COMPULSATOR RESEARCH AT THE UNIVERSITY OF TEXAS AT AUSTIN--AN OVERVIEW

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Abstract: The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has been developing specialized pulsed power supplies and exploring the unique applications available with these high power devices for many years. The compensated pulsed alternator (compulsator) was invented[1] at CEM-UT and appears to have tremendous potential as a power supply for a variety of fields including fusion, industrial applications, directed energy weapons, low frequency sound sources, and electromagnetic launch (EML) technology. Several machines have been built and tested, successfully demonstrating the principal of operation. They have also verified the premise which prompted their development; that a compact rotating machine, operating at high efficiency, can provide a series of appropriate high current pulses without the necessity of complicated conditioning and switching networks. This paper is intended to provide an overview of research in the field including a brief history of the device, electromagnetic and mechanical design considerations, status of machines currently in operation and under development, and future technology.

Introduction

The compulsator is a specialized alternator in which primary consideration has been given to maximizing the power generating and current carrying capability of the machine. Several techniques are employed to reduce the internal impedance of the device and increase its terminal voltage, while innovative mechanical design allows the machines to survive the extremely high forces imposed during the discharge.

The compulsator is a power supply which spans the gap between capacitors and homopolar generators (HPG's), overcoming each of their weaknesses in terms of use with mobile multi-shot EML's. The capacitor, which has served as the workhorse for most laboratory-based experiments, is less desirable for mobile platforms because of its relatively low energy density. The highest energy density of commercially available, state-of-the-art capacitors is 0.34 kJ/kg,[2] while industrially supplied rotating machines have demonstrated 4.19.[3] Also, some question has been raised as to the ability to cool the newer designs as required for rapid-fire operation. Finally, these capacitors achieve improvements in energy density by operating at extremely high voltages. Voltages above a few kilovolts are not required, nor are they desirable for most EML applications.

The homopolar generator, on the other hand, can supply very high currents and has an excellent energy density, but due to its lack of power, it necessitates a complicated conditioning circuit. In spite of considerable effort in the pulsed power industry, it does not appear that a multi-shot opening switch capable of commutating currents in the several megampere level is forthcoming. However, even if a dramatic breakthrough in opening switch technology is made, or if the problems associated with capacitors are overcome, the compulsator has several advantages over these supplies.

The compulsator falls into the area of acceptability in terms of energy density and delivered power for EML's of tactical interest. The compulsator has the advantage of providing single-element power conversion. This greatly simplifies the power train by eliminating the energy storage inductor and opening switch of the HPG system, and the charging alternator, diodes, conditioning inductors, and switches of the capacitor driven system. With the compulsator, shaft power from the prime mover is supplied, and the gun is driven without any intermediate conditioning devices.

The capacitor and the HPG provide an exponentially decaying current, but are typically sized to maintain a relatively flat current pulse for the time of interest. This results in reasonable gun lengths and peak projectile accelerations, but implies that a considerable amount of energy remains in the circuit at the time the projectile exits the gun. The remaining energy, which is roughly equivalent to the projectile energy, is impractical to recover. Ringing circuits, which would provide a means of energy recovery, are not compatible with most HPG or capacitor systems. Typically, in order to avoid a damaging muzzle arc, a crowbar switch is closed and the remaining circuit energy is dissipated resistively. This fact, along with the charging losses associated with the required conditioning devices, leads to relatively low operating efficiencies.

In the compulsator, an alternating voltage drives the current pulse to a naturally occuring current zero. The compulsator is designed to provide a pulse width such that the current zero coincides with the projectile exit. This eliminates the muzzle arc without the need of a crowbar switch, and since there is no magnetic energy trapped in the discharge circuit, leads to high efficiency. Also, since only a small fraction of the stored energy is dissipated each shot, the system can deliver a burst of shots at a very high repetition rate, and the prime mover operates at a high efficiency since it is supplying energy in a relatively narrow speed range.

In summary, the compulsator appears to be the power supply of choice for most EML applications in which weight, volume, and efficiency are of concern. Experiments at CEM-UT have demonstrated that the machine can perform as described, and with recent advances in pulse shaping techniques, and the incorporation of composite materials, the next generation of machines will be approaching the needs of a fieldable EM weapon system.

Principal of Operation

As in a conventional alternator, voltage is produced by the relative motion of a multi-pole armature and field. Higher voltage can be generated by increasing the excitation field strength, the relative speed of the two components, or by increasing the length of the armature. The tip speed of the rotor is generally limited by material strength, or dynamic issues. Field strength is dependent on the saturation level of ferromagnetic materials, or by the allowable current density of the excitation conductors. The third alternative is practically achieved by using a multi-turn winding, however since internal impedance increases with the square of the number of turns, a gain in output current is not necessarily achieved.

Compensation

The main difference between compulsators and conventional alternators is achieved through the use of compensation. This term refers to a method of reducing armature inductance through compensating currents which limit the volume occupied by the armature-produced fields. To optimize the effect, currents of equal magnitude and opposite sense flow in a conductor which is located physically close to the armature. The total magnetic flux produced by the armature is reduced, and the fields are contained between the armature and the compensating conductors. A very common example of compensation is provided by the coaxial cable in which the inductance is a function of the ratio of the radii of the two conductors.

