DESIGN OF COMPENSATED-PULSED ALTERNATORS WITH CURRENT WAVEFORM FLEXIBILITY

M. D. Driga, S. B. Pratap and W. F. Weldon

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Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

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Introduction

An entire family of new technologies in the areas of defense, space technology, fusion, and industry (such as electromagnetic launchers, electromagnetic counter-measures systems, high energy lasers, etc.) demands increasingly higher current (mega-amperes) and energy (tens of megajoules) pulses. Efficiency, operational and functional considerations require that such pulses are characterized not simply by their magnitude and duration, but also by a specific shape, a well defined magnitude versus time profile.

The problem must be viewed under the perspective that the required levels of energy and current are difficult to provide at any pulse shape, and that the pulsed electrical machines, acting as power supplies are subjected to electromagnetic loading, thermal, and mechanical stresses unequaled in more normal operations.

In comparison to other pulsed power supplies the compensated pulsed alternators (compulsators) [1,2] show real capabilities to be further refined and generalized in order to achieve the positional and temporal selectivity in compressing the flux in order to provide pulse shaping (output waveform flexibility). The desired current profile must be obtained under the constraint of a given load impedance which may be, in turn, characterized by its time profile. Then, in a lumped parameter approach the system can be modeled as a generator which, in the presence of the induced electromotive force, modifies its own internal impedance to produce a current pulse of a prescribed profile into a given load. Such capabilities apply to both iron and air core compulsators. However, the air core (ironless) variants are emphasized here because of their higher energy and power densities due to the higher rotor speeds and flux density permitted in them.

Two particular applications will be considered in this paper. One concerns power supplies for railgun systems in which the projectile is constrained to a maximum permissible acceleration. A flat pulse will assure that during all the launch time, the average acceleration is close to the maximum value, achieving the desired final velocity in a shorter and uniformly stressed barrel of the gun, while satisfying the imposed constraint.

The second case requires producing high magnetic fields using a sharply peaked pulse of current.

Compulsator Configurations

The compulsator is an appropriate device for pulse shaping having beside the excitation and armature windings, the shield (passive compensation) and/or the active compensation winding. All these elements represent degrees of freedom which can be modified in order to achieve a certain change of the output current profile. Two topological configurations for a compulsator, external rotor and internal rotor are shown in figures 1a and 1b respectively.[3] The armature winding includes also, the active compensation winding, where such winding is used.

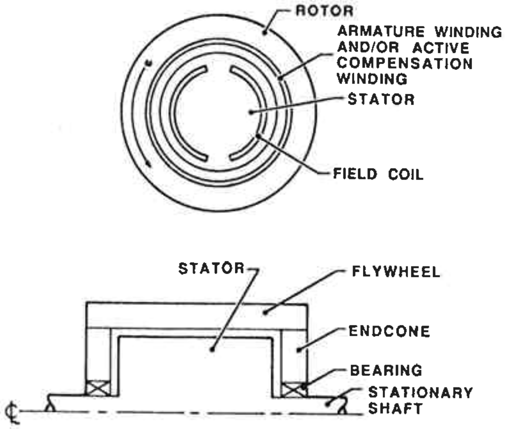

Figure 1a. Compensated pulsed alternator (external rotor variant)

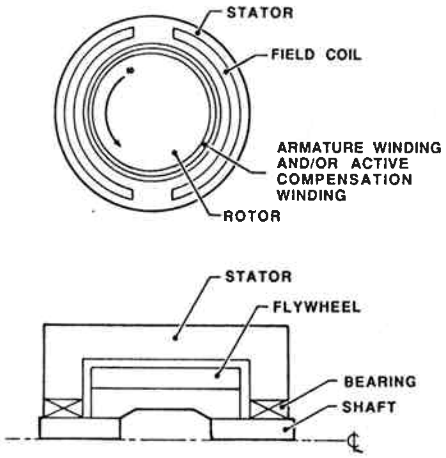

Figure 1b. Compensated pulsed alternator (internal rotor variant)

In the compulsator with external rotor (fig. 1a) the rotor flywheel provides natural banding for the armature winding and stores required inertial energy and more importantly allows complex field winding distributions in order to achieve the "harmonic synthesis" leading to pulse shaping. In the topological configuration with internal rotor the field coil dimensions can be increased in order to reduce losses and to permit an asymmetrical distribution of the magnetomotive force. One important advantage is that the stator provides containment in the case of rotor failure.

Methods for changing the output current time profile

Conceptually we can consider the compulsator as a source of induced electromotive force having an internal impedance which varies during the pulse, such that the time profile of the output current can be shaped and controlled, for a given external impedance. Functionally there are two general methods for pulse shaping: topological distribution of conductors and dynamic interactions between conductors which can be used separately or in conjunction.

