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MASTER

DESIGN, FABRICATION AND TESTING OF A FAST DISCHARGE HOMOPOLAR MACHINE (FDX)

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Summary

The Fast Discharge Experiment (FDX) is a 0.36 MJ, 200 V homopolar machine designed to discharge in one millisecond. All components, including dual brush actuation systems, a room-temperature 2×10^6 A-t pulsed copper coil, two aluminum rotors with copper slip rings, low inductance return conductors, coaxial transmission line, four fast closing (30 μsec), megamp switches, hydrostatic journal bearings, squeeze film thrust bearings and a fiberglass reinforced epoxy structure have been fabricated and assembled. The detail design of machine components is presented.

Preliminary testing, including rotor spin-ups, brush actuation, switch making, and pulsed field coil tests have been concluded. A low speed, short-circuit discharge of FDX has recently been conducted. Experimental data from these tests are compared with theoretical predictions.

Introduction

Anticipated power requirements in high energy physics applications, particularly controlled thermonuclear experiments, have established the necessity for designs of inexpensive, powerful, pulsed power supplies.

Fast discharging homopolar machines inertially store large amounts of energy (at least 50 times more per unit volume than a static capacitor) and then electromechanically convert the energy in about one millisecond. These machines, at a cost of two cents per joule, are substantially less expensive than capacitor banks, which cost about 25 cents per joule. Although fast discharging homopolar machines have been considered as possible power supplies for some systems, to date no experimental data exists for rotating electrical machinery operating in this regime. The CEM has designed, manufactured and began the testing of a very fast discharging homopolar machine. FDX is the first fast discharging homopolar machine to be tested. The successful discharging of this machine in one millisecond will verify theoretical analysis, and will prove the feasibility of using homopolar machines as pulsed power supplies for future high energy applications.

The Fast Discharge Experiment (FDX) (Figure 1) is a fully compensated pulsed field homopolar generator. Using two counterrotating rotors shaped for minimum inertia, the machine stores 0.36 MJ of energy at an angular velocity of 3000 $\frac{\text{rad}}{\text{sec}}$ (28,650 r/min). From 1500 $\frac{\text{rad}}{\text{sec}}$, the rotors will stop in approximately one ms producing about 2.0 MA into a short circuit (Figure 2). The rotors will than reverse directions as the machine rings on its internal inductance. Because of exaggerated current densities in the brushes, the machine cannot discharge into a short circuit from full speed (3000 $\frac{\text{rad}}{\text{sec}}$). However, from full speed, the machine can discharge into a useful (0.275 μH) load in about 3.5 ms. The pulsed magnetic field averages 4.0 T in the active portion of the rotors during discharge, resulting in a machine voltage of 208 V at full speed.

