PULSED POWER ELECTROMECHANICS - PERMANENT MAGNETS VERSUS COPPER COILS

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PULSED POWER ELECTROMECHANICS – PERMANENT MAGNETS VERSUS COPPER COILS [*]

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Abstract

A number of emerging military systems operate using short, repetitive, high-power pulses. Rotating electromechanical machines incorporating inertial storage are natural candidates for supplying these high power pulses. The short duty cycle characteristic of these devices introduces an interesting physics trade off in the choice of field excitation. A quantitative comparison of permanent magnet machines to copper coil systems is performed on an equal weigh basis. The results indicate that copper coil based systems using exciters are superior to permanent magnet counterparts in pulsed applications of 20 s and less. The recommended use of copper coils becomes stronger when the issues of magnet life due to vibration, thermal cycling, and slot harmonic heating are considered.

I. INTRODUCTION

Rotary submarine launchers, electromagnetic aircraft launcher, rail guns, active armor, and high power microwave devices are characterized by high power delivery repeatedly for short duty cycles. The power demand makes it impractical to have continuous generation capability matching the peak demand. So, some type of load leveling is required.

Typical candidates for load leveling are capacitors or rotating machines. Capacitor banks have the advantage of quick pulse delivery (<1 ms), but the inability of providing more than a single shot without recharge, and a poor energy / volume ratio (0.011 MW-Hr/m^3) [1]. Rotating machines offer greater flexibility for these applications [2][3]. Although field excitation coils have been the norm in the past, permanent magnet machines are receiving greater attention [4] [5]. Assuming that an electromechanical device is chosen for the task, this paper attempts to address the question, "Which field excitation is better, wound rotor or permanent magnet?"

This question can be addressed at the level of fundamental constitutive properties. The current density allowed in copper coils is dictated by the adiabatic heating it can sustain. The specific heat, density, and conductivity are the constitutive properties which dictate the temperature rise during the charge cycle, and thus the allowed current density. The maximum change is capped by either the insulation or the material melt temperature of the conductor. Magnetic energy can be computed as the integral of the product of magnetic vector potential with current density over the volume of the conductor. Permanent magnets are limited by the energy product of the magnet, reflected through the integrated product of the magnetic field intensity and magnetic field density. The comparison is complicated by secondary issues, among those being the additional weight required by the exciter of a copper coil system, and the degradation of the permanent magnet energy product with temperature.

Either permanent magnets or copper coils and steel can be considered for use in nearly any design of a pulsed generator. This paper attempts to quantify the implications of particular selections in three case studies, a radial flux generator, an axial flux generator, and an inside out design. In each case the air gap field from a permanent magnet configuration, composed of 45 MGO magnets, is compared to that from a copper coil configuration. The current density is chosen commensurate with a 100˚C temperature rise.

II. CURRENT DENSITY

Central to the comparison is the question of how hard the copper coils can be excited. The issue is complicated by the fact that a pulse forming network is the typical load to the generator to provide the ultimate load with the pulse duration and shape needed. Generally, one of two approaches is used to charge the pulse forming network. The first is that the output current is held constant through the pulse. The second is that the output current field is ramped, consistent with a linearly increasing power, e.g. in the charging of a capacitor.

Consider a one turn winding having cross sectional area A, length L, conductivity σ, mass density ρ, carrying current density J. The resistive dissipation in the winding is

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$$P = \left(J \cdot A\right)^2 \frac{L}{\sigma A} \tag{1}$$

Adiabatic heating demands a commensurate temperature change ΔT in δt seconds of

$$P\,\delta t = \rho C_p \left(AL\right)\Delta T \tag{2}$$

Substituting (1) into (2) yields the current density in this one turn winding independent of area to be

$$J = \sqrt{\frac{\rho\sigma C_p \cdot \Delta T}{\delta t}} \tag{3}$$

Irrespective of the conductor size, the current density is dictated by the adiabatic temperature jump allowed. The conductivity, density, and specific heat for copper are respectively $5.8 \cdot 10^7$ S/m, $8.9 \cdot 10^3$ kg/m^3 (0.323 lbs/in^3), and 383 J/kg/K. The conductivity drops to $4.3 \cdot 10^7$ S/m at 100˚C.