A compulsator is similar to a coaxial cable in that opposing currents flow on the outer surface of the rotor, and the inner surface of the stator bore. To lower inductance, the magnetic air gap between the opposing currents and the thickness of the conductors are minimized. However, compensation can be provided by a variety of methods, and since the compulsator is a multi-pole machine, the degree of compensation depends on the relative alignment of the armature and compensating poles. In some types of machines, this results in an inductance which varies with rotor position. Manipulation of the inductance variation is the primary method of achieving a desired pulse shape and increasing power through flux compression. Compensation is also useful in limiting armature reaction in ferromagnetic machines, and protecting the excitation winding from armature-discharge-induced transients. Three basic methods of providing compensation have been explored.

Passive compensation is achieved when the compensating currents are induced in response to the transient armature fields produced during the discharge. The simplest form of this machine involves the use of a continuous conductive shield (fig. 1a). During a discharge, equal and opposite currents are induced in the shield. 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.

Compensation can also be provided by a second winding which is connected in series with the armature (fig. 1b). This method, referred to as active compensation, forces the compensating current to flow in a defined sense. When the armature and compensating poles are aligned and the currents are 180° out of phase, a low inductance (roughly equivalent to the passive case) is achieved. However, as the rotor moves to a position in which the two currents are in phase, a high inductance results. The inductance variation is sinusoidal in nature, and compression ratios (defined as L_{max}/L_{min}) as high as 46 have been measured in a relatively small device. The active machine generates a narrow pulse of very high peak power. Power is enhanced in this device since an additional voltage related to the changing inductance (or the compression of flux) is generated under load.

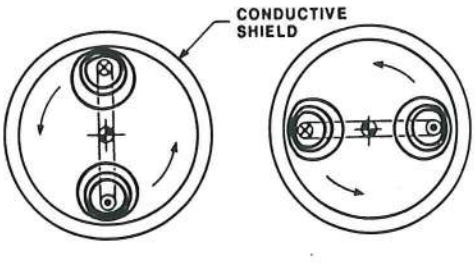

Figure 1a. Passive compensation

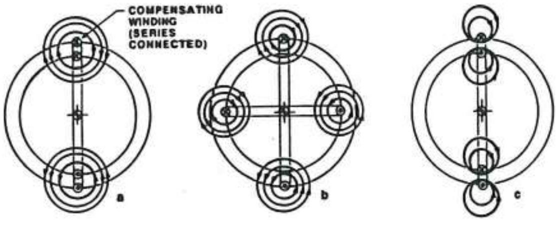

Figure 1b. Active compensation

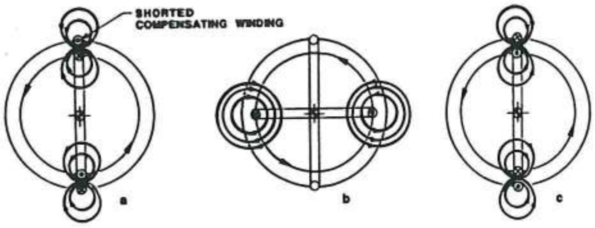

Figure 1c. Selectively passive compensation

Figure 1. Compensation methods

Another form of compensation, which results in a square pulse shape, is being explored for EML applications (fig. 1c). This technique is dubbed selectively passive compensation, since the currents are induced, but compensation is not provided equally in all rotor positions. The technique can be employed in several ways, including non-uniform shielding or the use of a shorted compensating winding. Either method results in an inductance which is dependent on rotor position. However, the compensating current is never in phase with the armature current and the compression ratio is considerably less than in the active machine. Also, the frequency of the inductance variation is twice that of the machine electrical frequency. This machine is extremely difficult to analyze since there are many variables related to the type of compensating winding, the orientation of the winding with respect to the excitation field, and the phase angle with respect to the open circuit voltage in which the pulse is initiated.

Inductance variation and typical current pulses are presented for the three types of machines in figure 2. The active machine uses inductance variation to increase power and decrease pulse width. The selectively passive machine uses inductance variation to produce a square shaped pulse, at the expense of peak power. The passive design has an inductance which is constant at the lower value. This machine, which is the simplest to analyze and fabricate, produces a sinusoidal shaped pulse of an intermediate peak power. A comprehensive discussion of pulse shaping techniques is available in the publications of Driga [4, 5] and Pratap [6, 7].

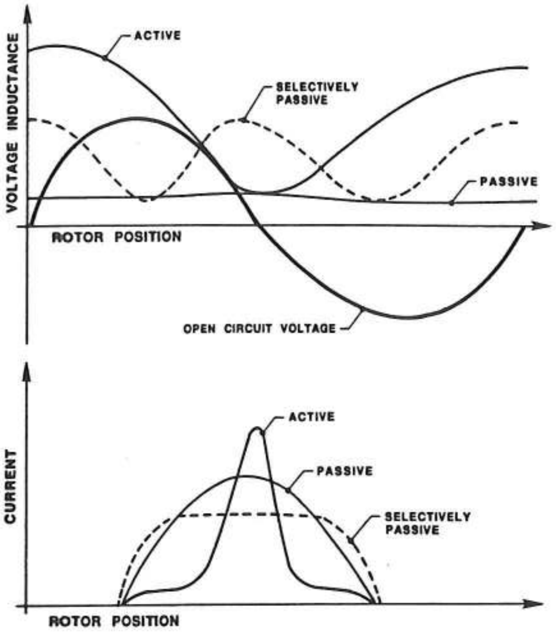

Figure 2. Inductance variation and current waveshapes

Air-Gap Windings

Another method of improving performance is through the use of air-gap windings [8]. The air-gap winding is attached to the smooth surface of the rotor or stator rather than being imbedded in slots as in conventional machines. The air-gap winding accomplishes two beneficial effects: the inductance of the armature winding is reduced considerably, and higher voltages can be generated.

