ADVANCED COMPULSATORS FOR RAILGUNS

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Presented at the
4th Symposium on Electromagnetic
Launch Technology
Austin, Texas
April 12-14, 1988

Publication No. PR-68
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Abstract: In order to maximize the penetration of a projectile into a target the acceleration on the projectile during the launch must be minimized. Low accelerations permit the design of long and slender projectiles which have better penetration capability. From this standpoint power supplies for electromagnetic launchers must be able to provide rectangular current pulses with a high average to peak acceleration ratio.

This paper discusses further developments made at CEM-UT to obtain the desired pulse shape from a compensated pulsed alternator (compulsator) when it is used as a power supply for railguns. A general theory of the pulse shaping technique is presented first. This is followed by a discussion on the trade-offs between various equivalent generator configurations. Finally, the electromagnetic design of the compensated pulsed alternator being developed for Task C of the Electromagnetic Gun Weapons System Program is presented.

Introduction

The simplest type of compulsator is the passive compulsator in which an armature winding spins relative to the excitation field and the compensation for the armature winding is provided by a continuous conductive shield. The passive compulsator inherently delivers a symmetric or an asymmetric sinusoidal current pulse. The sinusoidal current pulse is adequate for most railgun applications however the resultant acceleration ratio (average acceleration/ peak acceleration) is 0.5 or less. In order to address these issues a research effort was conducted to generate various current pulse shapes with the compulsator and especially the rectangular or flat topped current pulse. In these shaped pulse machines the armature winding remains essentially similar to the passive machines and the main difference is in the type of compensation provided.

Several geometries and designs evolved during this effort, of these, three are presented here since they are most suitable for tactical applications. The compensation provided is passive in the sense that no current is injected into the compensating component. The currents in the compensating component are induced by electromagnetic coupling with the armature winding. The main difference between this machine and the simple passive machine is that the compensation is selective, i.e., the armature winding is compensated in certain angular positions and is uncompensated for some other angular position. Therefore, the best way to describe this method of compensation is selective passive compensation. Figure 1 shows a machine using compensating windings shorted on themselves. There are two ways that the compensating winding can be wound. One is a lap winding similar to the armature winding and the second is to use single shorted turns, each turn shorted on itself. Figure 2 shows another