The topological distribution approach includes the method of "harmonic synthesis". An appropriate choice of even harmonics will create a flat current pulse, while a synthesis of odd harmonics will result in a peaked current output.

The dynamic interaction category includes altering a basic magnetic flux distribution, created by the field coils, by using a nonuniformly distributed shield, or compensating winding which compresses the magnetic flux in selected areas, leaving the flux unchanged in the rest of the machine, and "dynamically" shaping the pulse.

Classification of methods for pulse shaping can also be made according to the technology used:

-Excitation winding distribution (harmonic synthesis method, multiple Gramme ring type field coils, etc.)
-Electromagnetic nonuniformity in the shield (passive compensation)
-Asymmetric active compensation
-Nonuniform distribution of the armature winding (changing pole pitch and phase-shift)
-Change of alignment (change of axis between different machine windings: field, active compensation, armature, shield)
-Use of a pulse transformer incorporated in the machine.

Pulse Shaping by Variable Alignment of Magnetic Axes

In this section a machine is described which provides different output current versus time profiles by a change in the alignment of the magnetic axes of the compensating winding and the excitation field winding. First a detailed description is given of a method of obtaining a flat current pulse using this technique. This is followed by an extension of the technique for various other current pulse shapes.[4]

For simplicity a two pole machine is considered. This machine has a lap wound, full pitch armature winding which occupies 30 to 80% of the pole pitch. The winding is composed of stranded and transposed wire which is epoxy bonded to the stator or rotor. The compensating winding is also two pole, lap wound and full pitch. The compensating winding is the primary current pulse shaping component. A cylindrical shield made of a highly conductive material is also provided. This shield is placed on the same member as the compensating winding but further from the armature winding compared to the compensating winding. The shield is the secondary pulse shaping device. The magnetic axis of the compensating winding is displaced about 50 to 70 electrical degrees from the axis of the excitation field. There is no galvanic contact between any pair of windings, the only coupling is through the magnetic field produced by these windings.

The basic principles involved in pulse shaping in this case are:

1) a short circuited coil will maintain its initial flux linkages when subjected to a changing magnetic field. The flux linkages are maintained at the initial value by a current set-up in the coil and oriented in a manner to exclude the changing magnetic field.

2) The power output of an alternator is limited by the internal inductance of the alternator.

As the armature winding spins with the rotor, the mutual inductance between the armature and compensating windings and therefore the flux linking the compensating winding changes with rotor position. The variation of the mutual inductance is more or less sinusoidal with angular position. The mutual inductance is maximum when the magnetic axes of the armature and compensating windings are aligned as shown in figure 2. 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 and the inductance of the armature winding is minimum. When the magnetic axes of the two windings are perpendicular to each other as shown in figure 3, there the mutual inductance between the two windings is zero. In this position the flux produced by the armature winding permeates the entire region within the shield, bringing the inductance of the armature winding to its maximum. This cycle of maximum and minimum inductances occurs twice per rotor revolution.

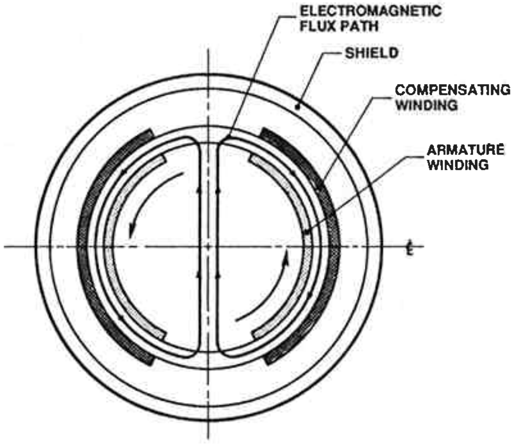

Figure 2. Machine in maximum mutual inductance position: flux is compressed in the air-gap

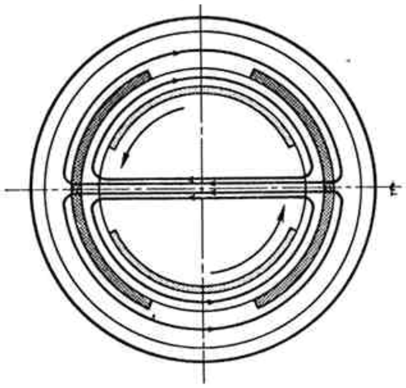

Figure 3. Machine in zero mutual inductance position: flux permeates the entire space within the shield

The current pulse is initiated when the mutual inductance between the two windings is close to, but less than the maximum value. Since the inductance of the armature winding is low in this position, the current in the armature winding rises rapidly. This continues until the mutual inductance starts to decrease and the armature inductance begins to increase. The increasing armature inductance limits the power output of the machine thus leveling the output current pulse. Toward the end of the pulse the mutual inductance begins to increase, reducing the armature inductance. This compensates for any increase in impedance of the load. This compensation helps in maintaining a flat current pulse (fig. 4).