The inductance of the air-gap winding is lower than a winding imbedded in slots because it is radially thinner. The cross-sectional area of the conductor is dictated by thermal considerations and is therefore constant for a given performance. When the conductor occupies only a small fraction of the pole pitch, as in the slotted winding, it necessarily has a larger radial depth. This implies that the effective separation distance between the armature and the compensating winding or shield is larger, and more total flux is produced, resulting in a higher inductance.

Higher voltages can also be generated with an air-gap winding. In the ferromagnetic case, all of the excitation flux must pass through the teeth located between the armature slots. The amount of flux which can be produced prior to saturation of the teeth is therefore reduced by the percentage of the area occupied by the slots. Once saturation of the tooth occurs, the effective air-gap is increased by the depth of the slot, and further increases in flux are extremely costly in terms of excitation power. The conclusion of this argument is that at relatively low performance levels in which the teeth are not saturated, the slotted armature operates at a high efficiency. However, the air-gap winding performs better in this respect at high average flux densities since its radial depth is less than the slotted winding. Higher voltages are also possible in the air-core geometry because the winding is physically closer to the field coil and therefore has a better coupling, although this effect is much less dramatic than the saturation argument which applies in the ferromagnetic case.

The main drawback to the use of air-gap windings is the difficulty of mechanically supporting the conductors in the face of high azimuthal discharge forces and, in the case of a rotating winding, centrifugal loads.

Air-Core Machines

One of the latest and most exciting technologies to be incorporated into rotating pulsed power supplies is the use of non-ferromagnetic materials (most notably fiber-reinforced epoxy composites) as an energy storage medium and for structural containment [9]. These machines are referred to as air-core machines since the magnetic permeability of the material is approximately that of air. The advantage of composites lie in their high strength-to-density ratio and modulus of elasticity, which allows composite rotors to be operated at extremely high tip speeds. Conservatively, a factor of three increase in operating speed is obtainable through the use of composites, which results in increased energy and power densities. The disadvantage of the concept is the difficulty of establishing the excitation field. For most applications, a cryogenic or superconducting field coil is necessary to produce an acceptable operating efficiency.

Machine Topology

There are many topological variations of the machine which may be considered, each of which has several advantages and disadvantages. The differences result from the type of excitation winding, the type of compensation, and the choice of rotating component. The basic components of the machine are: the excitation winding, the armature winding, the compensating winding or shield, the rotor, the stator, the bearings, and the brush mechanism. Generally speaking, the excitation windings are more massive and more likely to require cooling than the armature, and the excitation winding and the compensation winding or shield must have zero relative velocity.

The rotating field machine is generally preferred over the rotating armature when passive compensation is being employed. For this machine, the duty of the brush mechanism is drastically reduced, and, since the field is moving with respect to ground, shielding stray fields is relatively simple. In the ferromagnetic configuration, the stator is laminated and the rotor can be a solid steel forging, allowing the machine to operate at significantly higher tip speeds. The stationary armature winding is much easier to support, and it can sustain a higher discharge torque (one of the primary limitations on the power of the device). It is also less prone to turn-to-turn insulation or mechanical failures related to relative motion of the conductors and fatigue. Since banding is not required to contain the fragile armature winding, the effective gap between the armature and the compensating shield may be considerably less than in the case of the rotating armature. This results in lower inductance and higher peak currents. Unfortunately, for many designs the field coil is extremely massive or requires a cryogenic coolant, and must occupy the stationary position. This is generally true of the air-core machines.

If active compensation is required, many of these advantages do not apply and the rotating armature is the geometry of choice. Since the compensation winding is connected in series with the armature, a high current brush mechanism is mandatory, regardless of the component actually rotating. In this case, a rotating field arrangement would need two separate brush mechanisms, the second one supplying excitation current. Also, to achieve a high compression ratio, both the rotor and stator must be laminated if ferromagnetic materials are used.

Having discussed the arrangement of the windings, one now turns to the issue of the location of the rotor. In the traditional arrangement, the rotor occupies the central volume of the machine, and the outer component is stationary. While there must be relative motion between the components to produce a voltage, this layout is not a requirement, in fact, there are several advantages to the alternatives.

In the first of these, the outer segment of the machine rotates while the inner portion is stationary. It is immediately obvious that this geometry has a potentially higher energy density than the inside-rotor machine. This is a natural choice for the rotating armature, and therefore for an air-core machine, since the rotor structure provides support for the winding, and the bond between the armature and the rotor is always in compression. Also, it is apparent that the machine operates at a lower frequency than a comparably sized inside-rotor machine operating at the same tip speed. This has positive and negative connotations. The lower frequency machine will generate less voltage, and therefore less power, but has a longer pulse width and can potentially deliver more energy per pulse. For many EML applications, the question is not one of providing adequate power, but of providing a sufficiently long pulse width with a machine of reasonable size and energy density.

Unfortunately, there are several practical concerns which make this geometry difficult to implement. Mechanically, the rotor is more difficult to support and to couple to the prime power system. Also there is an issue of rotor containment. Since there is no structure external to the rotor, serious safety concerns present themselves in the event of a rotor failure.