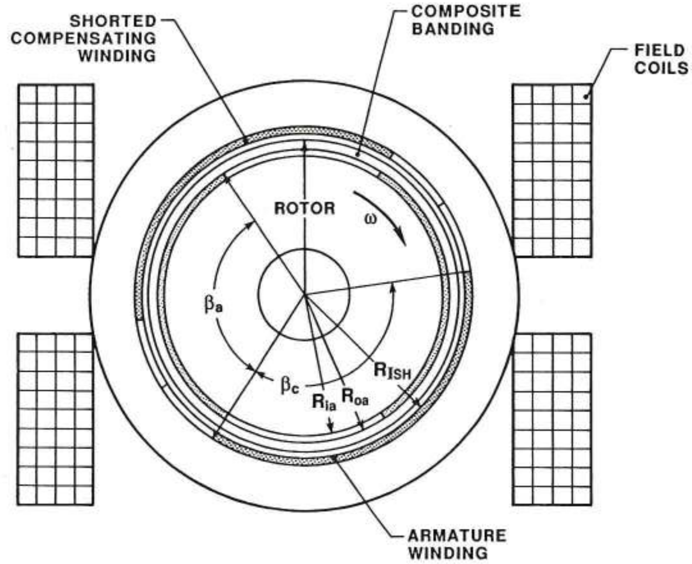

Figure 1. Compulsator with shorted compensating windings

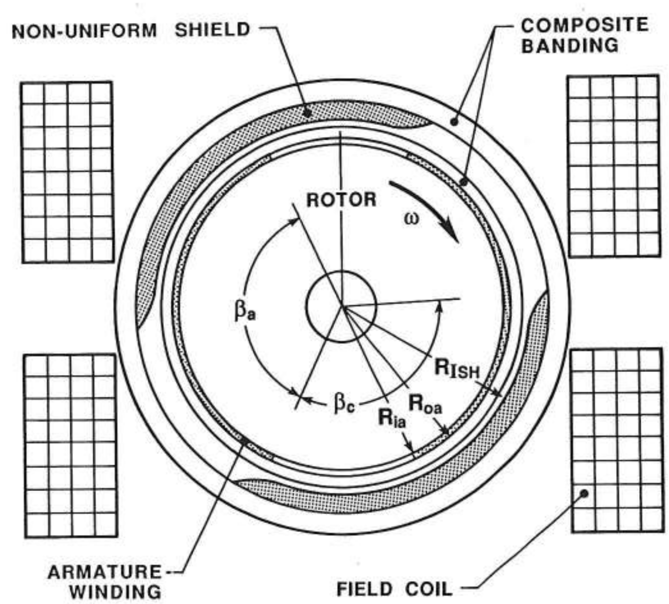

Figure 2. Compulsator with a non-uniform compensating shield

variation of the same machine where a discontinuous conductive shield is used as the compensating component. The common feature in all these three variants is that, due to the selective nature of the compensation, the armature inductance undergoes two variation cycles per revolution, for the two pole machine shown. For a multi-pole machine the armature inductance would go through two variation cycles per pole pair. This is better understood by considering figure 3 which shows schematically the principle of selective passive compensation. After solving the circuit equations for the geometry shown in Figure 3 the equivalent inductance of the armature winding is obtained as

$$L_{aeq} = L_a - \frac{M^2_{ac}}{L_c}$$

where

$$M_{ac} \doteq M_{max} \cos\Theta$$

L_{aeq} = equivalent inductance of the armature winding
L_a = inductance of the armature winding without compensation
L_c = inductance of the compensating winding
M_{ac} = mutual inductance of the two windings
Θ = the relative angular position of the magnetic axis of the two windings

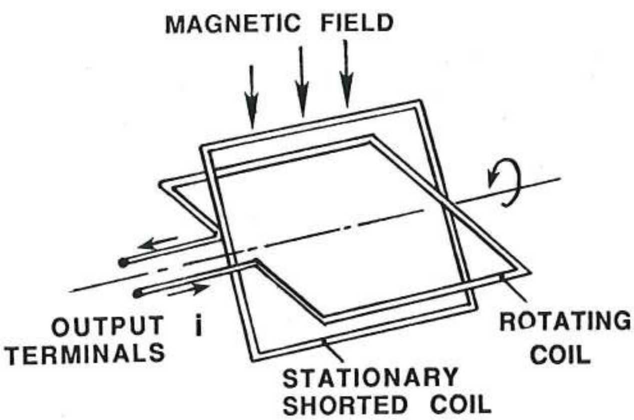

Figure 3. Schematic--principle of operation of selective passive compensation

$$L_{aeq} = L_a - \frac{M^2_{max}\cos^2\Theta}{L_c}$$

$$= L_a\left[1 - k^2_{max}\cos^2\Theta\right]$$

here $k_{max} = \frac{M_{max}}{\sqrt{L_a L_c}}$, the maximum coupling coefficient

$$L_{aeq} = L_a\left[\left(1 - \frac{k^2_{max}}{2}\right) - k^2_{max}\cos 2\Theta\right] \quad [1]$$

<u>**Pulse Shaping Theory**</u>

Having established the nature of the inductance variation we will now consider how different pulse shapes can be obtained from the machine configurations of Figures 1 and 2.

The total inductance variation can be rewritten as

$$L = L_1 - \Delta L\cos(2\omega t - 2\psi)$$

where L_1 includes the constant term of equation 1 plus any other constant inductances in the circuit.

The circuit resistance is neglected for the present analysis since we are interested in the first current pulse after initiation. This is a valid assumption especially for compulsators, which operate at a high frequency, so that the period of the current pulse is much shorter then the decay time constant of the circuit.

