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M. D. Driga, K. E. Nalty, R. C. Zowarka,
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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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Center for Electromechanics
The University of Texas at Austin
Austin, TX 78712

Summary

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has carried out several major experimental programs using homopolar generator (HPG)-charged inductors; namely, the fast discharge experiment (FDX) field coil experiments, the General Dynamics single-shot railgun, and the compact homopolar generator/inductor (CHPG/I) experiments. As a result of this experimental and theoretical work, CEM-UT experience with modeling and predicting the performance of HPG-charged inductive energy store systems has been refined. This paper presents techniques found useful for estimating and modeling of HPG inductive energy store systems.

Introduction

In the last years the homopolar charged inductors have evolved as a promising compact, high performance and relatively inexpensive power supply for a variety of electromagnetic launcher (EML) applications. An essential contribution in this direction was the CEM-UT designed and fabricated compact homopolor generator (CHPG) with a liquid nitrogen cooled inductor which significantly advanced the state of the art in stored energy and power density.

The Center for Electromechanics tradition in designing, fabricating, and testing homopolar generator charged inductors goes back to the formation of CEM-UT in 1972 and the first HPG design, envisioned as a competitive power source for toroidal coils in Tokamak fusion reactors.

However, the first true experiment in this direction performed in 1977 at CEM-UT was the "slow" discharge of a 5-MJ homopolar generator into the field coil of a "fast" discharging homopolar machine, FDX, with the intent of producing a relatively high, pulsed excitation field.

In 1981, a joint project between CEM-UT and General Dynamics Corporation, was the driving of an electromagnetic gun with the CEM 10-MJ HPG charging an energy storage inductor. The inductor selected was a Brooks coil design of 13 μH.

The CHPG, already mentioned was completed in August 1982 and stores 6.2 MJ weighing 3,400 lb_m representing a gain in stored energy density of at least a factor of two over previous HPG's.

A 3,000 lb_m liquid nitrogen cooled, aluminum inductor, rated to store 3.1 MJ at 1.0 MA, was built to provide power conditioning for different electromagnetic launcher applications.

The modeling of these experiments, the theory developed to predict the results, the tests performed, and the comparison of the results obtained from tests with the theoretical assumptions led to a refinement of the techniques for designing and fabricating HPG charging inductors.

An application of such modeling was used in the design and fabrication of the group of six HPG which will constitute the 60-MJ power supply installed at the new CEM facility for research in pulse power technology at Balcones Research Center. The inductors in which the power supply is discharging are optimized using results from the mentioned experiments.

Theoretical Considerations

A simple circuit model for a homopolar pulsed power supply discharging into an inductor is an RLC circuit in which the capacitor models the homopolar machine[1,2]. The expression for the capacitance C is:

$$C = \frac{4\pi^2 J}{\Phi^2}$$

where C = capacitance (F)
J = moment of inertia for HPG (kgm^2)
Φ = total magnetic flux (volt sec) .

For this reason the standard curves describing the RLC circuit are widely used to characterize the HPG discharge into an inductor. The circuit parameter

$$\gamma = \frac{R}{2}\sqrt{\frac{C}{L}}$$

defines if the system is overdamped ($\gamma > 1$), underdamped ($\gamma < 1$) or critically damped ($\gamma = 1$).

There are several effects which complicate the physical picture and require corrections which in many cases are substantial:

- Armature reaction with strong demagnetizing effects
- Flux and current transient diffusion phenomena
- Charging losses

Armature Reaction

In HPG's the rotor iron serves both as an excitation flux return path and as a conductor for the armature discharge current which in turn produces a magnetic field normal to the excitation magnetic field. Actually the superposition of the two magnetomotive forces (excitation and rotor current) create a resultant field which leads to a strong saturation of selected parts of the rotor resulting in a decrease of induced voltage. This nonlinear phenomenon is known as "armature reaction."

There are several ways to evaluate the armature reaction. One is with three-dimensional finite-element codes-transient, nonlinear, which demand very powerful computers. In the present paper a simplified model is presented. This model shows a good agreement with the experimental data. It replaces the magnetic circuit of the generator with a cylinder of ferromagnetic material with the same cross-sectional area. The mean length of the flux lines is the length of the cylinder connected in series (magnetically) with a cylinder of air modeling the air-gap and a cylinder of copper modeling the coils. To reflect the closed path seen by the flux, this series of cylinders is infinitely repeated in both directions and surrounded by periodic field coils. The reason for such topological transformation is to provide a geometry which allows easy solutions of the field equation for eddy currents.