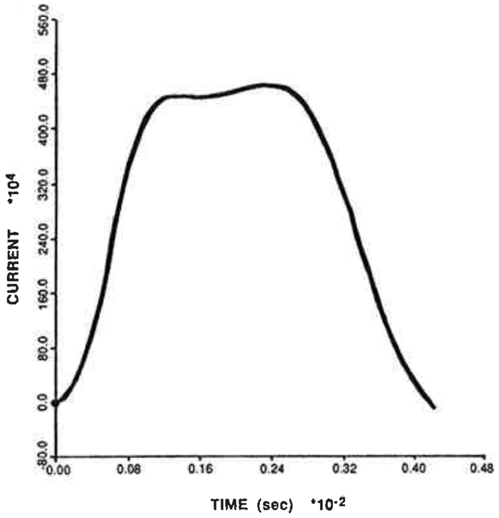

Figure 4. Output current pulse

In the absence of the shield, the maximum inductance of the armature winding would be much higher with the result that the current pulse would droop significantly thus giving a current pulse with a valley in the center (fig. 5). Therefore the shield is a pulse-shaping component, which may or may not be provided depending upon the desired pulse shape.

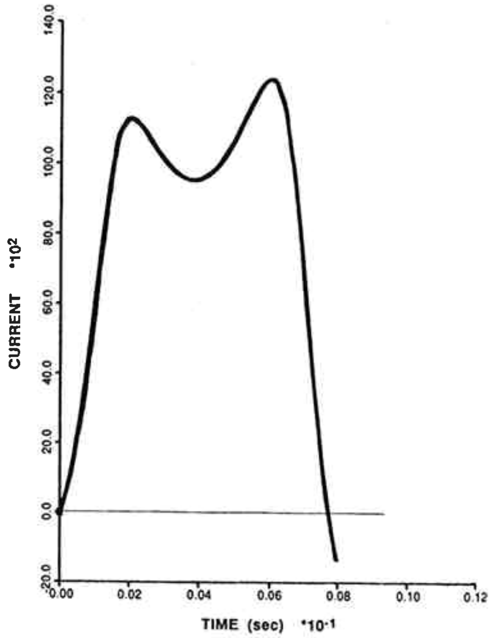

Figure 5. Current pulse shape in absence of the shield

Pulse Shaping by the Use of a Pulse Transformer Incorporated in the Machine

The machine described in the previous section assumed that the load was connected to the armature winding, with the pulse initiation switch also provided in the armature circuit. Pulse shaping can also be obtained by connecting the load to the compensating ing winding and initiating the pulse in the armature circuit. Since the armature and compensating winding are magnetically coupled, a current pulse in the armature winding induces a pulse in the compensating winding. Figure 6 shows the current in the compensating winding then the current in the armature winding is as shown in figure 7. Therefore by using a machine similar to the one described in the previous section and connecting the load to the compensating winding a different family of pulse shapes can be obtained.

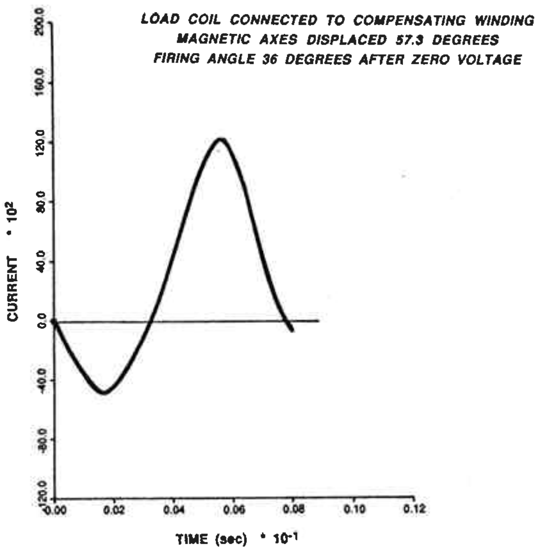

Figure 6. Current in the compensating winding (pulse transformer incorporated in the machine)

