ADVANCED COMPULSATOR TECHNOLOGY

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Presented at
The 6th Electromagnetic Launch Symposium
The Institute for Advanced Technology
Austin, Texas

April 28-30, 1992

Publication No. PR-159

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ABSTRACT—Rotating electrical machines with their inherently high inertial energy density are finding applications in a variety of laboratory based as well as field based pulsed power systems. Of particular interest to the electromagnetic/electrothermal launch community is the compensated pulsed alternator. This machine has over the past few years shown greater potential, because, besides the high energy density various means have been devised to increase the waveform flexibility. Efforts continue simultaneously to enhance the energy density. Various designs have evolved in the process and each have their advantages and disadvantages. The type of compulsators to be used is very dependent on the application. The issues involved in the appropriate selection are discussed.

Electrothermal guns require a current profile which is quite different than their EM counterparts. A new method of obtaining this current pulse is discussed. This new variant also facilitates the self-motoring of the machine between bursts. This machine as applied to a 60 mm ETC is discussed.

INTRODUCTION

Two basic types of compulsators, as applicable to EMLs, have been presented in previous literature, i.e. the passive compulsator [1,2] which delivers a sinusoidal or a displaced sinusoidal pulse to the load, and the selective passive compulsator [3,4] which delivers the flat topped current pulse. In both these machines the pulse width is some fraction ($\sim 0.75\tau$) of the electrical period. The use of high strength and high specific stiffness composite rotors in electrical machinery has resulted in higher tip speeds and therefore higher energy densities. However, this also implies higher rotational speed machines if the diameter of the machine is to be reasonably small. The result is that higher energy densities are obtained only with shorter pulse widths. In most EML applications there is an upper bound on the projectile acceleration due to stress considerations. This implies that for a given muzzle velocity the pulse width has a lower limit.

A multiphase passive compulsator overcomes these limitations by synthesizing a longer pulse from several shorter pulses. Fig. 1 shows a circuit schematic of this machine with two phases. In the operation of this machine

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Fig. 1. Multiphase compulsator circuit schematic

the different phases are staged at the appropriate time. The result is that the total pulse width as seen by the EML is longer than the electrical period. The two phases may be phase displaced to any angle desired. The peak voltages and the firing angle for the two phases can be fixed independently. This provides significant pulse shaping flexibility. Fig. 2 shows the acceleration and jerk profile obtained with the multiphase passive compulsator. Due to the staging there is a higher jerk compared to a pulse from a selective passive machine with the same peak acceleration. The total action is shared between the two phases however the peak current is the same. Therefore it is necessary to minimize the number of phases to keep the size of the switches reasonably small.

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Fig. 2. Acceleration and jerk with a two-phase machine

The internal structure of the multiphase machine is very similar to a single phase machine. The compensation is provided in the form of a continuous conductive shield. There are two armature windings corresponding to the two phases. These two windings can be placed at two radially distinct layers or in a single layer with conductors of the two phases adjacent to each other. The former approach is preferred, as it is easier to fabricate. A self excited room temperature field coil is required similar to the other concepts.

With the addition of the new concept described above the types of air-core compulsators for EMLs can be summarized as shown in Table I.

TABLE I. TYPES OF COMPULSATORS

Inside (Conventional) Rotor	Outside (Shell) Rotor
a) Single Phase Passive Compulsator	
b) Single Phase Selective-Passive Compulsator	
c) Multiphase Passive Compulsator	

With this variety, the selection of a particular type for a given application becomes critical. The approach to the selection is the topic of the next section.

There are two types of requirements which result in two general types of machine designs. One is a power limited design and the other is an energy limited design. A power limited design is one which can generate the required power, with the shear stress at the flywheel-armature interface being the limiting parameter. This type of machine is typically required with weapon systems requiring muzzle energies in the 10's of megajoules and a long time between shots - 10's of seconds. The machine needs to store only enough energy for a single shot and normally such a machine stores more energy than is required for a single shot due to the power constraints. An energy limited design is one which is primarily designed to store a certain amount of energy. The size of such a machine is such that the power can be generated with low shear stress at the flywheel-armature interface. This type of machine is required for weapon systems with relatively low energy per shot, a high shot rate with several shots per burst so that it is difficult to motor between shots and adequate energy must be stored for at least one burst. It is necessary to distinguish between these two machines as the issues in their selection are different.

