FUTURE TRENDS IN PULSED POWER TECHNOLOGY AT THE CENTER FOR ELECTROMECHANICS AT THE UNIVERSITY OF TEXAS AT AUSTIN

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Introduction

In the past decade, the feasibility of using rotating electrical machines as pulsed power supplies has been demonstrated. Tokomaks, laser-flash lamps, and electromagnetic (EM) accelerators are examples of devices successfully powered by pulsed generators. Although they are not well suited for driving all loads, i.e., very high voltages (MVs) or microsecond pulse widths, for applications that require a large amount of energy (multi-MJs) and/or field portability, pulsed generators are an attractive alternative. Typically, the features which make them attractive are:

- direct coupling to prime power source,
- high energy density,
- impedance matching and pulse shaping with load,
- suitable for rapid, multi-shot operation, and
- low cost.

It should also be noted that when very high voltages or short pulse widths are required, a rotating machine can be used as the first stage in a pulse-forming network.

Future trends at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) include improving energy density, power density, and shaping current and voltage waveforms as required for specific applications. By improving energy and power density, a low weight machine for a given application would be realized, which is important for field portability. Pulse shaping is needed to give rotating machines the flexibility required to more efficiently drive loads as diverse as railguns or tokomaks which require a flat topped current pulse, flash lamps which require a short peaked pulse, or coaxial induction accelerators which require a series of pulses at a rising frequency.

Technical Discussion

Figure 1 shows the parameters with which a machine designer has to work and how they interrelate. By utilizing lower density materials, weight of stationary components and stress in rotating components is reduced. Increased rotational speed proportionally increases voltage and energy increases with the speed squared. One must design current collectors for higher speeds and armature windings for higher power levels to take advantage of the increased energy and power.

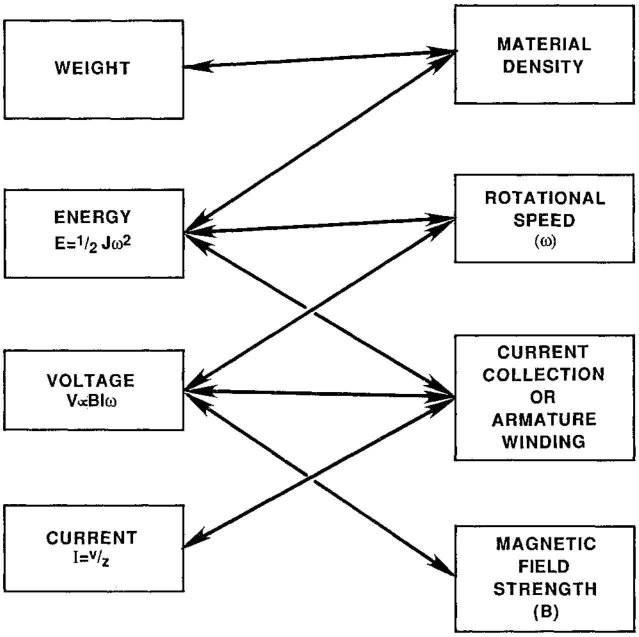

Figure 1. Rotating machine parameters

Most of the machines made to date at CEM-UT have a magnetic circuit made of steel, which is a ferromagnetic material. These machines are currently operating at or near peak performance levels for these materials. One of the ways to increase energy and power densities is through the development of air-core generators. An air-core generator is one in which ferromagnetic material (steel) is not used for energy storage or as a magnetic flux path. The steel is replaced with epoxy impregnated graphite, glass, or boron fibers. There are several advantages to the use of such materials. Through a combination of higher strength and lower density, composite flywheels or rotors can be operated at a much higher tip speed. Although the production of excitation flux is more difficult, the machine is not limited by the magnetic saturation limit of steel. Table 1 compares typical operating parameters of composite and ferromagnetic materials.