The generated voltage can be written as

$$V(t) = V m \sin(\omega t - \phi)$$

Then for the armature circuit we may write

$$\frac{d(Li)}{dt} = V m \sin(\omega t - \phi)$$

which yields the solution

$$i(t) = \frac{Vm}{\omega L}\left[\cos\phi - \cos(\omega t - \phi)\right]$$

with the initial condition that $i(t) = 0$ at $t = 0$, also

$$i(t) = \frac{Vm(\cos\phi - \cos(\omega t - \phi))}{\omega L_1\left[1 - \frac{\Delta L}{L_1}\cos(2\omega t - 2\psi)\right]}$$

$$\text{Since } \frac{\Delta L}{L_1}\cos(2\omega t - 2\psi) < 1 \text{ for all t}$$

The denominator may be expanded in a converging power series to give:

$$\left[1 - CRD\cos(2\omega t - 2\psi)\right]^{-1} \doteq 1 + \sum_{n=1}^{\infty} CRD^n\cos^n(2\omega t - 2\psi)$$

where $CRD = \frac{\Delta L}{L_1}$ ≡ The differential compression ratio.

Using trigonometric identities this can be rewritten as

$$\left[1 - CRD\cos(2\omega t - 2\psi)\right]^{-1} \approx \left(1 + \frac{CRD^2}{2} + \frac{3}{8}CRD^4\right) +$$

$$\left(CRD + \frac{3}{4}CRD^3 + \frac{5}{8}CRD^5\right)\cos(2\omega t - 2\psi)$$

$$+ \left(\frac{CRD^2 + CRD^4}{2}\right)\cos(4\omega t - 4\psi)$$

$$+ \left(\frac{CRD^3}{4} + \frac{5}{16}CRD^5\right)\cos(6\omega t - 6\psi)$$

$$+ \frac{CRD^4}{8}\cos(8\omega t - 8\psi)$$

$$+ \frac{CRD^5}{16}\cos(10\omega t - 10\psi)$$

The expression for the current can therefore be written as

$$i(t) = \frac{V_m}{\omega L_1}\left[\cos\phi - \cos(\omega t - \phi)\right]$$

$$\Big[A_o + A_2\cos(2\omega t - 2\psi)$$

$$+ A_4\cos(4\omega t - 4\psi)$$

$$+ A_6\cos(6\omega t - 6\psi)$$

$$+ A_8\cos(8\omega t - 8\psi)$$

$$+ A_{10}\cos(10\omega t - 10\psi)\Big]$$

Here $A_o = 1 + \frac{CRD^2}{2} + \frac{3}{8}CRD^4$; $A_2 = CRD + \frac{3}{4}CRD^3 + \frac{5}{8}CRD^5$

$$A_4 = \frac{CRD^2 + CRD^4}{2};\quad A_6 = \frac{CRD^3}{4} + \frac{5}{16}CRD^5$$

The last equation for the current clearly illustrates two points:

(i) the presence of higher harmonics in the current wave, and

(ii) the amplitude of the harmonics is governed by the differential compression ratio as well as the phase angles ϕ and ψ.

This forms the basis for synthesizing current pulses of different shapes. Let us now consider specific cases to illustrate these points.

Case 1

a) Initiate the current pulse at peak positive voltage which implies $\phi = -90°$.
b) At initiation the circuit inductance is at a minimum which implies $\psi = 0°$.

Figure 4 shows the different current pulses obtained for various differential compression ratios under the above conditions. The current pulse shape approaches a sinusoidal pulse for low values of the differential compression ratio since the amplitude of the higher harmonics diminishes.

Case 2

a) Initiate the current pulse at zero voltage which implies $\phi = 0°$.
b) At initiation let the circuit inductance be low and approaching its minimum value, say $\psi = 68°$.