COMPULSATOR SELECTION ISSUES

Two poles versus four poles

To get the longest pulse width at the highest tip speed, and therefore highest energy density, it is necessary to keep the

number of poles to a minimum. This is especially true of the single phase variant of the compulsator. When energy limited systems are being considered, energy density needs to be maximized which normally results in the selection of a two pole machine. Both, the shell as well as the conventional machines, have some difficulties with a two pole design. The shaft of the conventional rotor would have to spin through a high magnetic field with a two pole design. Using a conductive shaft material causes severe eddy currents. This results in two options neither of which are desirable. One is to use a ceramic shaft and the other is to use a copper clad inconel shaft. In the latter option the copper which acts as a shield would have to be actively cooled.

The force distribution in a two pole machine is quite nonuniform during discharge. The center of force on the two pole windings is at diametrically opposite points. The conventional as well as the shell machines have higher stresses due to the nonuniform discharge pressure but the shell rotor is particularly sensitive to it. In the shell rotor this discharge pressure adds to the stress in the banding which is already high due to the spin stresses. The nonuniformity of pressure results in local bending which adds to the hoop stress. Also, it is difficult to manage the deflections under the nonuniform loading especially when the clearances between stationary and rotating parts need to be at a minimum.

With the four pole machine the field strength reduces at distances away from the field winding towards the center, until at the center the field strength is zero. This permits the use of a conductive shaft which does incur eddy current losses but this loss is much lower compared to the two pole machine. Also the four pole winding has the center of force distributed at four equidistant points along the circumference. This load distribution is much easier to manage.

For energy limited systems there is a higher mass penalty in using a four pole option as opposed to a two pole. However for power limited systems where enough energy is stored the mass penalty may be insignificant. Table II summarizes the results obtained for selective passive machines designed to deliver 9 MJ muzzle energy. It is assumed that the time between shots is adequate so that it is not necessary to re-motor between shots. From Table II it can be seen that for the shell rotor the difference in mass of the two and four pole machines is quite small. The energy stored in the four pole machine is still more than required for a single shot. The energy needed to be stored for a single shot is approximately 100 MJ. In the case of the conventional rotor the two pole design is indeed power limited however the four pole design is energy limited, which results in a slightly higher mass difference between the two designs.

TABLE II. COMPARISON OF DESIGN OPTIONS FOR A POWER LIMITED 9 MJ SYSTEM

Parameters	Conventional Rotor		Shell Rotor	
	2 - poles	4 - poles	2 - poles	4 - poles
Mass (kg)	6822	8200	4808	5119
Energy stored (MJ)	224	100	377	131
Peak O.C. voltage (V)	5936	7700	4900	5420
Amp-turns/pole (MA-T)	3.78	3.1	4.06	2.9
Electrical frequency (Hz)	170	170	170	170
Machine RPM	10200	5100	10200	5100
Outer diameter (m)	1.17	1.38	1.25	1.49
Total length (m)	2.075	1.833	2.05	1.974
Tip speed (m/s)	519	308	670	403

Shell Versus Conventional rotors

The main advantage of the shell rotor over the conventional rotor is that the banding which protects the delicate armature winding is out of the air gap. This results in a better coupling between the armature and the compensating winding. However there is another effect which must also be considered which offsets this advantage partially. The field strength outside the field coil decays faster than within the field coil. Equations (1) and (2) illustrate this effect quite clearly. This would normally mean a higher ampere turn required in the shell configuration. However a better coupling between the armature and compensating windings gives lower inductances and therefore a lower voltage is required. With the result that the ampere turns required remain about the same for either configuration. Table II illustrates this effect also.