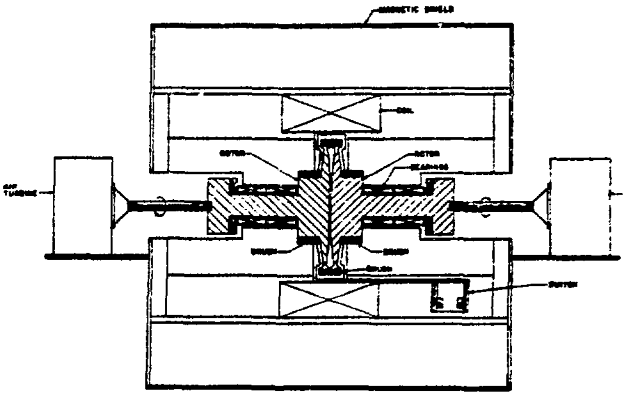

Figure 1. FDX Homopolar Machine

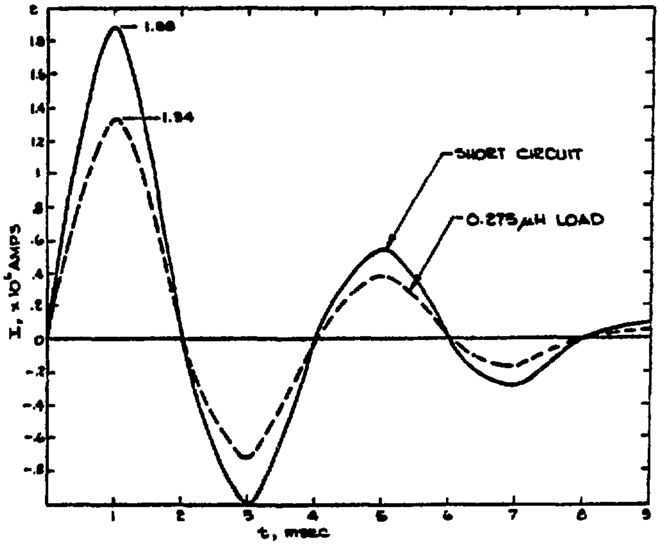

Figure 2. FDX Output Current

The FDX machine was designed to investigate limitations and therefore exceeds the state-of-the-art in some parameters. The current collection system, traditionally the difficult mechanism in a homopolar machine, will have to operate in very high magnetic fields (up to 6.0 T), withstand large current densities (up to 8,000 A/cm^2) and make contact with a rotor surface moving at 450 m/sec. The rotors are made of aluminum, a first for homopolar machines, and the slip ring surfaces have been coated with copper. FDX has a room-temperature, four-turn copper field coil which is pulsed by the existing CEM 5 MJ slow discharge homopolar machine (Figure 3). A making switch capable of carrying 2.0 MA with a current rate of rise of 2900 A/μsec was required for current initiation. This rise time precludes a conventional making switch. A metal-to-metal switch based on the magnetic repulsion system was designed and is presented in a companion paper.[1]

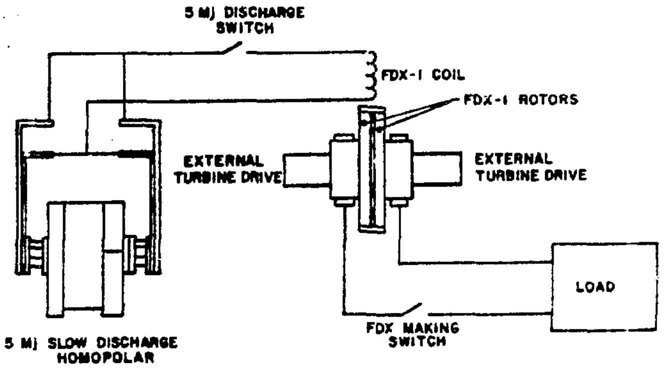

Figure 3. 5 MJ Machine as Power Supply for FDX Field Coil

FDX will explore the forces generated during a discharge from misalignment of the rotors with respect to the compensating turns as well as the repulsion forces between the rotors and compensating turns. The machine will investigate the electromagnetic diffusion effects in conducting components. Designing this machine has produced magnetic field calculations using a homopolar generator as a power supply, current diffusion predictions, rotor and bearing analysis and a complete fast discharging homopolar machine design.

Manufacturing of the machine is completed and testing has begun. Component tests have been completed and an initial, short circuit discharge has been achieved.

FDX Machine Design

The FDX machine consists of two 30.5 cm diameter, counter-rotating aluminum rotors, supported in cantilevered oil-lubricated hydrostatic journal bearings, inside the FDX field coil. It has dual current collection systems, a coaxial transmission line, and four fast-closing (30 μsec) making switches. The FDX field coil is a room temperature, pulsed copper coil driven by the existing CEM 5 MJ, slow discharge, homopolar machine. Each rotor is driven through a shear link by a turbine which operates on compressed air. Upon initiation of discharge, rapid decelleration of the rotors will shear the links, decoupling the rotors from the turbines. These turbines are mounted on each end of the 2.0 cm thick magnetic shield (see Figure 1) which surrounds the rotors, coil, and supporting structure and contains the high, pulsed magnetic field. The supporting structure is fabricated from glass cloth reinforced epoxy in order not to shield the rotors from the pulsed magnetic field nor to reduce the field level due to eddy-current generation. Two brush mechanism and transfer designs were required, one to collect current from the rotors' shoulders to the stationary comp turns, the other to transfer the current from one rotor into the other. The shoulder brush mechanism is inherent only to FDX; however, the rotor brush mechanism is applicable to most multiple rotor homopolar configurations. Because of the extremely fast rise time (2900 A/μsec) and large current (2×10^6 A), a one shot mechanical switch based on the magnetic repulsion principle was required. The switch initiates current in FDX by rapidly expanding an aluminum ring which bridges two stationary contacts. In the final design four switches located symmetrically around the outer coaxial transmission line were necessary to maintain as nearly as possible uniform current distribution, minimal impedance, and adequate access.