Applying Ampere's law to the contour A (fig. 1a)

$$\oint_A \bar{H} \cdot \overline{d\ell} = \iint_{S_A} \bar{J} \cdot \overline{ds} = NI + \iint_{S_A} \bar{J}_{eddy} \cdot \overline{ds} \qquad (I)$$

which singles-out from the total magnetomotive force, the eddy current contribution. For the simplified cylindrical geometry the current density for eddy currents

$$\bar{J}_{eddy} = \sigma \bar{E}_{eddy} = -\frac{\partial B_z}{\partial t} \int_b^{r_o} \left(\frac{\sigma r}{2}\right) \bar{a}_\theta dr \qquad \text{(II)}$$

where

σ = conductivity $(\Omega m)^{-1}$
B_z = z component of flux density (T)
r = radius (m)
a_θ = unit vector

Substituting II in I leads to

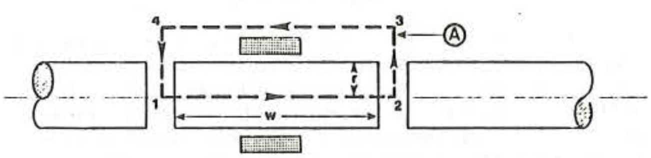
$$\int_o^w \left(\frac{B_z}{\mu}\right) dz + \int_o^w \frac{\partial B}{\partial t} \left(\frac{\sigma r_o^2}{4}\right) dz = NI \qquad \text{(III)}$$

and B_z can be taken out of the integral sign. Considering the material homogeneous, follows directly that the time constant for the magnetic field

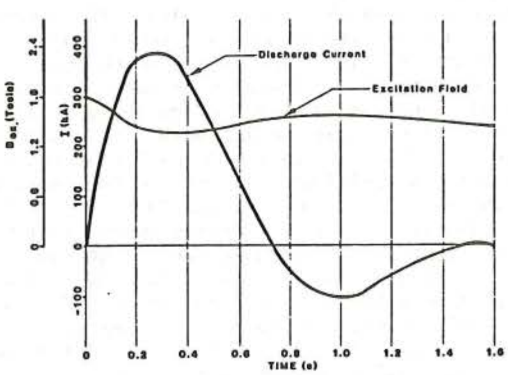
$$\tau = \frac{\mu \sigma r_o^2}{4}$$

The CHPG has a constant magnetic cross section design with circular symmetry, consistent with the previous assumptions. Model the machine as a cylinder whose length is the mean flux path and whose area is that of the bore of the rotor. For the path contained in iron, we have $\mu = 10\mu_o$, $\nu = 4 \times 10^6$ mhos/m, ℓ = 0.96 m, and r = 0.194 m. For the path contained in copper, we have $\mu = \mu_o$, $\sigma = 9.8 \times 10^7$ mhos/m, ℓ = 0.00127 m, and r = 0.194 m. For the air, we have $\mu = \mu_o$, ℓ = 0.003 m and σ = 0.0. Using these numerical values in (5), τ becomes

$$\tau_{exc} = 0.484 \text{ s}$$



a. Idealized model



b. Measured values for discharge current and excitation field

Figure 1. Armature reaction in HPG/I

The value of the time constant when considering only the iron contribution is

$$\tau_{exc} \cong 0.472 \text{ s}$$

It can be seen that the iron dominates the time constant. Using similar consideration we arrive at a transient model which yields:

$$\frac{\dot{B}_T}{B_T} = -\frac{\dot{B}_\theta B_\theta}{B_T^2} = \frac{k^2 I \dot{I}}{B_T^2}$$

where the dot indicates the derivative with respect to time.

To account for μ_r changing, and to simplify computer models, we may limit $\dot{B}_T/B_T$ to the eddy time constant. Due to the difference in geometry between the CHPG and the infinite cylinder model, we have to choose K empirically (k = 3.6 gives good results).

A simple model for armature reaction using the short time constant formula for the armature field provides a good match to experimental data. The excitation time constant used was 0.47 s, and the sensitivity for the B_θ was chosen as k = 3.6.