Figure 5 shows different current pulse shapes for various differential compression ratios. This example is especially useful for understanding how a flat pulse is obtained for loads such as the railgun. For simplicity the only variable inductance considered so far is that of the compulsator. The railgun represents a variable (increasing) impedance load due to the increasing inductance and back electromotive force. Considering the curve for CRD = 0.33 in figure

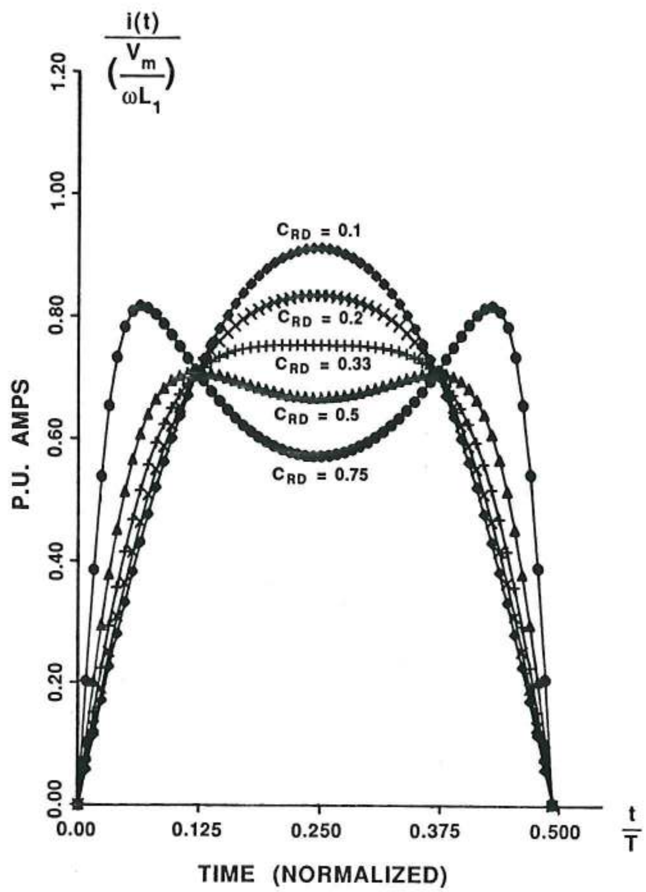

Figure 4. Current pulse shapes for Case 1

5 it is clear that the second current peak during the latter quarter of the pulse can be flattened by the increasing railgun impedance thus resulting in a flat pulse.

Practical Considerations and Tradeoffs

The expression for the inductance variation in equation 1 is approximate, since it only accounts for the first harmonic in the mutual inductance variation. It is, however, an adequate representation for the development of the theory. Neglecting the higher harmonics for the machine in figure 1 with the compensating winding has very little effect on the current pulse shape, since these harmonics have a low amplitude. However, for the machine with the discontinuous shield shown in figure 2 the higher harmonics are relatively strong and cannot be neglected. Figure 6 shows the armature inductance variation for the three types of compensation, i.e., the single shorted turns compensating winding, the lap wound compensating winding, and the discontinuous shield. The comparison is performed for an identical armature winding for all three cases, and the example selected is the compulsator being developed for Task C of the Electromagnetic Gun Weapons System Program. Therefore, the parameters indicated in figures 1 and 2 take the values $\beta_a = 150°$, $\beta_c = 150°$ for the wound compensation and $\beta_c = 120°$ for the discontinuous shield.

Figure 6 indicates that there is very little difference in the inductance variation with the wound conductors. However, the discontinuous shield machine