The allowed current density assuming a 58% packing factor, a 100˚C rise, with a 9.6 s duty cycle would be

$$J_{@\,58\%\,Cu} = 0.58 \cdot \sqrt{\frac{4.3 \cdot 10^7 \cdot 8.9 \cdot 10^3 \cdot 383 \cdot 100}{9.6}} = 2.26 \cdot 10^7 \frac{A}{m^2} \tag{4}$$

Suppose the pulsed power device is charging a capacitor of capacitance C to a final voltage V_f in τ seconds with a constant current I_a. If the energy source is a flywheel of inertia I_m with initial speed Ω_0, the rotational speed will decay as

$$\Omega = \sqrt{{\Omega_0}^2 - \frac{C{V_f}^2}{I_m}\left(\frac{t}{\tau}\right)^2} \tag{5}$$

Let $\beta = C{V_f}^2/(I_m {\Omega_0}^2)$. Since power is the product of torque and speed, the torque will have the time dependence

$$T = \frac{I_a V_f \left(\frac{t}{\tau}\right)}{\Omega_0 \sqrt{\left(1 - \beta \cdot \left(\frac{t}{\tau}\right)^2\right)}} \tag{6}$$

The field current I_f will have the same time dependence as torque since armature current is controlled as constant. The field current can be expressed in terms of its end value I_e as

$$I_f = \frac{I_e \sqrt{1-\beta}\left(\frac{t}{\tau}\right)}{\sqrt{1 - \beta\left(\frac{t}{\tau}\right)^2}} \tag{7}$$

The power dissipation in the rotor conductors with cumulative resistance R_f over the excitation time τ is

$$Loss = R_f \int_0^\tau {I_f}^2\, dt = R_f \frac{\tau {I_e}^2 \left(\left\{\tanh^{-1}\left(\sqrt{\beta}\right) - \sqrt{\beta}\right\}\left(1-\beta\right)\right)}{\beta^{\frac{3}{2}}} \tag{8}$$

Consider a rotor excited with a constant field current I_0 for τ seconds. The dissipation loss in a rotor excited with this current will be identical to the one in the real rotor if

$$I_e = I_0 \sqrt{\frac{\beta^{\frac{3}{2}}}{\left(\left\{\tanh^{-1}\left(\sqrt{\beta}\right) - \sqrt{\beta}\right\}\left(1-\beta\right)\right)}} = 2.198\ I_0 \tag{9}$$

Assuming a 100˚C change in temperature and a packing fraction of 58%, again for a 9.6 second duty cycle, the ending rotor field current density should be

$$J_{@\,58\%\,Cu} = \frac{I_e}{I_0} \cdot 0.58 \cdot \sqrt{\frac{4.3 \cdot 10^7 \cdot 8.9 \cdot 10^3 \cdot 383 \cdot 100}{9.6}} = 4.99 \cdot 10^7 \frac{A}{m^2} \tag{10}$$

Thus, depending on the excitation profile, the current density can be pushed to between 2.26 and $4.99 \cdot 10^7$ A/m^2 for this choice of a duty cycle.

III. Energy Densities of Permanent Magnet versus Copper Coils

A. Case Study #1 Radial Flux

The basic permanent magnet and copper coil test rigs used for comparison are shown in Fig. 1. The permanent magnet approach is assumed to be composed of 45 MGO magnets at room temperature in a Halbach array. To make a fair comparison on a weight basis, the equivalent copper rig has to be penalized twice. First, because of the density of the steel and the copper is greater than that the neodymium iron boron magnet material, the steel/copper volume has to be reduced by the increased density. Second, a penalty has to be added for the weight of the exciter that is required if a copper field coil is employed but not in a permanent magnet approach. So, for an equivalent weight comparison, the active volume of the copper coil system must be smaller.

In reality, some comparable penalties should be imposed for the magnet due to the following:

- The magnet will not be operated at 20˚C, but at a higher temperature.
- The field from a permanent magnet is always energized. Additional weight penalties should be factored in because resistors are required to limit in-rush current during the charging cycle for a

permanent magnet. In addition, thyristors are required to isolate the voltage source after charging whereas the field can be isolated and clamped with a crow bar circuit after charging.

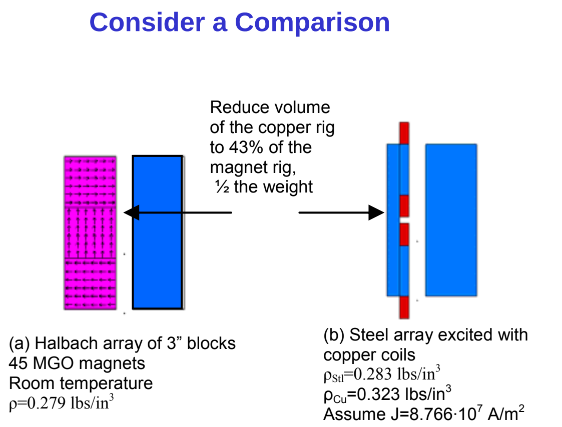


Fig. 1 Halbach array against a copper coil array with 57% less volume.