As an example the discharge current and the excitation field are shown in Figure 1b for one of the runs of the CHPG. The fields are measured with Hall probes. The excitation power was deliberately shut off one second after the discharge begun. The armature reaction lags the excitation current.

Transient Field Diffusion Phenomena

To solve problems involving transient field diffusion in HPG a transient finite element electromagnetic code was developed at CEM-UT. The TEXMAP code was reported in (3) and has a feature "PENFLD" capable of computing the field penetration, as a marching in time, Galerkin formulation.

An alternate method employed for field diffusion calculation in simpler homopolar devices was to use for the diffusion equation[2]

$$\frac{\partial^2 Jr}{\partial z^2} = \mu\sigma \frac{\partial Jr}{\partial t}$$

a infinite series solution for the current density, J

$$J(z,t) = J_{of}[1 - \sum_{n,odd} \frac{4}{\pi n} \cos \frac{\pi n 2}{w} \exp(-\frac{n^2 t}{\tau d})]$$

where

J_{of} = final value of current density $(\frac{A}{m^2})$

$\tau_d = \frac{\mu\sigma w^2}{\pi^2}$ time constant for diffusion (sec) .

The coupling of the transients in the machine with the transients in transmission line and inductive load are difficult in the simplified approach, and automatically taken into account in TEXMAP code if enough nodes are allowed for the finite element model.

5-MJ Charging FDX Field Coil

The FDX was a 0.36-MJ 200-V homopolar machine designed to investigate limitations of homopolar machines, exceeding the state-of-the-art of HPG's (fig. 2).

To decrease the capacitance of the machine, a high field of excitation was needed. It had a room temperature, four turn copper field coil, pulsed by the CEM 5-MJ slow discharge homopolar. The coil (fig. 3) had a total inductance of 8.5 μH and an initial resistance of 62 $\mu\Omega$ which increased to 74 μH due to the 73 °C temperature rise during the pulse. The eddy

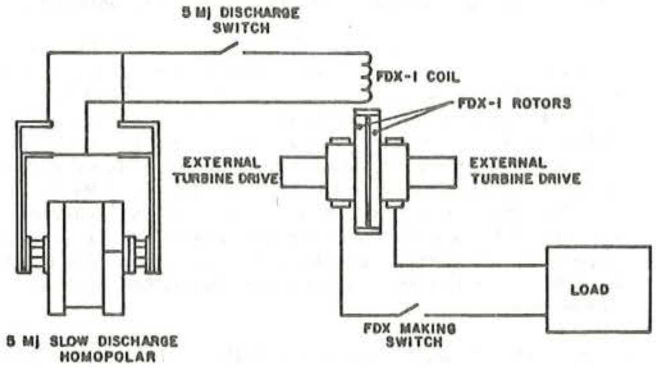


Figure 2. FDX experiment

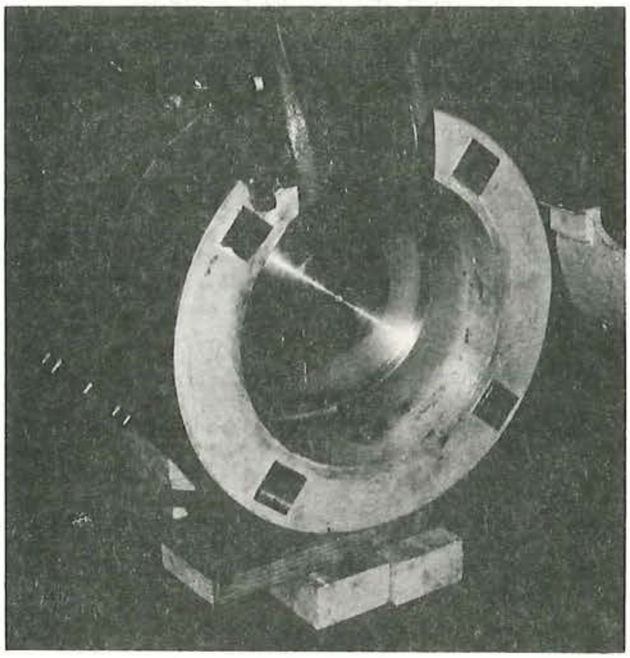


Figure 3. FDX field coil

currents in the rotors and surrounding structure produced a lag between the time of maximum current in the FDX coil (0.364 MA) and the time of maximum excitation field (0.35 T average). The time lapse measured 0.22 s.