The effect of these factors is illustrated quantitatively:

$$\text{Power Density (PD)} = \frac{VI}{W} = \frac{V^2}{ZW}$$

where

V = peak voltage
I = peak current
Z = total circuit impedance
W = weight

and

$$V \propto B\ell\omega$$

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where

B = average flux density
ℓ = total active conductor length
ω = rotational speed.

Therefore, the power density is

$$PD \propto \frac{(B\ell\omega)^2}{ZW}.$$

Using parameters shown in table 1 as an example,

$$B_{air} = 2\ B_{steel}$$
$$\omega_{air} = 3\ \omega_{steel}$$
$$W_{air} = 1/3\ W_{steel}$$

$$PD_{air} = 108\ PD_{steel}$$

$$\text{Energy Density (ED)} = \frac{1/2 J\omega^2}{W}$$

where

J = rotor moment of inertia.

Since J is proportional to density

$$J_{air} = 1/3\ J_{steel}.$$

Substituting parameters yields

$$ED_{air} = 9\ ED_{steel}.$$

Table 1. Composite vs. ferromagnetic materials

PARAMETER	COMPOSITE MATERIALS	FERROMAGNETIC MATERIALS
Rotational Speed (ω)	1,200 m/s	400 m/s
Field Strength (B)	4 T	2 T
Density (ρ)	0.1 lb/in.^{3}	0.3 lb/in.^{3}
Permeability (μ_R)	1	40 (at 2.0 T)

These calculations show two orders of magnitude increase in power density and one order of magnitude increase in energy density. However, they do not include the effects of going to a nonferromagnetic magnetic circuit. Table 1 shows the permeability (μ) of air to be 1/40 the permeability of steel at 2.0 T. Therefore, to excite an air-core machine, either a very large field excitation power supply, a superconducting magnet, or a self-excited machine configuration is needed. All of these options decrease the gains in energy and power density achieved with the composite materials. It should be noted that the advancements being made in high temperature superconductors could resolve the issue of how to excite an air-core generator.

Machine Concepts

Self-Excited, Air-Core Homopolar Generator

Figure 2 is a cross section of a self-excited air-core homopolar generator (SEAC HPG). This machine has a composite flywheel with a 1,200 m/s rotor tip speed which stores 1.2 GJ of energy.

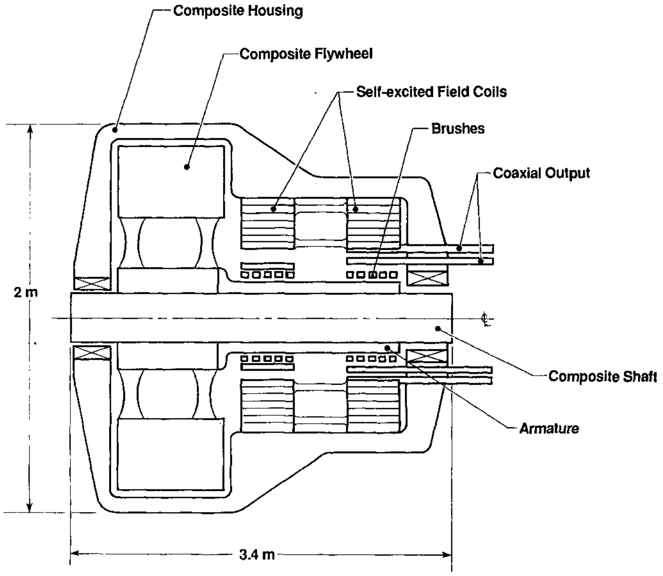
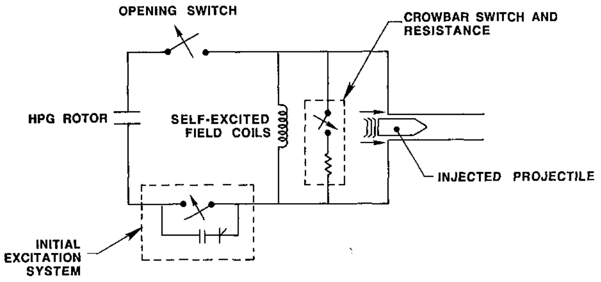