The second alternative machine discussed is the counter-rotating version. This geometry potentially has the highest energy density, voltage generation, and peak power. Another distinct advantage is that the machine is reactionless with respect to ground, implying that no discharge torque is transmitted to the mounting platform. The implementation of this concept, however, is extremely difficult. All of the concerns expressed with the outside-rotor machine apply. In addition, two sets of difficult bearings and brush mechanisms are required. The pulse widths and power levels generated by these machines are generally not compatible with the EML requirements of today, but the concept is worth consideration for EML's of the future, in particular for space-based systems where platform stability is an important issue. It also has potential for use with directed energy weapons (DEW's) and other systems requiring very fast pulses.

Mechanical Considerations

Mechanical issues which must be addressed in the design of any compulsator may be broken into basic categories: rotationally induced forces and losses, discharge related forces, and thermal issues. As energy and power densities of the devices increase, the difficulty of addressing these issues has also become more complicated, and the incorporation of composite materials has introduced a new set of concerns related to their non-isotropic properties.

It is generally desirable to operate rotating machinery in a subcritical mode to avoid the increased vibration and stresses associated with the transition through a critical frequency. This is particularly true of pulsed power equipment since it is required to motor to speed from rest, and hence through any criticals, many times in the course of its useful life. Also, by its nature, pulsed power machinery is much more highly stressed, and is constructed with high tolerances and close fits in order to maximize performance, and therefore is more susceptible to damage from vibration. There is a significant cost associated with this goal in terms of machine weight, size, and efficiency, however. The size, type, and location of the bearings, the allowable length-to-diameter ratio of the rotor, size of the shaft, size of the end plates and their mount, choice of materials, and the allowable tip speed are all greatly influenced by this decision. Many of these components are larger and heavier than required from stress considerations. There is an increasing possibility that composite machines will operate in a supercritical mode to further increase their performance-to-weight ratio. Composite materials have a very high damping coefficient, greatly reducing the peak oscillations which would be experienced in the transition through a critical frequency.

Spin stress considerations are also an important design influence, particularly stresses associated with the support of the conductor. There is always a conducting component on the rotor. This would be the field coil and compensating shield or winding in the rotating field case, or the armature winding. The support of these components against stresses due to spinning at high speeds and discharge forces is a prime concern in the mechanical design of the system. The armature and compensating windings are composed of finely stranded copper or aluminum wire and have very little inherent structural strength. They are therefore supported by a high strength banding. The banding is generally the highest stressed material in the machine. Since its thickness directly influences the armature inductance, it is made as thin as possible.

One other issue which greatly influences the design, particularly in the choice of materials, is the control of unwanted induced currents. In the case of the rotating armature machine, every conducting material on the rotor will experience eddy currents when the field is energized. To control the magnitude of the currents, the conducting materials are laminated in the axial direction. This can cause considerable structural difficulties. In the case of the air-core generators currently being designed, it was discovered that most forms of graphite-epoxy composite cannot be used in large volumes because of its slight transverse conductivity.[10] This led to the choice of s-glass, a lower strength and stiffness material, for the construction of the rotor. It also requires that the area where graphite is absolutely necessary, in the armature banding, be laminated. It is hoped that with an improvement in surface coating or fabrication technique, the transverse conductivity of this material can be reduced to an acceptable level.

Discharge-induced forces can reach tremendously high values, particularly in the case of air-core machines. These forces are generated in both the rotor and stator conductors and must be transmitted through an epoxy bond to the structure of the machine. In general, torques of several MN-m are generated. There is also a magnetic pressure between the armature and the compensating winding or shield due to the compression of flux. This pressure is partially beneficial in that it loads the epoxy bond in compression, greatly increasing its shear strength. The shear strength of the epoxy which encapsulates the winding and forms the electrical insulation system is one of the primary design limitations of the devices.

As with any high power device, cooling of critical components is an issue. In the case of the compulsator, the areas requiring attention are the field, armature and compensating windings, and bearings. The approach to date has been one of simplicity, to design the component with sufficient thermal inertia to survive a short high power burst. As the systems approach the point of fieldability, more attention to cooling is required. The compulsator being designed for the EM Gun Weapon System program is beginning to address this issue, and will approach a true steady state capability.

History and Status

Engineering and Prototype and the ARFC: During the 1970's Lawrence Livermore National Laboratory (LLNL) was developing a laser fusion facility and had a need for high power, short duration electrical pulses. In this concept, flashlamps are used as power amplifiers for a solid state laser. A network of lasers is focused upon a deuterium and tritium pellet, quickly compressing and heating the pellet to the point of fusion. The pellet is held in place through the process by inertial confinement. Lawrence Livermore National Laboratory had steadily increased the peak power of the device using capacitor banks as the primary source of pulsed power. However, it was realized that capacitors could not supply the series of repetitive pulses which was ultimately required. The compulsator was conceived and patented in 1978 in response to these needs and an engineering prototype was fabricated and tested to demonstrate the principle of operation [11].

Since extremely short pulses of very high power were desired, an actively compensated machine was chosen for development. The prototype, shown in figure 3, is a vertical shaft, rotating armature machine. It was designed to generate an open circuit voltage of 6 kV at a maximum speed of 5,400 rpm, and deliver approximately 70 kA, 600 μs pulses into a flashlamp load. At the design speed, the machine stores 3.4 MJ, and the single phase, four-pole winding operates at an open circuit frequency of 180 Hz.