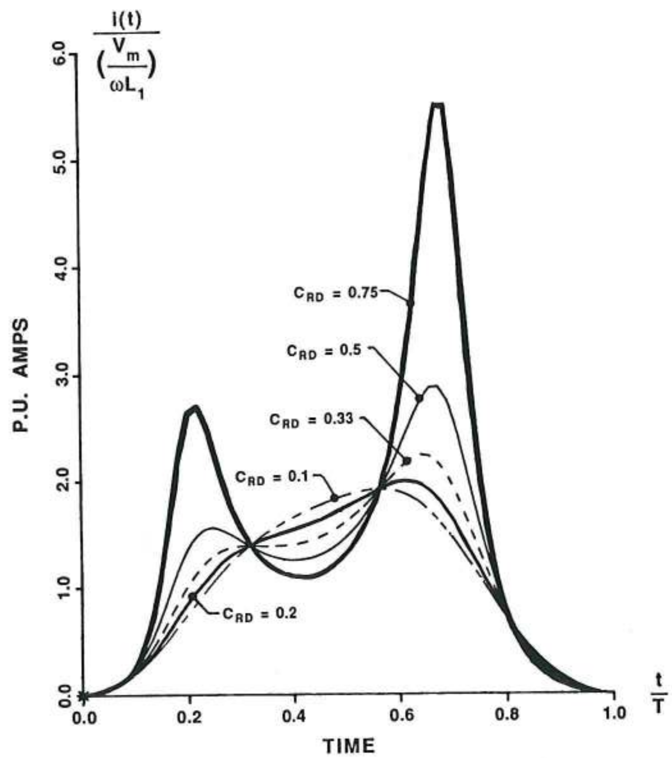

Figure 5. Current pulse shapes for Case 2

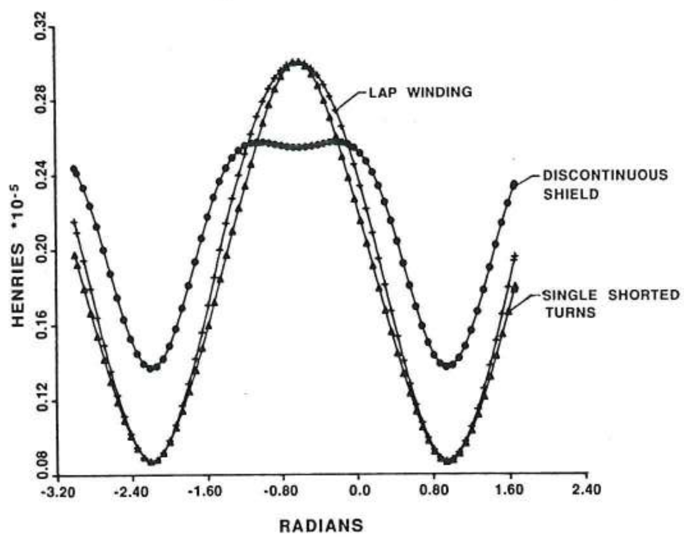

Figure 6. Armature inductance as a function of rotor position

has a considerably different inductance variation. The variation not only indicates the presence of stronger, higher harmonics, but also that the differential compression ratio is lower. The reason for this can be better understood by considering figures 7a and 7b. Since the wound compensating conductors are stranded they allow the magnetic flux to permeate through thus giving a higher inductance compared to the compensation with a discontinuous shield. Also, since the angular span of the armature winding is greater than the angular span of the discontinuous shield, part of the armature winding remains uncompensated in the minimum inductance position, thus