Figure 2. Self-excited, air-core homopolar generator

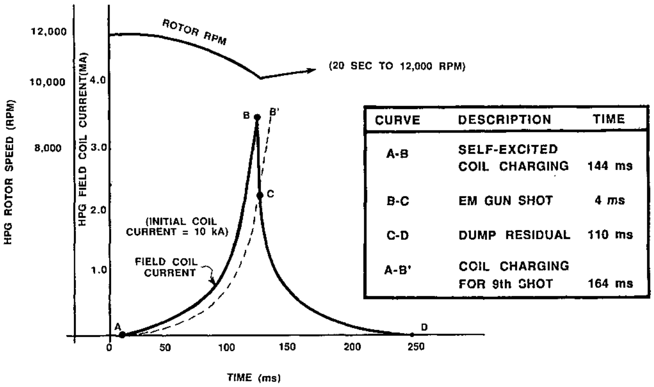
Figures 3 and 4 show the circuit diagram and predicted performance of the SEAC HPG driving an EM railgun. After the rotor is at speed, an initial excitation system is used to produce a small magnetic field in the machine. The machine then "bootstraps" its way to a very high magnetic field (≈ 5 T) by converting energy in the flywheel into magnetic energy. Because the composite materials are nonconductive, there is very little trapped magnetic flux in the machine; therefore the self-excited field coils can be used as an inductor to power the railgun via a high current opening switch.

As shown in figure 3, when the opening switch is actuated, current is commutated into the railgun which has been simultaneously closed into the circuit via the injected projectile armature. The opening switch can be actuated at any time. This stops current flow through the HPG current collectors allowing one to transfer any predetermined amount of stored rotor energy into the inductor rather than requiring all of the energy in the rotor to be transferred as is typical. Since the HPG current collectors are no longer carrying current, they can be lifted clear of the rotor slip ring, allowing the rotor to freewheel or be remotored. Single-shot operation and burst modes are still possible but now intermediate firing frequencies are an alternative. Figure 5 shows the substantial increase in energy density gained by implementing the SEAC HPG concept.



CIRCUIT DIAGRAM

Figure 3. SEAC HPG driven gun system--circuit diagram



CURVE	DESCRIPTION	TIME
A-B	SELF-EXCITED COIL CHARGING	144 ms
B-C	EM GUN SHOT	4 ms
C-D	DUMP RESIDUAL	110 ms
A-B'	COIL CHARGING FOR 9th SHOT	164 ms

PREDICTED PERFORMANCE

Figure 4. SEAC HPG driven gun system--predicted performance

To make the SEAC HPG successful, substantial component development is required. High speed, composite flywheels with thick cross sections and bearings and brushes at high slip speeds operating in high fields must be developed. Martin Marietta Energy Systems Inc., Enrichment Technology Application Center (ETAC) has demonstrated the feasibility of operating composite flywheels at tip speeds over 1,200 m/s as shown in figure 6. The issues at this point are focused on how to build composite flywheels with cross sections as thick as 30 cm. The high voltage homopolar generator (HVHPG)[1], shown in figure 7, is providing valuable insight into the operation of rotating machine components in very high (5 T) magnetic fields. For example, the thrust bearing runner in the machine was a ceramic disk because it would have developed nearly 12 V across bearing lands if it had been conductive. The machine also had to be electrically self-motored because neither hydraulic, electric, or turbine drives could be operated in the ambient field. Finally, during initial tests of the machine, both the inner and outer current collectors (brushes) in the armature circuit experienced difficulties. $\overline{J} \times \overline{B}$ forces of about 400 N/brush at 500 kA are such that the inner brushes lift and the outer brushes are pressed down very hard. Some arcing occurred under the inner brushes and some brush straps on the outer brushes were bent. These issues are currently being addressed and the machine is scheduled for the second round testing in December 1987.