As is inherent in the rotating armature concept, the rotor was laminated to prevent large eddy current losses when the field coil is excited. The design of a laminated rotor, with a length-to-diameter ratio of 3.2, which had sufficient stiffness to operate subcritically at 5,400 rpm, proved to be one of the more difficult aspects of the machine. The rotor was composed of 2,913 silicon steel laminations which were shrunk fit onto a 9.6 cm (3.8 in.) 4340 steel shaft. Because the shaft alone did not have sufficient stiffness for subcritical operation, the laminations were loaded in compression to increase their flexural modulus. An axial preload of 2.7 MN (600,000 lb) was maintained by two large titanium belleville washers. Several methods of insulation were tested to ensure sufficient interlaminar resistance was maintained under this load [12].

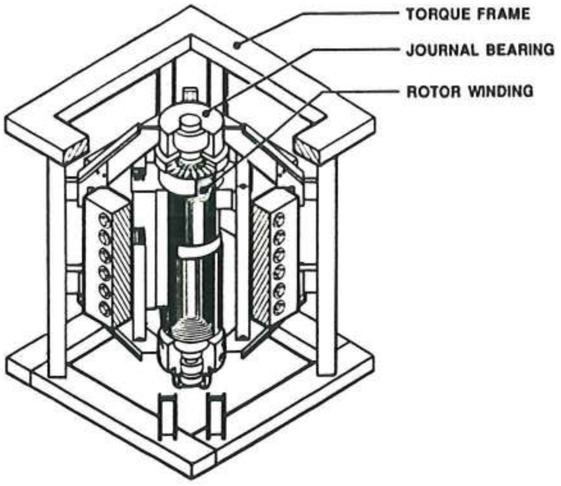

Figure 3. Prototype CPA

The prototype machine was discharged into the flashlamp load a total of 27 times, and successfully demonstrated the principle of operation. On the most successful run, from 4,800 rpm, the machine delivered 140 kJ to the load at a peak current of 30 kA and a pulsewidth of 1.3 ms.[13] On the first attempted discharge from full speed, a short circuit in the rotating armature developed. The armature insulation was composed of a fiberglass tape which had been preimpregnated with epoxy. This system had adequate mechanical and dielectric strength but left many voids in the insulation. It is theorized that due to these voids small relative motion of individual conductors occurred, wearing away the insulation and resulting in its ultimate failure.

Several valuable conclusions were drawn from the project. The concept of active compensation was successfully demonstrated as an inductance variation of 7:1 and pulse shapes as predicted were obtained. The inductance variation was considerably less than anticipated, however. This was attributed to eddy currents in the solid pole faces of the stator limiting the maximum inductance of the machine. While this effect was forseen, the degree to which the inductance would be altered was underestimated. Also, due to time and budget constraints, a laminated stator, which would solve the problem, could not be constructed. During the course of the project, a space harmonic method of numerical analysis was developed which agreed with the measured inductance values. Finally, it was concluded that the development of an improved insulation system was required if the concept was to proceed.

In order to develop new insulation techniques and prove that higher compression ratios were possible, the active rotary flux compressor (ARFC) was fabricated. To accomplish these goals within a modest budget, a relatively small device was designed. The ARFC has an overall diameter of 0.51 m (20 in.), a rotor diameter of 0.20 m (8 in.) and weighs approximately 450 kg (1,000 lb). The machine is an actively compensated, four pole device with a laminated stator and is similar to the larger compulsator in all respects but one. The ARFC does not have a field coil and does not generate an open circuit voltage. An initial current pulse is injected into the windings from a capacitor bank with the rotor in the high inductance position. As the machine rotates into the low inductance orientation, flux is compressed between the armature and compensating windings, resulting in a dramatic rise of current. The flux compressor can therefore be thought of as a current and power amplifier to be used in conjunction with a capacitor. The device produced an inductance variation of 46:1 and a gain of peak current by a factor of 8 in a resistive load [14]. Also, a technique of vacuum impregnating epoxy within a dry fiberglass and conductor matrix was developed. This process, which is still used today, resulted in a superior insulating and support system than was previously achieved with the pre-preg method. Finally, the tests were significant in that they provided a means to verify and further refine the numerical modeling techniques required for future development.

Rapid-Fire CPA

With the emergence of a serious EML program in the early 1980's it became apparent that compulsators designed specifically for this application were required. In 1983, the rapid-fire compulsator conceptual design was completed [15]. The finished machine is shown in figure 4. The rapid fire machine is a ferromagnetic, passively compensated configuration. Passive, rather than active compensation was chosen because the pulse shape it offered more closely fit the needs of an EML. Also, the passive machine is somewhat simplier in nature, and is easier and cheaper to construct. The basic parameters of the machine and EML are shown in table 1.