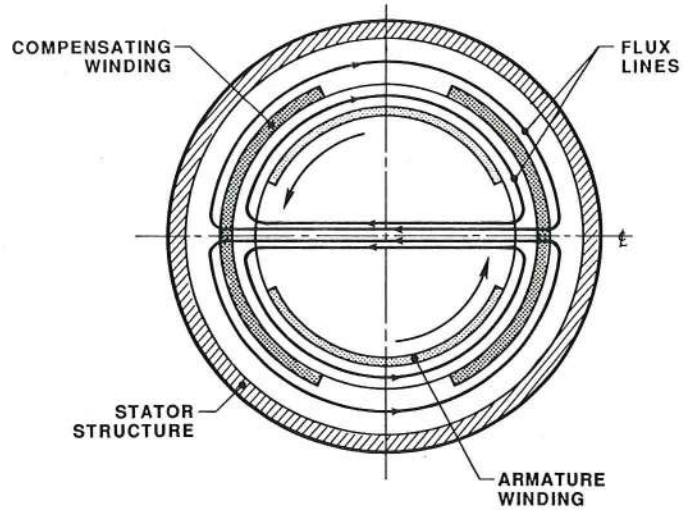

Figure 7a. Wound compensation--maximum inductance position

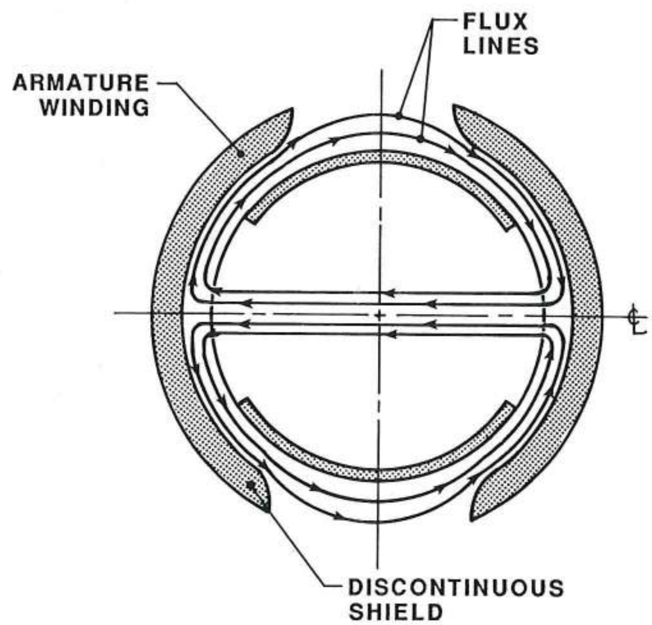

Figure 7b. Discontinuous shield compensation--maximum inductance position

raising the minimum inductance compared to the wound compensating conductors. Increasing the angular span of the discontinuous shield would achieve the desired minimum inductance but lower the maximum inductance, thus maintaining the same differential compression ratio.

In order to obtain the required differential compression ratio with a discontinuous shield the angular span of the armature winding must be reduced. This implies that for the same power level and radial armature conductor thickness the discontinuous shield machine would be stressed higher mechanically and also thermally. Figure 8 shows a comparison of the current pulses obtained from a discontinuous shield machine and a wound compensating conductor machine, for the same differential compression ratio and performance. The discontinuous shield machine is more robust and easier to fabricate and would therefore be used where the loading on the armature winding is acceptable.

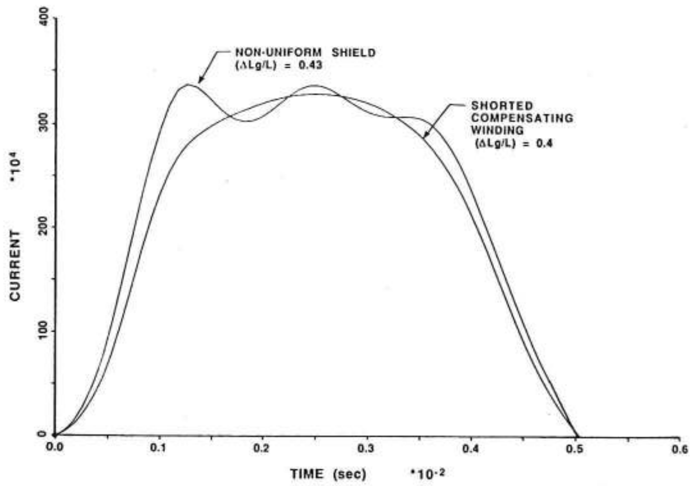

Figure 8. Comparison of current pulses with the two compensation techniques

The main difference between the two wound compensating conductors (i.e. the single shorted turn windings and the lap winding) is that the lap winding constrains the same compensating current through all the turns whereas the single shorted turn winding has as many degrees of freedom as there are conductors. The current through each shorted turn approximately follows the mutual inductance variation with the armature winding. The turn closest to the pole spacer has current in it only for a short duration when the magnetic axis of the armature coincides with the magnetic axis of the turn. This effect diminishes for conductors further away from the pole spacer. This is illustrated in figure 9 for eight shorted conductors per pole. The single shorted turns configuration helps to reduce the radial loading on the compensating winding. Furthermore, it provides greater flexibility in the discharge pulse shape since each shorted turn can be made of conductors which vary in cross section, and conductivity thus making the compensation more selective.