To develop very high speed (300 m/s) current collectors, a 400 m/s brush test facility [2], basically a small HPG with a 20,000 rpm rotor is being built. This machine will be used to test brushes operating in both continuous and pulsed modes. Several brush concepts show potential for improved performance over the commercially available sintered copper-graphite brushes which are now being used. Commercially available copper-graphite brushes used low melting temperature materials (lead and tin) as a binder. At high performance levels, these binders melt and copper and graphite very rapidly abrade in the form of dust. Therefore, one of the concepts being pursued is to sinter copper and graphite with no binders. Initial tests have been completed and the new high temperature brushes showed very low wear at a comparable current density (1,500 A/cm^2) and voltage drop (1.0 V) to the industry standard. However, the tests to date have been limited to a tip speed of 160 m/s.

Another concept for high speed, continuous duty brushes involves actively cooling the brush/slip ring interface with a liquid or a gas. Since most of the heat is generated at the interface through friction and voltage drop, the problem is directly addressed by injecting a coolant into the interface. Experiments have shown that when water is used, the thermal input causes a phase transformation which absorbs the thermal energy and very effectively cools the brush. Figure 8 shows several prototype brushes. Once again these brushes have only been tested to 160 m/s slip speeds. After the high speed brush tester is completed in July 1987, both of these brush concepts will be tested at higher speeds to determine performance limits.

Air-Core Compulsators

Two issues are involved with future trends in compulsator technology. These are: 1) the implementation of composite materials which present issues similar to those on the SEAC HPG, and 2) different configurations and orientations of armature and excitation windings to perform pulse shaping.

Figure 9 is the cross section of a new air-core compulsator being built to power a multi-shot railgun. It is being designed to produce a 32 MJ pulse every 20 s continuously and is therefore actively cooled. Initial tests are scheduled for mid-1989 and thus this machine will be a focus of attention at CEM-UT for the next two years.

Figure 10 is a photograph of a 1.3 MJ per pulse iron-core compulsator [3] which is currently being assembled for testing in August 1987. This machine is uncooled and is therefore limited to 10 sequential pulses before it must be passively cooled. However, it will be tested at the much higher firing rate of 20 Hz. Each pulse has a peak voltage of 2,000 V and a peak current of 950 kA with a pulse width of approximately 2 ms.

Table 2 compares these two machines. Referring to the earlier calculations which showed two orders of magnitude increase in power density and one order of