The calculations for the field penetration were performed using TEXMAP, transient nonlinear finite element electromagnetic code[3] and the agreement with measured data was good. The demagnetization due to the armature reaction was between 8 to 14 percent of the full excitation field for the 5-MJ HPG.

10-MJ HPG Charging Brooks Inductor

In 1984, General Dynamics sponsored additional research at CEM, using the 10-MJ HPG and Brooks inductor to power a rep-rated electromagnetic propulsion experiment. This project necessitated an upgrade of the inductor charging busbar path to enable higher inductor peak current (therefore energy). This upgrade consisted of two major tasks; 1) the 103.2-cm^2 aluminum busbar circuit was replaced with a 180.6-cm^2 copper circuit, and 2) the crowbar switch position was changed and a new, identical switch added in parallel to the original (fig. 4).

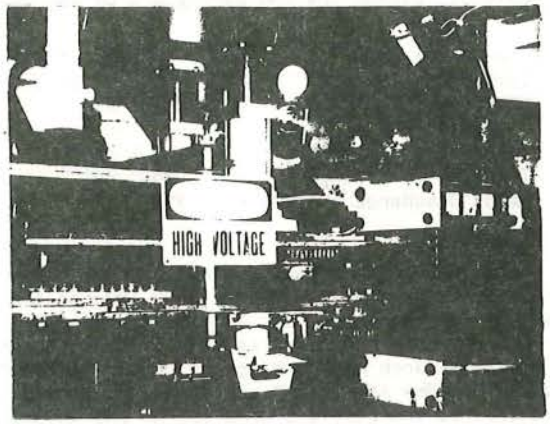


Figure 4. HPG charging Brooks inductor

Performance

The HPG-inductor circuit was modeled using lumped parameters and calculated or known values. The charging performance of the inductor, warm and liquid nitrogen-cooled, are summarized in Table 1.

Experiments

To protect the HPG from back EMF generated by the experimental railgun, a mechanical signal, generated by the closure of both crowbar switches, was used to enable the experiment's controller. Crowbar switch triggering was by digital timer, set to correspond with peak inductor current.

The charging circuit was overdamped due to the external (warm) elements in the circuit, especially the lengthly and narrow transition busbars. Also, the heavy tie-ins to the inductor output plates, at 180.6 cm^2 of copper, acted as a significant heat input to the inductor, raising its resistance. Thus inductor charging efficiency was reduced, and the crowbar pulse current amplified (Table 2).

Table 1. Brooks inductor performance after system modification

	WARM	LN_2-COOLED
Resistance, μΩ	18.3	12.7
Inductance, μH	10.0	10.0
Rise Time, ms	356	350
Peak Current, kA	105	460
Energy Stored, MJ	0.11	1.57

Table 2. GD-460 Discharge parameters

HPG Discharge Speed, rpm (s^{-1})	5,000 (523.6)
HPG Brush Tip Speed, m/s	192.8
HPG Excitation, A	1,200
HPG Open Circuit Voltage, V	42.5
Peak Inductor Current, kA	460
Peak Crowbar Current, MA	1.1
HPG Energy, MJ	8.78
Inductor Energy, MJ	1.57

CEM CHPG Charging a Compact Storage Inductor (CSI)

The CHPG developed at CEM-UT has been the object of several papers.[4,5] The machine has the parameters given in Table 3.

Table 3. Dimensions and parameters of the CHPG

Stored energy	-	6.2 MJ at 6,245 rpm
Terminal voltage	-	50 V at 6,245 rpm
Effective machine capacitance	-	4,960 F
Internal resistance	-	7.5 $\mu\Omega$
Internal inductance	-	30 nH
Rated discharge current	-	750 kA

It began as an effort to design, fabricate, and test an HPG which will substantially advance the state-of-the-art in density of stored energy and delivered power, under the sponsorship of the U.S. Army Armament Research and Development Command (ARRADCOM) and the Defense Advanced Research Projects Agency (DARPA). It inertially stores 6.2 MJ and weighs 3,400 lb_m which is a gain in energy density stored of at least a factor of two.