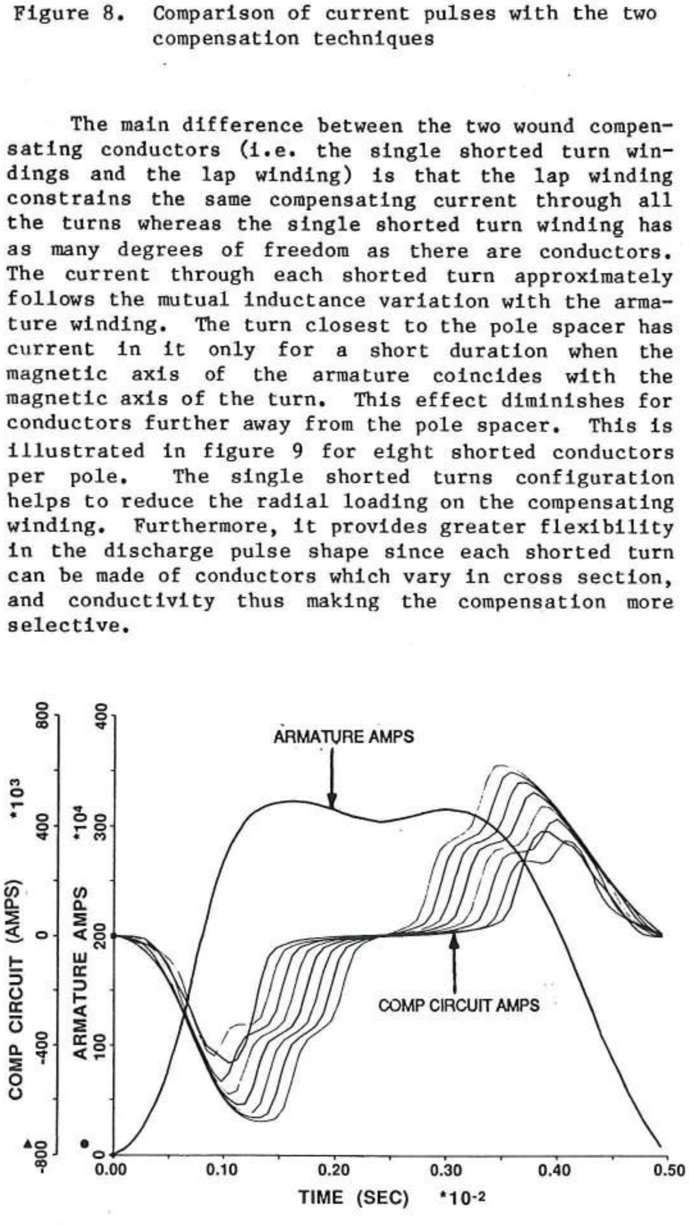

Figure 9. Current in the individual shorted conductors of the wound compensating winding

Electromagnetic Design of the EMGWS Compulsator

The machine described here is based on some of the principles described in the previous sections. This machine is being designed to drive projectiles ranging from 1.13 to 2.88 kg to 9 MJ of muzzle energy with a railgun. The machine is air cored with the armature winding wound on the rotor which spins inside a stator housing the field coil and compensating winding.

The field coil is made from aluminum conductors and provides the excitation magnetic field. Its geometry is very different from most air-core machines which use a distributed field coil. Figure 10 shows the cross section of the field coil. Also shown in figure 10 is the radial flux density distribution at the radius of the armature winding. This field coil geometry has several advantages over the distributed field coil geometry, they are:

1) The shear stress distribution at peak current is uniformly distributed along the armature winding due to the nature of the radial flux density distribution.

2) It allows the stator housing to directly support the shield under the discharge loads. This would be difficult to achieve with a distributed field coil.

3) The forces generated in the field coil are more manageable since the displacement under these forces is directed radially outward, away from the rotor.

4) This geometry simplifies the fabrication and assembly of the field coil.

The field coil provides 5 MA-T per pole excitation at a nominal current density of 3.0 kA/cm^2. In order to reduce the losses in the field coil at this current density it is cooled to 80 K with liquid nitrogen. This is especially important since the field coil operates in a self-excited mode, where the magnetic energy and the resistive losses are supplied from the rotor inertial energy.