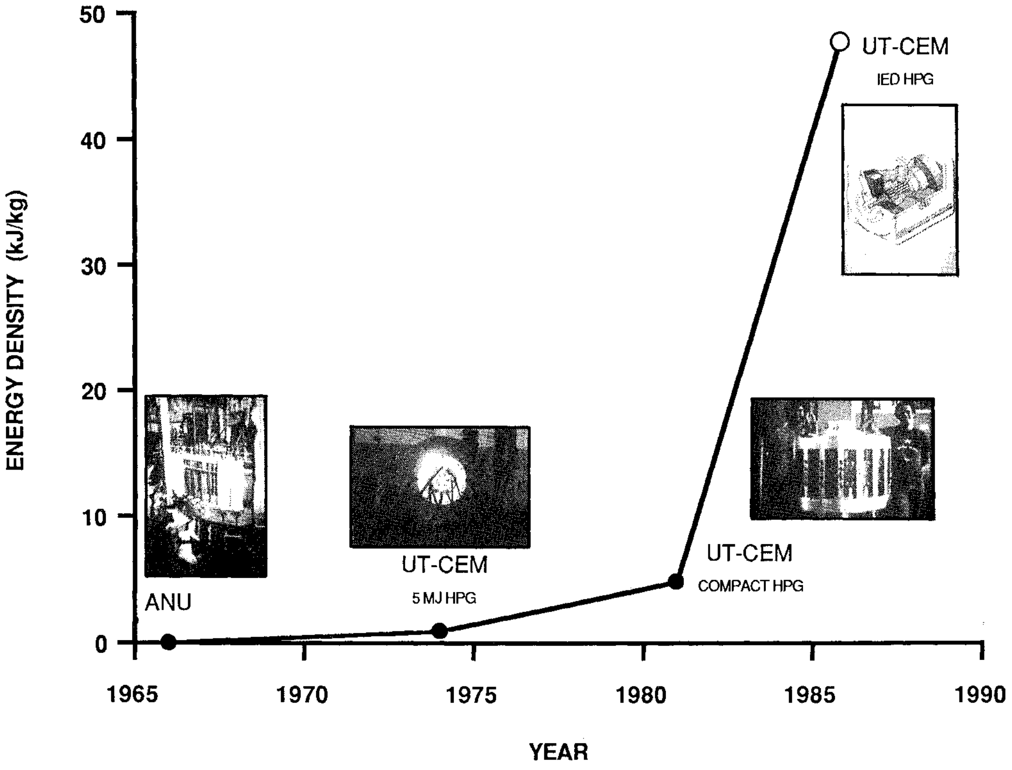


Figure 5. Homopolar generator energy density

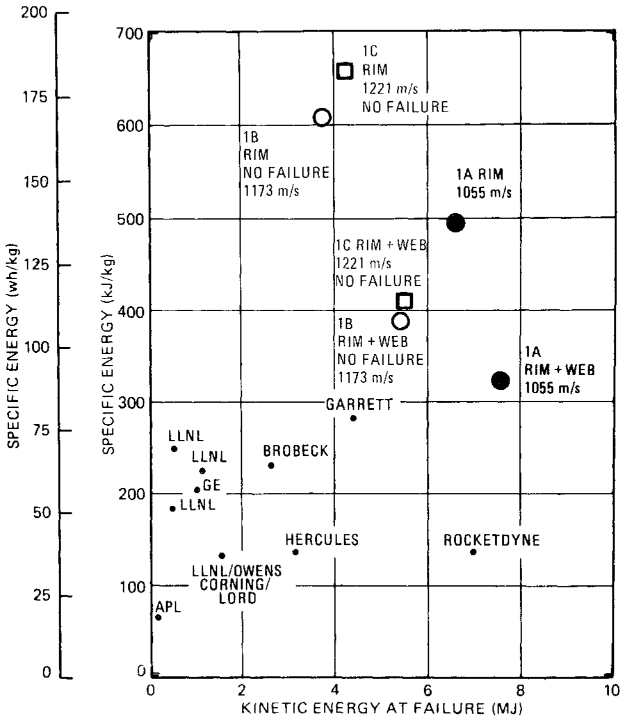


Figure 6. Composite flywheel technology

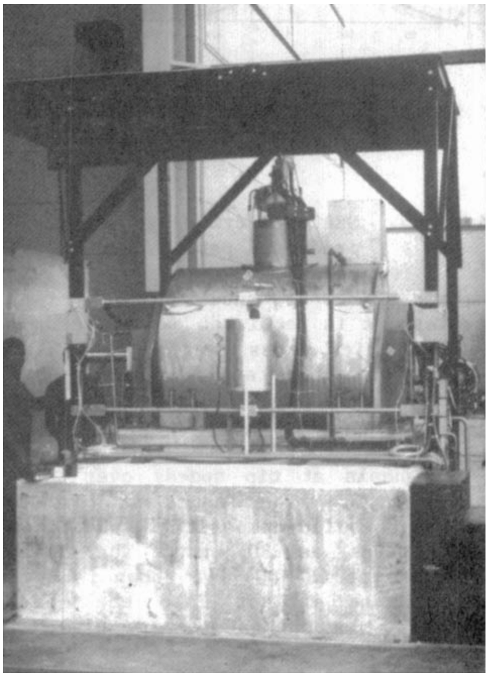


Figure 7. High voltage homopolar generator with super conducting excitation

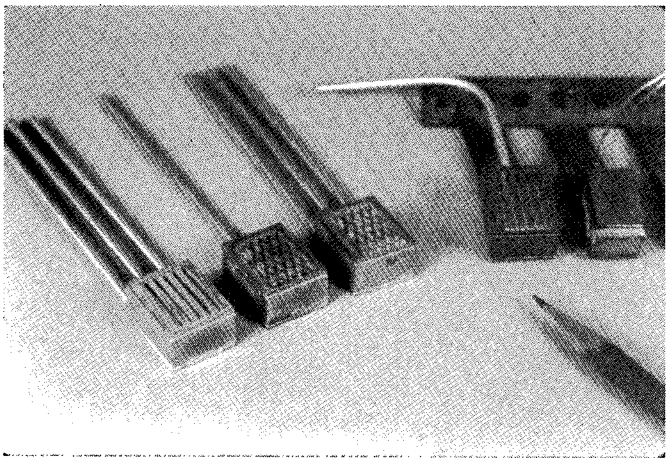


Figure 8. Actively cooled current collectors

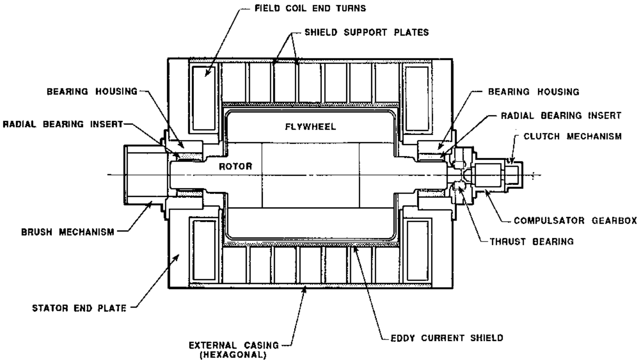


Figure 9. Cross section of 32 MJ/pulse, air core compulsator

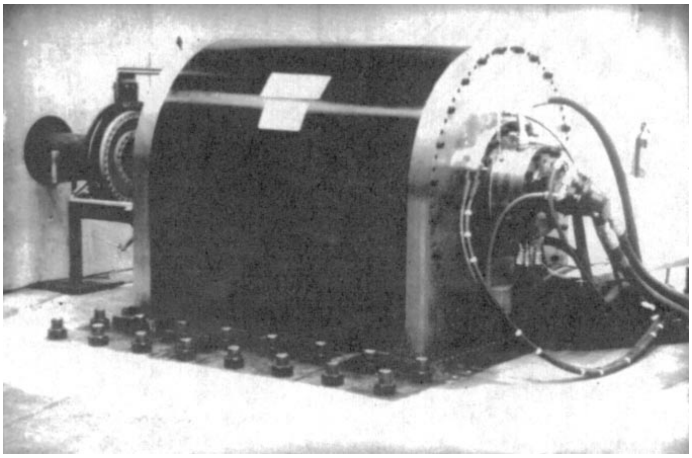


Figure 10. 1.3 MJ/pulse, iron core compulsator

magnitude increase in energy density, one can see the result of actual machine designs. Power density went up by a factor of twenty and stored energy density by a factor of 4.6. Delivered energy density went up by a factor of 30. There are two reasons that the power density and stored energy density did not meet theoretical predictions. First, the mass of the field coil had to be increased to provide a low resistance for self-excitation. Second, the air-core compulsator rotor is rotating at 600 m/s, not 1,200 m/s. This is a result of stiffness and strength limitations of the materials used as a banding over the armature windings and the desired pulse width. New composite materials are being developed which will allow future machines to operate at higher tip speeds.