The rotors are made from 7050 aluminum alloy which was selected for its strength, conductivity and lack of notch sensitivity. The rotors are tapered with a brush contact surface on the outer diameter. The inner brush surface is at 1/2 the outer diameter. These surfaces are flame sprayed with a layer of copper to create a slip ring surface for the current collection system. The shaft of the rotor and the thrust bearing runner which is bolted to the shaft are hard anodized, providing electrical insulation and a hard bearing surface. The maximum stress in the rotor (275 MPa) occurs during discharge and is caused by current repulsion forces.

The FDX coil has four turns of 3.5 cm thick by 7.5 cm wide copper bar. It has a total inductance of 8.5 μH and an initial (room temperature) resistance of 62 μΩ which rises to 74 μΩ due to a 73°C temperature rise during the pulse. Due to eddy currents in the rotors there will be a lag between the time the current in the FDX coil reaches its maximum value of 0.364 MA and the time the excitation field reaches its peak value. The time lapse between beginning the discharge of the 5 MJ machine into the FDX field coil and the maximum excitation field at the FDX rotors is 0.22 sec (see Figure 4).

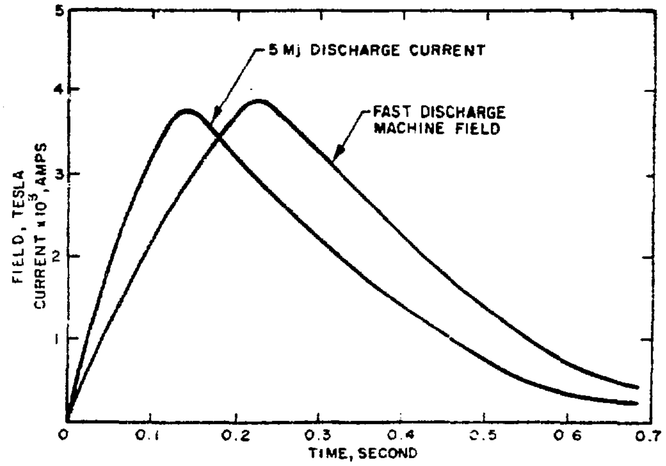

Figure 4. 5 MJ Machine-Fast Discharge Field Coil (Predicted Performance)

The eddy currents and their magnitude in time determine the magnetic pressure applied to the rotors and the temperature of the rotors at discharge. Because of eddy current and field penetration problems a compromise was incorporated by making the return conductors from aluminum instead of copper. The lower conductivity of aluminum will avoid exaggerated values of eddy currents and accelerate the field penetration. A superconducting coil would solve the eddy current and penetration problems allowing a more efficient return conductor.

Hydrostatic bearings were chosen because they allow extremely high stiffness and introduce damping into the rotor/shaft/bearing system. There are two journal bearings on each shaft. They are conventional, orifice-compensated, four-pocket bearings made from a 60% Cu/40% Pb material. A one-sided hydrostatic thrust bearing is used to axially position the rotor. The thrust bearing in the air turbine is used to counter the force from the hydrostatic thrust bearing. Upon discharge the two rotors are forced together with a force of approximately 4.5×10^5 N. The thrust bearing withstands this force by changing from the hydrostatic into a squeeze film regime for the period of the discharge.