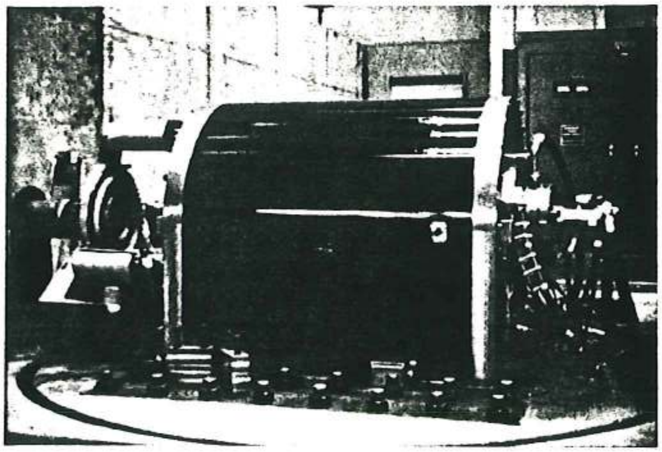

Figure 4. Rapid fire CPA

Table 1. EM compulsator driven gun systems--parameter comparison

	Rapid fire CPA	Task C CPA	Small Cal. CPA
Projectile Energy (kJ)	160	9,000	64
Velocity (km/s)	2,000	2,500 to 4,000	2,000
Rate of fire (rounds/min)	3,600	3	600
Voltage (kV)	2	8.0	3.6
Peak current (kA)	944	3,500	560
Stored energy (MJ)	38	250	13.5
Peak power (MW)	1,200	27,000	15,000
Compensation	passive	selectively passive	passive
CPA mass (kg)	11,000	12,500	1,000
Energy density (kJ/kg)	3.4	20	13.5
Power density (kW/kg)	109	2,160	1,580

The most difficult aspect of the machine design and fabrication involved the compensating shield. The shield serves several purposes. First, it must be an efficient electrical conductor in order to compensate the armature winding properly and produce an acceptable inductance. Also, it needed to be a high strength material, since a considerable tensile preload was required to prevent separation of the shield and rotor at speed due to spin growth. A 7050 T74 alloy aluminum was chosen. The shield was thermally assembled onto the rotor with a 1.042 mm (0.041 in.) radial interference. In addition to the interference fit, epoxy was introduced into the interface in order to help transmit the estimated 4.1 MN-m (3.0 Mft-lb) discharge torque.

The initial tests of the machine occured in June 1986. The machine was mechanically tested, generated open circuit voltage, and successfully discharged into a short circuit at speeds up to 4,200 rpm. The tests were very encouraging in that the machine demonstrated the predicted voltage and internal impedance. On the first run to the design speed of 4,800 rpm, a mechanical failure occured. An epoxy bond of the field winding to the rotor in the end turn region failed, loading the windings into the shield, which deflected and contacted the stator. The field winding, compensating shield, and armature winding were destroyed as 38 MJ was dissipated frictionally in these components. Fortunately, however, the remainder of the machine survived the incident intact and an ambitious rebuild effort was launched.

The machine was redesigned to incorporate Inconel® 618 alloy end turn containment rings. Also, an improvement in the surface preparation technique used prior to the epoxy bonding process was employed in an attempt to improve this aspect of the design, However, the Inconel® rings were sized to support the windings in any event.

Since the rebuild, the machine has performed admirably. A summary of the test results is presented in table 2.[16] The machine was been tested at speeds up to 3,000 rpm, and has generated 1,200 V, 560 kA pulses in the 3-m railgun. During these tests the machine has accelerated 66 g solid armature projectiles to a peak velocity of 1,868 m/s. A total of 16 high current (> 500 kA) discharges have been made successfully. Also, several multi-shot discharges, in which two projectiles are launched at a high rate of fire (60 Hz), were accomplished. With the advent of successful solid armature projectiles it appears that the machine will exceed its design goals of rapid fire launch of 80-g projectiles at 2 km/s at a speed of only 3,600 rpm. Most importantly, the generator has demonstrated the abilities which prompted its development; single element conversion of mechanical energy

Table 2. Summary of compulsator powered injector/3m railgun shots (Sep-Dec, 1987)

PARAMETER/RUN#	Run #83	Run #85	Run #86	Run #87	Run #93	Run #94	Run #95	Run #95	Run #96	Run #96	Run #97	Run #97	Run #102	Run #108	Run #110	Run #110	Run #112
Date of Test	9/4/87	9/15/87	9/21/87	9/24/87	10/14/87	10/14/87	10/16/87	10/16/87	10/26/87	10/26/87	11/10/87	11/10/87	11/20/87	12/11/87	2/2/88	2/2/88	2/9/88
Compulsator Speed (rpm)	2451	2451	2427	2433	2491	2376	2494	2416	††2500	2416	2497	2451	2899	2304	1747	1846	2920
Excitation (A) (%)	750 (77.5)	750 (77.5)	750 (77.5)	750 (77.5)	750 (77.5)	750 (77.5)	750 (77.5)	750 (77.5)	750 (77.5)	750 (77.5)	750 (77.5)	750 (77.5)	881 (91.1)	750 (77.5)	750 (77.5)	750 (77.5)	881 (91.1)
Open Circuit Voltage (V)	792.5	777	774	775	802	787	793	714	††800	705	775	708	1030	787	¥	¥	909
Firing Angle (deg)	142.7	142.7	172.8	154.8	153	150.4	167	154.7	158.7	146.1	145.2	142.7	144.9	142.3	141	141.8	142.7
Peak Railgun Current (kA)	471.6	520.8	417	555	559	551	447	484	527	486	496	544	593	519	-102/328	-104/258	623
Railgun Muzzle Current (kA)	-114.3	-46	210	210.6	173	172	227	173	209	126	44	121	56	198	201	191	210
Projectile Mass Initial (g)	65.1	67.2	64.8	65.4	65.8	65.7	66	66.1	66.4	67.4	66.1	64.8	66.6	66.3	65.9	66.3	70.8
Projectile Velocity (m/s)	452	755	1095	1889	1702	1725	1471	1364	1376	1370	1480	1744	1790	1600	1109	838	1602
Projectile Armature Voltage, Max. (V)	358	394	158	79	185	205	139	96	181	211	115	175	133	260	75	15	232
				Guns honed at Scot Ind.	Guns honed at Scot Ind.				H. S. camera	Guns honed at Scot Ind.	Guns honed at Scot Ind. H.S. camera			Exp. switch replacing ignitron	Double shot, 30 kA multiple restrikes-gun# 2 ¥ O.C. Voltage distorted due to multiple restrikes	Double shot, 30 kA multiple restrikes-gun# 2 ¥ O.C. Voltage distorted due to multiple restrikes	