Table 2. Air-core vs iron-core compulsator parameters

PARAMETER	AIR-CORE (COMPOSITE) COMPULSATOR (10 pulses)	IRON-CORE COMPULSATOR (10 pulses)
Mass	10,200 kg	11,000 kg
Power	35.7 GW	1.9 GW
Energy Stored	166 MJ	38 MJ
Energy Per Pulse	32 MJ	1.3 MJ
Power Density	3.5 MW/kg	0.17 MW/kg
Energy Density		
Stored	16 kJ/kg	3.45 kJ/kg
Delivered	3.1 kJ/kg	0.1 kJ/kg

Pulse Shaping

The basic principles of pulse shaping are made possible by varying inductance in an actively compensated machine and are as follows:

- change of inductance with active compensation,
- alignment of magnetic field axis and compensating winding, and
- shaped magnetic field through harmonic addition of field flux.

Figure 11 shows various pulse shapes that can be obtained from the same machine by varying the armature winding configuration, orientation of the magnetic field axis to the magnetic poled centerline and the time at which the pulse is initiated.

Figure 12 is the cross section of a two-pole compulsator designed to produce the flat pulse needed to produce optimum acceleration of a projectile in a railgun. Note the 57° misalignment of the armature winding with respect to the field coils.

As the armature winding rotates, the inductance between the armature and compensating windings and therefore the flux linking the compensating winding changes with rotor position. The variation of the inductance is more or less sinusoidal with angular position. The inductance is minimum when the magnetic axes of the armature and compensating windings are aligned as shown in figure 13. In this position, the flux produced by the armature winding is confined in the gap between the two windings because of the current in the compensating winding. When the magnetic axes of the two windings are perpendicular to each