A current collection system, consisting of two sets of inner brushes on the rotors' shoulders, and one common set of outer brushes on the rotors' outer diameters is being used on FDX. The FDX rotor brush mechanism (Figure 5) places the brush onto both rotor surfaces, connecting the rotors in series. The brush material used for FDX is a sintered copper-graphite composite previously tested and used on the CEM 5 MJ machine. There are 36, 2.54 cm wide by 5.4 cm long rotor brushes equally spaced around the rotor periphery. This represents a rotor brush packing factor of 95%. Actuation is possible by pulsing the pocket formed by the rubber diaphragm with either air or hydraulic fluid or by passing current through the braided wire strap, creating a current perpendicular to the magnetic field of the main coil. In passing a predetermined current through the strap, the brushes can be actuated with a given force at the peak field, creating a self actuating mechanism. A combination of both actuating techniques will probably be required to achieve the necessary timing. After establishing current flow, the brushes are forced onto the rotor by the repulsive forces between the brushes and the return conductor which conduct large currents in opposite directions. The rotor brushes must establish contact with the rotor surface moving at 450 m/sec and are required to conduct current densities up to 8000 A/cm^2. Both parameters exceed present performance levels. Addidionally, the brush mechanism must operate in a magnetic field as high as 6.0 T.

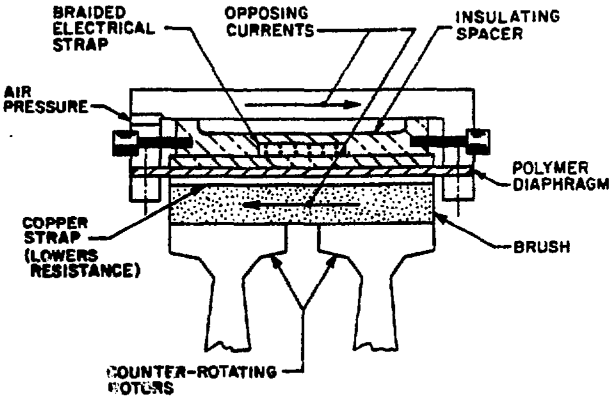

Figure 5. FDX Rotor Brush Mechanism.

There are 18, 2.54 cm wide by 5.04 cm long shoulder brushes equally spaced around the inner brush shoulder on each rotor. They represent a more difficult design goal than the rotor brush mechanism in that they must conduct the discharge current from the moving slip ring surface to the stationary compensating conductor with minimum inductance, while maintaining the 95% packing factor. As shown in Figure 6, the mechanism is actuated by an air cylinder mounted in a fiberglass structure. As in the other brush mechanism, the large current-induced repulsion forces in the conductors hold the brushes firmly on the surface after current begins to flow. Large shear and bending forces are present upon contact and are countered by the heavy section of the copper strap and the shear pin, which also guides the brush.

Because of the large current densities involved, both mechanisms require packing factors exceeding 95%. The brush mechanisms strongly influence the overall performance of the machine. These configurations combine simplicity, use of the current to maintain contact and high packing factors.

Since the machine as a source represents an impedance of 15.4 nH and 18 $\mu\Omega$, it was imperative to design a switch which added an absolute minimum of impedance to these values. The performance requirements made a metal-to-metal switch based on the magnetic repulsion principle particularly attractive. Conditions of access, symmetry and the desire to minimize impedance all indicated that it was advantageous to use four switches symmetrically arranged around the machine terminal in preference to one large switch. Having four switches, it becomes imperative that they close simultaneously. The peak discharge current will be 1.88×10^6 A, $\int i^2\, dt = 6.2 \times 10^9$ A^2-sec. The rate of rise of the current at the onset of the short circuit is 2,900 A/μsec. These are significant design parameters for the making switch. The first number determines the dynamic forces on the contacts. The second is an indication of the thermal load, especially of the contact points, and the third number determines the minimum rate at which the contact resistance must decrease in order to avoid sparking. It also determines the minimum jitter admissible between several switches. The open circuit voltage of 104 V determines the insulation requirements and thus the contact separation. The low open circuit voltage of 104 V also tells us that the possibility of prestrike is not a consideration in this particular design.