††Estimated values—open circuit voltage data prior to discharge not collected

to a series of high powered electrical pulses suitable for directly driving an electric gun. It is expected that full speed testing on the machine will occur in 1988 and the machine will then be used as a testbed for the development of solid armature projectiles and to research compulsator driven railgun issues for the benefit of future machines. It should be noted, however, that although the iron-based machine is heavy when compared to the air-core machines, it is very rugged, has minimal auxiliary and logistic requirements, and is transportable in its present state by a variety of platforms including the AC130H gunship.[17]

EMGWS Task C Compulsator

After several years of building laboratory devices, it became apparent that EML's had potential for use in future weapon systems. In particular, the area of armor penetration was one in which our present capabilities were judged insufficient, and it was felt that the enhanced velocity offered by the EM gun would be of great benefit. The Electromagnetic Gun Weapon System (EMGWS) program was created to demonstrate the advantages of EM weapons for armor penetration, to develop specialized projectiles for the higher velocities, to build a field portable system which would fire projectiles at energy levels comparable to today's tank weapons, and to demonstrate that the devices could be made of a size and weight which might be considered for mobile applications.

The specific program goals and compulsator characteristics are listed in table 1.[18] The machine, shown conceptually in figure 5, is a two pole, rotating armature, air-core configuration which operates at a tip speed of 580 m/s. A considerable amount of energy is stored in the excitation field, which is supplied from the rotor in a self-excitation scheme. Several design iterations were performed prior to the final selection of the inside-rotor, selectively passive configuration.

The original concept for the machine was an outside rotor, passively compensated design. After a more detailed examination of this configuration, it was felt that a subcritical design could not be performed, and that the risk factor of a supercritical machine, particularly in light of the many other unknowns associated with the use of composites, was too great at this time. Therefore, the concept evolved into an inside rotor, passively compensated machine. The passive configuration is somewhat superior to the selectively passive one in this case, because it has a slightly higher efficiency and requires a shorter gun. Unfortunately, the current state of the art in projectiles is not compatible with the higher accelerations associated with the passive design, leading to the choice of the selectively passive machine.

The machine generates a peak power of 27 GW, and delivers approximately 30 MJ per pulse into the 8-m railgun. Excitation is provided by a pair of 252-turn, liquid-nitrogen-cooled aluminum field coils. The coils are wound in a pancake configuration and contained within an aluminum casing which is in turn inserted in a vacuum vessel to provide thermal insulation. In this case, cryogenic cooling of the field coil was absolutely required to meet the performance goals. A pair of lap wound, 6 turn aluminum litz windings form the armature. The armature is cooled with high pressure helium gas (a second, uncooled rotor is also planned). It is epoxy bonded to the S-glass rotor and banded by a series of graphite rings. The graphite banding, which is the highest stressed component in the machine, must be laminated to prevent large eddy current losses due to its interaction with the excitation field. A 52-turn winding located on the bore of the stator, along with the conductive boundary of the field coil vessel and stator casing, provide selective compensation.

Obviously, this machine is a tremendous step beyond the present state-of-the-art represented by the rapid-fire CPA. Innovation in several areas is required. In addition to the obvious difficulties of spinning a thick-shell composite rotor to these speeds, several other potential problems have been discovered and solved. One of these concerns the high magnetic fields present in the rotor due to the nature of air-core machines, and the choice of the two-pole configuration. A detrimental aspect of the high field is that eddy current losses in any rotating, solid conducting material would be unacceptably high, dictating the use of insulating material throughout the rotor structure. The most serious result of this problem concerns the choice of shaft material. The bending stiffness of the shaft must be very high to result in a subcritical system. Composite materials are not desirable, however, due to their anisotropic nature and low shear modulus. It appears that an alumina ceramic material will meet these requirements, but there is naturally some apprehension with this choice. Other difficulties are related to the magnitude and location of the discharge-induced fields. Peak flux densities as high as 8 T are generated. This requires a very careful arrangement of the armature and compensating conductors, particularly in the end turn region, to minimize the fields produced. In general, a much greater fraction of the analysis associated with the design must be performed using a transient, three dimensional finite element code than is required in the ferromagnetic case. Finally, the selectively passive concept has never been experimentally verified.