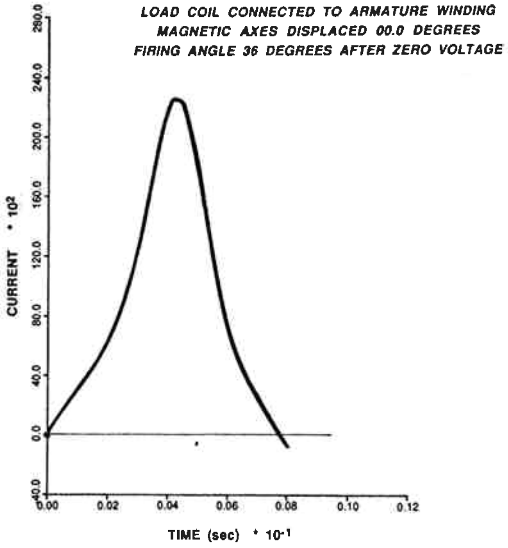

Figure 7. Current in the armature winding (pulse transformer incorporated in the machine)

Passively Compensated Machine With Nonuniform Shield

The last example is a passively compensated electrical machine, the compensation deriving from a nonuniformly distributed shield on the rotor. The excitation is provided by different field windings arranged to produce second and fourth harmonics in the magnetic field and in the EMF induced in the armature winding. The generator will store 77 megajoules (MJ) of kinetic energy and will discharge in 4.6 milliseconds (ms), delivering a current of 5.45 mega-amps (MA) to a railgun in an almost rectangular pulse. The railgun is designed to accelerate a 12 kilogram (kg) mass to a velocity of 2 kilometers/second (km/s) at a constant acceleration of 5.8 x 10^5 meters/second^2 (m/s^2). The cross-section through the rotor of the generator, shown in figure 8, shows the relative disposition of the excitation windings A and B, as well as the shield.

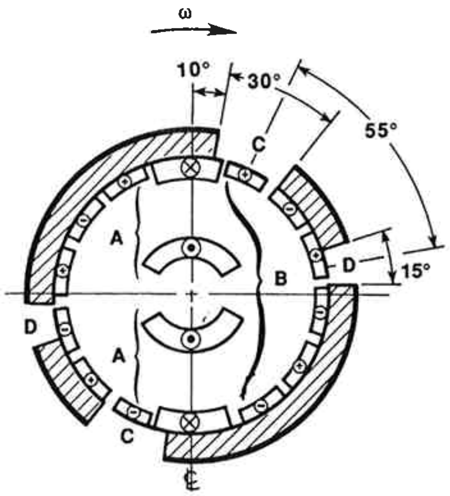

Figure 8. Passively compensated alternator: Excitation winding and shield distribution

The system A excitation coils are configured as a Gramme ring and provide the majority of the required excitation ampere-turns. The space distribution of the magnetic flux is triangular and an armature voltage of flat shape is generated. The system A excitation coils are concentrated winding coils. The polar pitch of the system A coils is 180°.

The system B coils provide additional magnetomotive force (with strong second and fourth harmonics) in order to increase the induced voltage in the armature in the initial period of the pulse, to achieve a high rate of rise of current in the load. The system B coils are distributed windings and the angle between the windings is such as to produce second and fourth harmonics in the excitation magnetic flux pattern in relation to the fundamental windings. The direction of excitation current flow in system B coils alternates setting up flux lines in opposite directions. The spacing between the windings and the direction of current flow are the primary determinants of the harmonic created. The system B coils produce about 18% of the magnetomotive force of the system A coils.

To assure regularity of the rectangular pulse, an aluminum shield surrounds the field coils.
Two pairs of longitudinal slots (C and D) are cut into the 1.5-cm thick, aluminum shield. Each slot in the first pair is 30° wide and its center is displaced about 25° from the center of a system A excitation coil. Each slot in the second pair spans an arc of about 15° and its center is displaced about 55° from the center of a slot in the first pair. This nonuniformly distributed shield compresses the magnetic flux in its conductive areas and allows the flux to develop freely in its non-conductive areas. The magnetic flux density distribution is then "dynamically" altered in a predictable manner as the field coils and shield are rotated on the rotor.

The output current pulse shape is shown in figure 9. The current provided to the railgun is 5.45 x 10^6 A for a duration of 4.6 x 10^{-3} s, with a steep rise and sudden decay. The variation in the amplitude, or ripple, of the current during the launch is less than five percent.

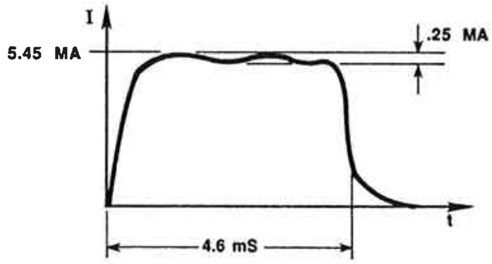

Figure 9. Output current for compulsator with non-uniformly distributed shield

Acknowledgements

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