The compensating winding is made from single shorted turns. The compensating winding occupies a 150° sector per pole and has 52 shorted conductors per pole. Each conductor is made from stranded and transposed Litz wire. The axis of the compensating winding is displaced 58° from the axis of the field coil in the direction of rotation of the armature winding. The compensating winding is distributed such that most of the turns occupy the cylindrical surface of the stator bore. Some of the turns are completed over end faces of the stator.

The armature winding is lap wound on the surface of the rotor and has six conductors per pole. Two of the end turns are completed over the cylindrical face of the rotor whereas one is completed over the end face of the rotor. This layout provides maximum coupling of the armature winding with the compensating winding. Figure 11 shows the layout of the armature winding on the surface of the rotor. The armature winding is banded with high strength graphite epoxy composite to protect it from the centrifugal loads. The banding is discontinuous axially in order to reduce the eddy current losses.

The current pulse obtained from this machine is shown in figure 9.

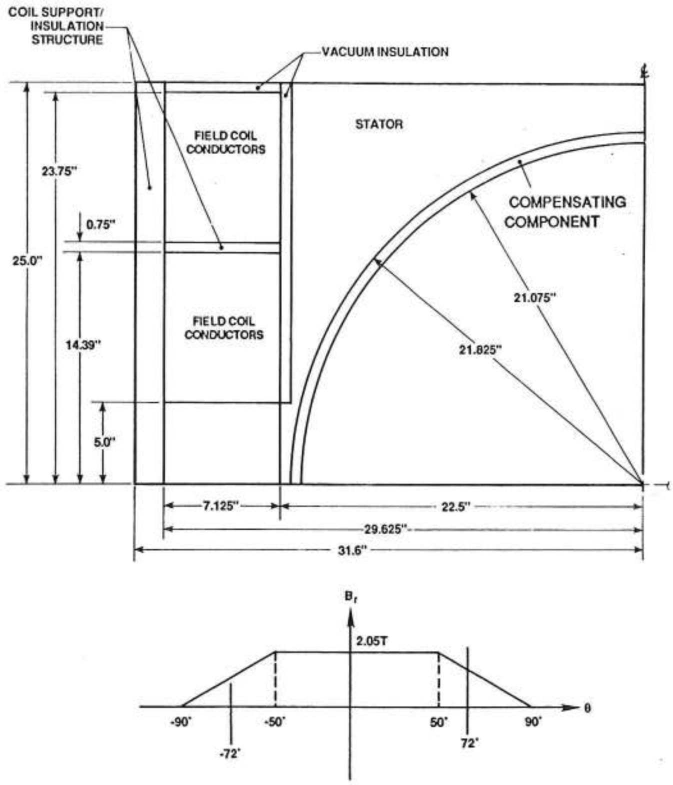

Figure 10. Cross section of the field coil

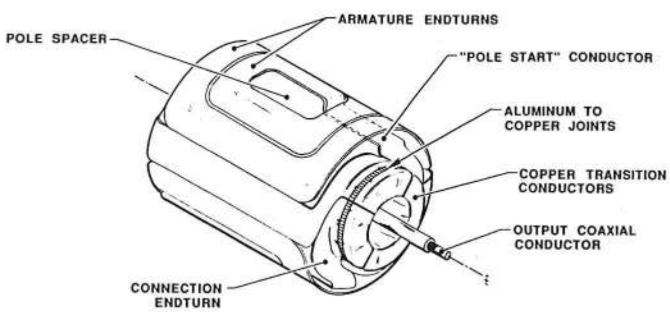

Figure 11. Armature winding layout

Conclusions

The compensated pulsed alternator is a versatile machine capable of producing a variety of pulse shapes from peaky to flat topped. This versatility is obtained from a single element which does the energy storage, conversion, and conditioning. The machine is also capable of providing repetitive pulses at a high frequency which together with the fact that it is possible to synchronize the projectile exit from the gun close to the naturally occuring zero current, makes it well suited to drive railguns.

Acknowledgements

This research was supported by the U.S. Army Armament Research, Development, and Engineering Center and the Defense Advanced Research Projects Agency, under Contract No. DAAA21-86-C-0281.

The author would also like to thank the Center for High Performance Computing at The University of Texas at Austin for time on the CRAY X-MP/24.

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