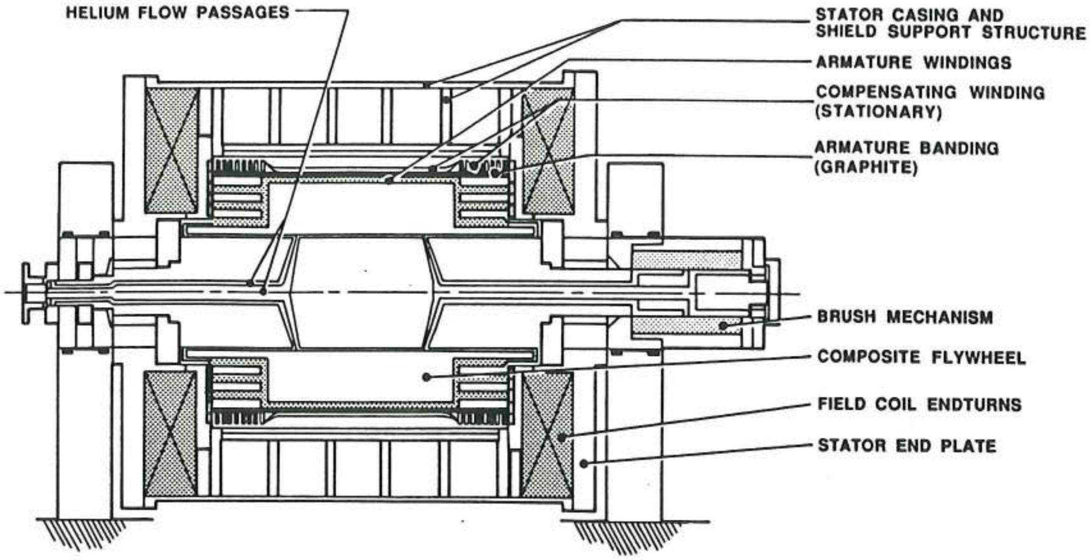

Figure 5. Task C conceptual design

In spite of the difficulties presented, a workable design has been completed, and a very high probability of success is currently assessed. Fabrication of the machine will commence in the spring of 1988 and should be completed in about 12 months. Testing is scheduled for the May-June 1989 timeframe.

The completed Task C machine will be a breakthrough in pulse power technology. At 8 kV and over 3 MA, it will represent the highest peak power rotating machine in the world, and open the door for many new technologies. The machine will also provide a valuable test bed for other EML-related experiments, and enable the design of the next generation of higher powered, more compact devices.

Small Caliber

The final machine discussed is the compulsator being developed for the small caliber program. The goals of this project are presented in table 1.[19] Although it is an air-core generator, the small caliber machine is considerably different than the Task C compulsator. This is primarily a result of the reduced nature of the requirements allowing more design flexibility.

The small caliber machine is a rotating field, four pole, passively compensated configuration. The machine is intended for use in light armored or, potentially, unarmored vehicles and is appropriately light and compact. Because of its small size, it is possible to excite the machine using a room temperature field coil. Although there is a considerable efficiency penalty, and some added weight associated with this option, it was considered more desirable for the intended ultimate use. Passive compensation is compatible with the gun length and allowable projectile accelerations, and greatly simplifies the design and fabrication of the device. A four-pole design was favored to alleviate many of the eddy current and armature-end-turn-related problems of the Task C concept. In this machine, a metallic shaft can potentially be used. Field concentrations at the ends of the machine are also reduced. This allows the active length of the small caliber machine to be proportionally longer than that of the Task C machine, resulting in more proportional voltage, and a higher rotor power density. The small caliber system should be completed in the summer of 1989, and a 5-month test period extending through January 1990 is planned.

Future Technology

There are a number of innovations and areas of improvement required before the compulsator-powered EM gun will be sufficiently compact to be truly competitive with today's conventional weapons. A tremendous gain has been made in the incorporation of composite technology to form air-core machines, but further progress is still needed. Also, while the Task C effort is beginning to address the issues of field portability, it is obvious that the auxiliary requirements must be reduced, system efficiency further increased, and issues related to long term operation (mostly thermal) must be resolved.

Some of the techniques which would address these issues have been discussed, and are likely to be included in the next generation of machines. These include the outside-rotor, or counterrotating geometry to increase power and energy densities, the design of machines to operate successfully in a supercritical mode to decrease support structure and proportionally increase the rotor length, and the use of superconducting excitation to greatly increase system efficiency and power.

However, there are several other areas in which innovative design effort is required. An improved method of transmitting discharge torque through the armature to the machine structure is necessary. Also, the packing factor of the armature conductor, and the ease and quality of terminations, must be better than is achievable with the present litz wire system. Folded armature conductors and the interweaving of the armature and composite fibers would improve these situations. The present dependance on hydrostatic bearings requires relatively massive auxiliaries, and a considerable fraction of the system prime power and cooling capacity. The development of a dependable, high load capacity, nonconducting rolling element bearing is feasible and would address these issues. In the area of electromagnetics, an efficient method of producing pulsewidths greater than the electrical frequency of the machine would be extremely beneficial. Finally, material research and development of composites specifically to address the needs and requirements of pulsed electrical machinery should be pursued.

The concerns mentioned are a small portion of the areas in which technological progress leading to improvements in machine performance is possible. Unfortunately, there is not a program in place to support basic research. The programs previously described are short term and very goal-oriented, drastically limiting the time and effort which can be expended on the development of new techniques. It is evident that a program to pursue basic research on the problems encountered in pulse power would be of great benefit.

Conclusions

The Center for Electromechanics is developing lightweight, extremely powerful compulsators specifically for use with EML systems. Experimental testing of several machines has been performed, verifying basic operating principles, the ability to analyze and predict performance, and the capability of the machines to drive EM guns. Tremendous gains in power density are achievable with the incorporation of air-core machines. The realization of the Task C machine, producing the highest peak power of any rotating machine ever built, will bring EM gun systems much closer to eventual deployment in mobile applications.

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