$$B_r = \mu_o \frac{K_1}{2} \left(\frac{r_a}{r_f} \right)^{\frac{N_p}{2} - 1} \quad \text{for all } r_a < r_f \quad (1)$$

$$B_r = \mu_o \frac{K_1}{2} \left(\frac{r_f}{r_a} \right)^{\frac{N_p}{2} + 1} \quad \text{for all } r_a > r_f \quad (2)$$

where,

- r_f = average radius of the field coil
- r_a = radius of the armature
- N_p = number of poles
- K_1 = line current density

A definite advantage of the shell rotor is that a better coupling between the compensating and armature also gives a better compression ratio and therefore a better acceleration ratio. Also the energy density of the shell rotor is better because it typically spins at a higher tip speed compared to the conventional rotor for the same electrical frequency, this too is illustrated in Table II. The mass estimates in Table II do not account for containment required with shell rotors. If

special containment is required some of the advantages related with the energy density might also be offset. However integrating the shell rotor system in a vehicle may allow the use of existing containment thus retaining the benefits of the shell configuration.

Relation Between Pulse Shape and Energy Density

Most railgun applications have an upper limit on projectile acceleration. Independent of the pulse shape the peak current through the gun is therefore fixed. A better acceleration ratio implies a higher average acceleration for the same peak acceleration. This in turn implies a shorter pulse width for the same muzzle velocity. A shorter pulse width requirement allows higher frequencies and therefore higher energy densities. The acceleration ratio due to a typical current pulse out of a passive compulsator is close to 0.375 (average/peak). Whereas the acceleration ratio obtained from a selective passive compulsator is typically in the range of 0.67 to 0.55. Thus for energy limited designs a selective passive compulsator results in a substantial increase in the energy density.

Wound Compensation

For better efficiency it is desirable to ramp up the field current fast before every shot and once again reclaim the magnetic energy after the shot is completed. When the shot rate is high the time available to accomplish the reclamation and recharging is quite small. The presence of the compensation complicates this process since eddy currents generated in the compensating winding/shield delay both processes. For the selective passive machine the solution is to have a continuously wound compensating winding rather discrete one turn conductors. A switch introduced in the compensating winding would remain open during the charging as well reclamation of the field coil and closed just prior to discharge. The duty on this switch would be quite nominal since it opens at zero current and does not have to withstand high voltages.

With a passive machine the continuously conductive shield would have to be replaced by two compensating windings. These two compensating windings would be phase displaced by 90 electrical degrees so as to provide multiaxis compensation. Each of these two windings would then be provided with their own switches, which would operate just as the selective passive machine. If these two compensating windings are transposed so that they have the same coupling with the armature then the performance so obtained would be the same as in the case of the compensating shield. A difference in the coupling would result in a slight variation in the armature inductance with rotor position. Equation (3) gives the inductance variation of the armature winding compensated by two orthogonal compensating windings.

$$L_{eff} = L_{uncomp} \left\{ 1 - \frac{k^2_{acm1} + k^2_{acm2}}{2} - \frac{k^2_{acm1} - k^2_{acm2}}{2} \cos(2\theta) \right\} \quad (3)$$

Here k_{acm1} and k_{acm2} are the maximum values of the two couplings

A COMPULSATOR BASED POWER SUPPLY FOR ET GUNS

Electrothermal guns have special power supply requirements which are quite different from EM guns. One basic difference is that they need higher voltages and lower currents for their operation. To break down the device, and begin conduction through it, a high voltage is typically required when the pulse is initiated. The ideal current pulse shape for the device is a quick ramp to a steady current level, followed by a faster ramp to a higher current and a fast shut off. To maximize the pulse width from a compulsator it is desirable to trigger the pulse close to zero volts. This is normally the trigger point for most EM guns. For ET guns this necessitates using some other device to breakdown the cartridge and start conduction. The multiphase compulsator described above overcomes these limitations and at the same time provides the required pulse shape. Several other compulsator based power supplies have also been considered for electrothermal gun applications, these are described in references [5,6].