To quantify the size reduction appropriate for the copper coils, the weight of the exciter was estimated to be 10% of the weight of the generator, and the weight of the rotor copper in the generator was estimated to be 20% of the working weight of the generator. Using these two assumptions, the second penalty against the steel/copper alternative should be about 50%. The weight of the steel and copper used in inset (b) of Fig. 1 is set to be equal to that of three (3") Halbach magnets, and then reduced by another 50%. When the density of the copper and steel is considered, the volume of the copper rig (with steel) must be reduced to 43% of the magnet array. Note the copper has been reduced assuming a 100% packing factor, so the current density is adjusted accordingly (4.99/0.58=8.76) to be consistent with this penalty in allowed volume.

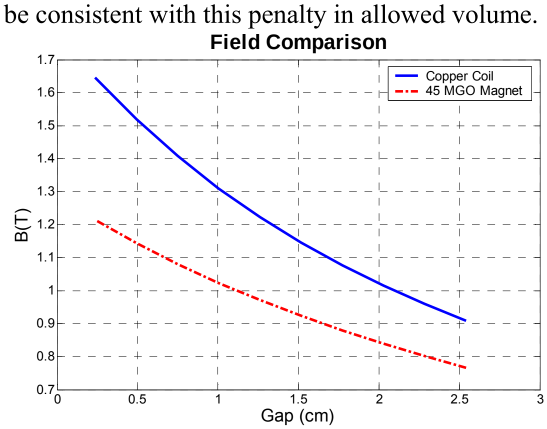


Fig. 2 Magnetic field density created for a copper coil versus a permanent magnet under pulsed power conditions.

For an air gap ranging from 0.25 cm up to 2.54 cm (1"), the flux through the lower pole face is computed using a finite element solver in saturation. Fig. 2 shows the copper coil produces a significantly larger air gap field, and so a larger current in the stator than the permanent magnet configuration.

B. Case Study #2 Axial Flux

A favored topology for this application using magnets is an axial flux machine in which the stator wraps the rotor and provides the steel for field closure. A cross-section representative of this arrangement is shown in Fig. 3. As with case study 1, the volume of the copper coil available is reduced to 0.43 of the volume of magnet used, and the copper excited with current density $J=8.76\cdot10^7$ A/m^2. The rms air gap field for the copper and permanent magnet options is 0.816 T, and 0.564 T respectively, and the B field along the segment annotated in Fig. 3 is shown in Fig. 4.

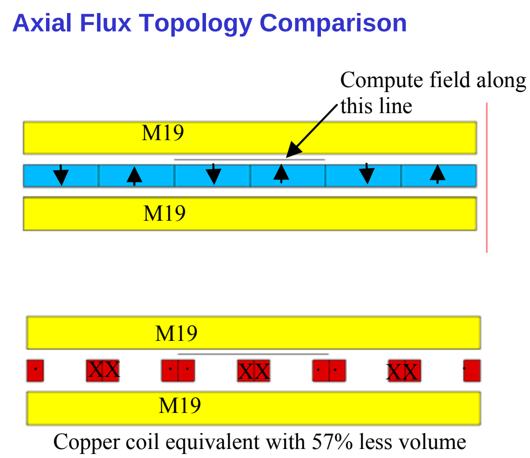


Fig. 3 Transverse topology – magnets versus equivalent copper cross-section.

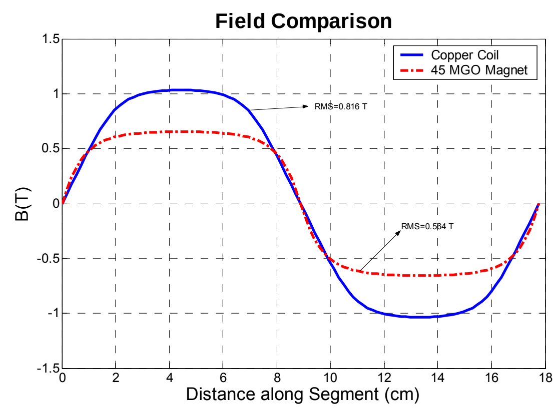


Fig. 4 Field comparison for an axial flux topology.