A 3,000 lb_m liquid nitrogen cooled aluminum inductor rated to store 3.1 MJ at 1.0 MA was built to provide power conditioning for a wide range of EML experiments.

In a short-circuit test from 1,360 rpm, the machine generated 1.02 MA, 36 percent higher than the design level. At this current level and with the fast current rise time (15 ms to peak), the internal resistance was 10 $\mu\Omega$. there was no significant armature reaction. The experimental machine components -- all peformed successfully.

The inductor design was optimized as to overall system performance. Several designs were tested, including those of Brooks coils, toroidal Bitter plates, and pie-segment configurations. This led to the choice of the five-turn coaxial inductor. The work leading to this design has been previously presented.[5] The 6.2-nH inductor has a 1.23-m outer diameter and a 0.91-m active length (fig. 5).

The inductor is expected to operate at 1 kV, but has been designed to withstand 5 kV. The 0.32-cm insulating gap between conductors is vacuum impregnated with high-strength glass-filled epoxy.

There is, however, one concern. The armature reaction at higher currents begins to play a more important role.

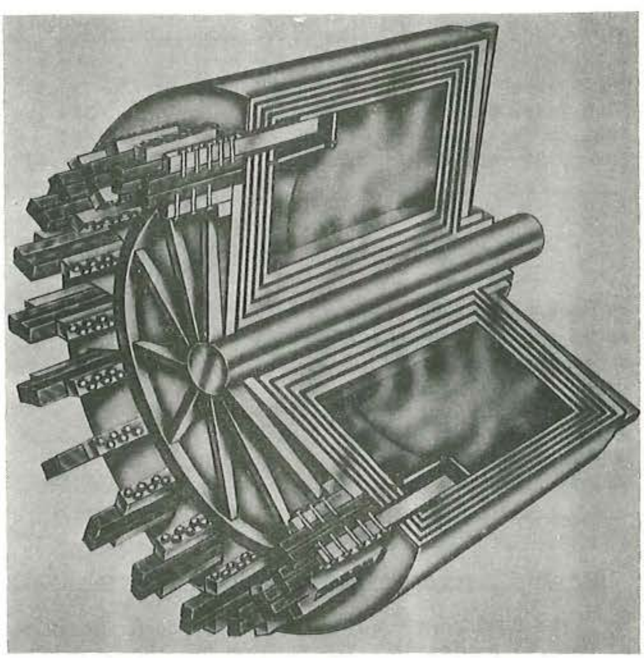


Figure 5. Compact storage inductor charged by CEM HPG

Inductor Design for the Balcones Homopolar Generators

As a conclusion of this outline on HPG charged inductors, a particular feature from the optimization process will be given. It applies[6] to the CEM new high current power supply built at Balcones Research Center at The University of Texas. The six HPG's, each of them rated at 10 MJ can provide 6 MA of pulsed current. (The system could be upgraded to 9 MA.)

An inductor was to be designed for the Balcones HPG (BHPG) to achieve a charging efficiency of around 50 percent at maximum current, 1.5 MA. The model for the BHPG/I system is based on the following system parameters:

$$J_{BHPG} = 49.2 \text{ N-m-s}^2 \qquad \phi_0 = 1.085 \text{ Wb} \qquad T_b = 1{,}370 \text{ N-m}$$

Rated angular velocity of the BHPG = 637 rad/s

$$R_g = 8.88\ \mu\Omega \qquad L_g = 0.175\ \mu H$$

Based on the armature reaction model, the flux linking the BHPG, ϕ depends on the BHPG current, i_g only for $i_g > 200$ kA as:

$$\phi/\phi_0 = 1 - [2.6 \times 10^{-14}(i_g - 200{,}000)^2 + 2.3 \times 10^{-7}(i_g - 200{,}000)]$$

The BHPG parameters above were implemented in a computer code which performs parameter search. A final inductor design has not been reached but the parameter space has been narrowed down to the following :

1) the inductor is to have two turns and the material will be ETP copper
2) the inductor length will be around 3.05 to 6.09 m
3) inductor outer diameter will be between 101.6 and 177.8 cm
4) to decrease the resistance, the inner conductors may be cooled with liquid nitrogen
5) the inductance is expected to be between 3 and 10 μH

Acknowledgments

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