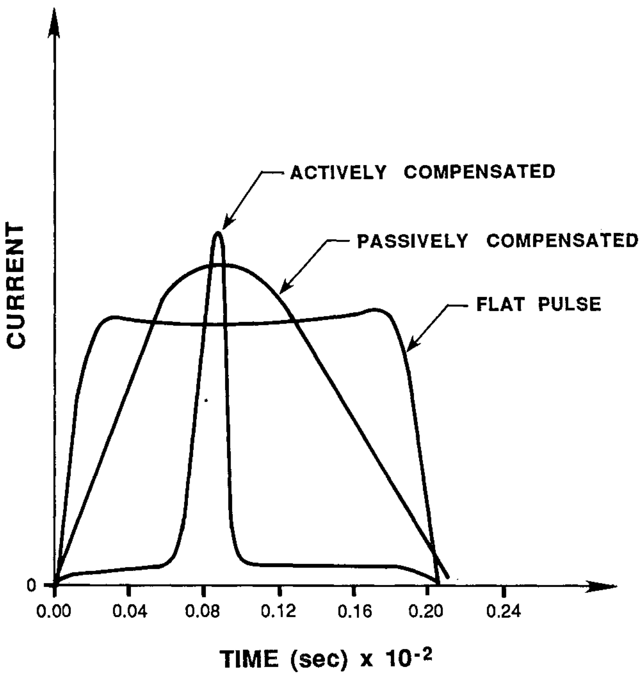


Figure 11. Characteristic compulsator pulse shapes

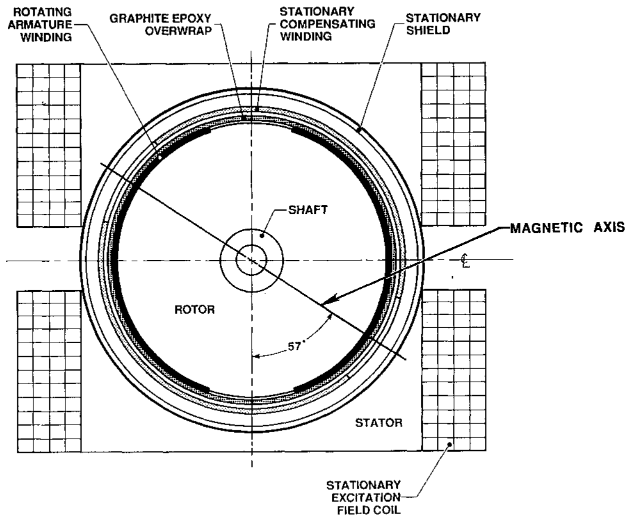


Figure 12. Cross section of a flat-pulse compulsator

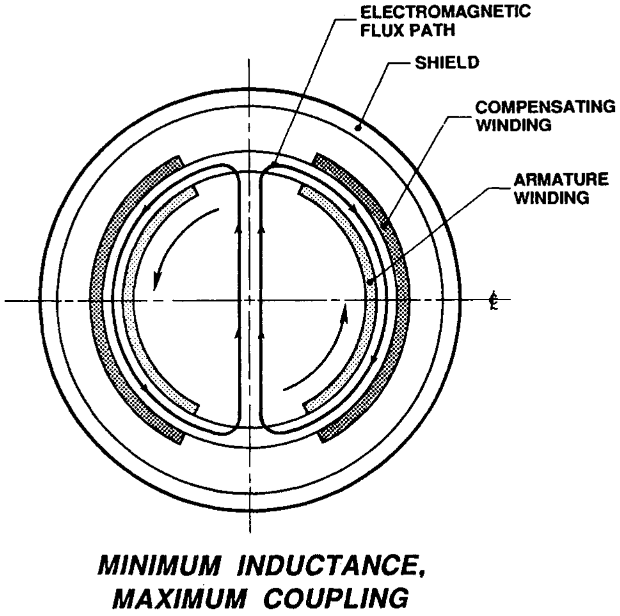


Figure 13. Compulsator rotor position for minimum inductance, maximum coupling

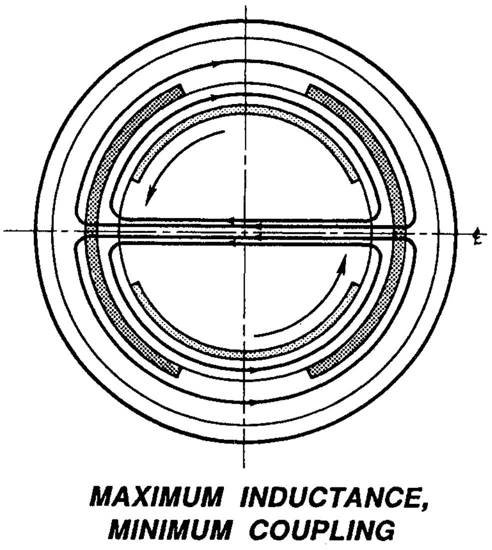


Figure 14. Compulsator rotor position for maximum inductance, minimum coupling

other as shown in figure 14, the inductance of the armature winding is maximum. In this position, the current in the compensating winding is zero.

To obtain a flat pulse, the current pulse is initiated when the inductance between the two windings is approaching but has not yet reached the minimum value. Since the inductance of the armature winding is low in this position, the current in the armature winding rises rapidly. As the rotor continues to spin, the inductance starts to increase. At the same time, the induced voltage is increasing due to the magnetic field being skewed 57° with respect to the magnetic pole. These factors compensate each other, thus leveling the current. Towards the end of the pulse, the armature inductance decreases which tends to increase the current. This is compensated by the increasing load impedance as the projectile is accelerated in the railgun. Since these effects counter each other, the decrease in induced voltage rapidly drives the current to zero reclaiming residual magnetic energy in the circuit. Having the projectile exit at or near current zero also eliminates the muzzle arc.

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- U.S. Army Armament Research, Development, and Engineering Center (ARDEC)
- Wright Patterson Air Force Base (WPAFB)

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[1] J. H. Price and J. H. Gully, "The High Voltage Homopolar Generator," IEEE Transactions on Magnetics, November 1986, Vol. MAG-22, Number 6, pp. 1690-1694.

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