Again, the copper coil produces a significantly larger air gap field.

C. Case Study #3 Radial Flux using Metal Coated Carbon Fibers

While the previous cases focused on conventional topologies for rotating machines, an unconventional approach was also analyzed. This inside-out machine incorporates the performance of iron coated carbon fibers bound in a carbon composite structure. This material can be treated as a soft steel backdrop for closure of the magnetic field. The relative permeability is quite low due to the packing of the fibers, but the saturation of the material remains high. An estimate of its BH material curve is shown in Fig. 5. The relative permeability at the origin is only 75.

The configuration with this material is very favorable to copper, and is shown in Fig. 6. Inertial energy storage is achieved by adding a flywheel, i.e. additional composite material, to the rotor.

The magnets and copper are mounted on the inside of the flywheel. The volume of the 1” by 3” magnets is reduced in two and then reduced again to appropriately account for the increased density of copper and steel as shown in inset (b). The rms B field for 45 MGO magnet and copper become respectively 0.74T and 1.35 T respectively; the B field plot comparison is shown in Fig. 7.

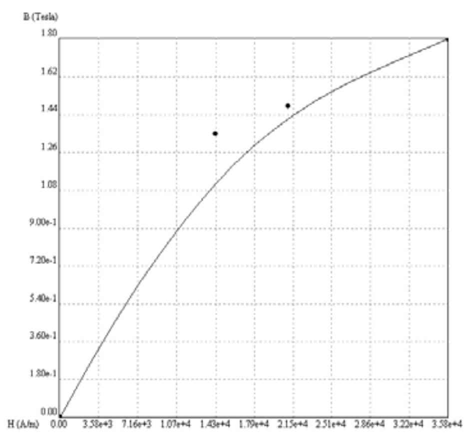
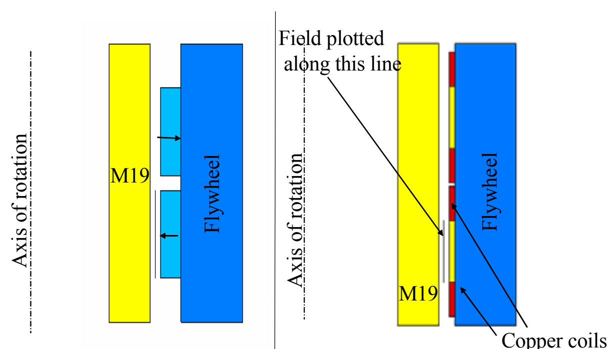


Fig. 5 Estimated B-H curve for coated carbon fiber.



(a) 1 by 3 inch magnets within a ½” air gap

(b) Equivalent copper and steel for ½ the volume again reduced by the weight densities for steel and copper

Fig. 6 Configuration using coated carbon composite fibers for the flywheel.

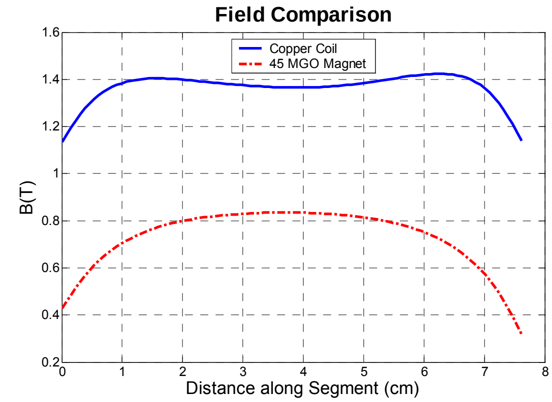


Fig. 7 Comparison of normal B field in the center of the ½” air gap.

IV. Conclusions – Permanent Magnets versus Copper Coils

Based on the point designs considered, pulse power generators with duty cycles in the neighborhood of 10 to 20 seconds, or less, can have significantly better performance per unit weight if they are wound rotor machines employing copper coils rather than permanent magnet machines. The technology developed in this direction will be superior to permanent magnet rotors in terms of power density. Three areas that will further advance the power density of this technology are as follows: (1) Integrating the copper and steel into the flywheel energy containment component, (2) Using high temperature insulators. Although ceramic insulators are difficult to work with, they can easily extend the useful temperature range towards 300˚C as opposed to the 180 ˚C used here, (3) Pre-cooling the rotor to allow for a larger adiabatic jump.

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