published in the summer of 1979.

The work described in this paper has been supported by the United States Department of Energy, Contract No. W-7405-Eng-48, Lawrence Livermore Laboratory, Los Alamos Scientific Laboratory, Naval Surface Weapons Laboratory, and the Texas Atomic Energy Research Foundation.