The multiphase air-core compulsator used for ET gun applications is a two phase device with the two phases placed orthogonally. The circuit schematic is similar to the one shown in Fig. 1. Compensation is provided in the form of a continuous conductive shield, it is therefore a passive device. The pulse is triggered when one of the phases is close to the peak voltage. At this time the other phase is close to zero volts and negative. Fig. 3 shows the trigger point for the two phases with respect to the open circuit voltage traces. A 60 mm ETC system was simulated using this type of compulsator. The overall diameter of this machine was 1.1 m and its length 1.4 m. The mass was 3,000 kg. The

Fig. 3. Trigger points for the two phases

Fig. 4. Current profile through ETC

corresponding current trace is shown in Fig. 4. This current trace is fairly close to the desired shape.

The 60 mm ETC mentioned above is being considered for a weapons system on board a ship. The shot rate for this device is 5 Hz with a 10 round burst, and 2 MJ/pulse delivered to the ETC. The time available to re-motor the machine between bursts is 5 s. This necessitates a motoring power of about 7.2 MW (9,650 HP). Ship integration issues allow the use of electrical power for motoring purposes, as opposed to a turbine. An advantage of this machine is that if the armature is supplied with a two phase power supply it could be operated as an induction motor with the shield acting as the squirrel cage.

For the 60 mm system, the energy removed from the rotor after a 10 round burst is about 36 MJ. This implies a discharge efficiency of about 55%. The total energy stored in the rotor of the compulsator before commencement of discharge is 109 MJ. The initial and final rpm of the machine for a burst is correspondingly 5,986 and 4,879 rpm. This corresponds to an electrical frequency of 199.5 and 162.6 Hz respectively. Fig. 5 shows the motoring efficiency

Fig. 5. 60 mm ETC compulsator motoring characteristics - efficiency

Fig. 6. 60 mm ETC compulsator motoring characteristics - power

with the armature connected to a 500 V power supply. Fig. 6 shows the input and output power versus slip. To keep the motoring efficiency reasonably high it is better to motor within a range slip of 6 to 15% by using a variable frequency power supply. The overall efficiency in this case is 75%. The overall efficiency for constant frequency motoring is 61% for this machine. The smaller the range of slip used, the higher the efficiency of motoring. However the upper limit for efficiency is at about 80% for this machine.

Conventional machines operate at a much higher efficiency (>98%). This is related to the fact that they are mostly iron-core machines. Iron-core machines have a much lower magnetization current requirement compared to air-core machines which makes them more efficient. Several trade-offs can be investigated to improve the motoring efficiency of the air-core compulsator. One of which is to use thicker armature conductors and thus lower its resistance. This would affect the discharge performance as the coupling of the armature with the compensation diminishes. The coupling could be regained by going to a larger diameter machine, which in turn would result in a higher mass.

The armature windings are designed specifically for their discharge performance. Due to the dual requirements on the armature windings i.e. discharge as well motoring there is very little flexibility on the applied voltage for motoring. Typically the armature windings are designed to perform at the required voltage during discharge. The voltage that can be applied during motoring is then given. In order to reduce the mass of the transmission cables one would prefer to use higher voltages and lower currents. This can be quite easily accommodated by using a two phase (90° phase displaced) compensating winding instead of a continuous conducting shield for compensation during discharge. The number of turns in this compensating winding can be adjusted to accommodate higher voltages (more turns than the armature winding) thus facilitating the use of any desired motoring voltage. The discharge windings would then be short

circuited during motoring and these would now correspond to the squirrel cage of a conventional induction motor.

CONCLUSIONS

As new applications and requirements are imposed on the compulsator this power supply has adequate versatility to adapt to the demands. Self-excitation of the field coil has already been discussed in previous literature. This eliminated the need to have a separate power supply for excitation. The application of self-motoring will also contribute equally well toward the integration of this machine with other systems. Selection of a compulsator for a particular application is very dependent on the application parameters. However some general guidelines can be followed once the system is identified as being either power or energy limited.

ACKNOWLEDGMENTS

This test program was conducted by the Center for Electromechanics at The University of Texas at Austin, and funded by U.S. Army ARDEC under contract no. DAAA21-85-C-0210.

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