The basic circuit of the magnetic repulsion system consists of a capacitor bank, switch (usually ignitrons), transmission line, repulsion coil and the movable contact. To be effective the moving part must be a good conductor and tightly coupled magnetically to the repulsion coil. An annealed aluminum ring 2.54 cm wide by 0.24 cm thick is used. In such a circuit the current in the coil and with it the magnetic field intensity take the form of a damped sinusoid (before appreciable ring expansion). The pressures generated are proportional to the square of the magnetic field intensity. In practice it is quite feasible to build coils having a good life expectancy and capable of peak pressures on the order of 70 MPa (10,000 lbf/in^2).

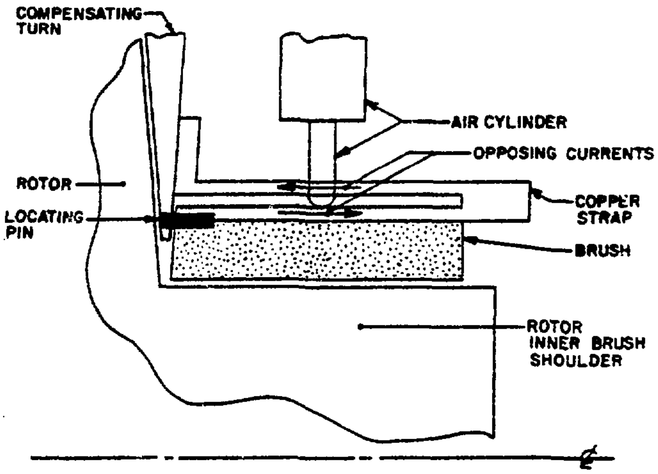

Figure 6. FDX Shoulder Brush Mechanism.

The switch consists of a stationary part arranged coaxially containing the coil and a contact sleeve that can be removed in order to permit loading of the contact ring. The contact sleeve is electrically coupled to the stationary part by means of two segmented spring contacts. The contact ring closely surrounds the driving coil. When the coil is pulsed (to close the switch), the ring expands rapidly, wrapping itself over the open contact gap. To rearm the switch for a subsequent test, the whole contact ring is collapsed and manually removed. A new ring is installed and the switch is ready for another operation.

Experiments Performed to Date

In any prototype machine and especially in a rotating electrical machine with energy densities such as in FDX, careful testing of all components must be completed and the subsequent problems resolved before a full scale discharge can be attempted. After resolving the individual problems, combinations of tests must be run to check on component interaction. FDX has been subjected to rotor-bearing frequency and stiffness tests; field coil pulses by the CEM 5 MJ homopolar generator; blow down tests of each brush system (individually and combined) while spinning the rotors, and switch firing tests while pulsing the field coil to verify simultaneous switch closing in a high magnetic field. After completing these tests, an initial discharge was conducted from a low rotational speed with a reduced field level, in short circuit configuration.

Results of the field coil pulses are shown in Figure 7 in which the measured field is compared with the calculated field. The measured field is shown to be somewhat higher than calculated which can be explained by conservative estimates for the transmission line and the 5 MJ homopolar machine parameters. The most recent coil test resulted in a field current of about 180,000 A and a corresponding average magnetic field of 3.5 T. The first coil discharge tests were conducted without the rotors and compensating conductors in place. After completing the tests the rotors were installed and the tests repeated. This establishes magnetic flux distribution with and without the eddy currents generated in the rotors and conductors and allowed adjustment of the field coil so that the rotors are centered in the magnetic field.

Brush blow down tests were run on each mechanism (rotor and shoulder) individually and together. Results from these tests showed that from 7,000 r/min, the rotors stop from brush losses in approximately 0.4 sec. As it was predicted that brush losses would be about 500 HP from 30,000 r/min, this rapid deceleration was to be expected. No brush activation or component failures occurred.

Testing of the making switches was first conducted off of the machine to determine contact shape and firing parameters. The firing circuit was extensively tested to make sure that all switches would close simultaneously. A closing time of 33 µsec after closing signal was determined and in all cases the circuit fired simultaneously. After mounting the switches on the machine, it was discovered that a voltage breakdown between the 4.5 kV magnetic coil and machine ground occurred. The coils were re-insulated and two simultaneous closing sequences were accomplished in a high magnetic field created by pulsing the main field coil.

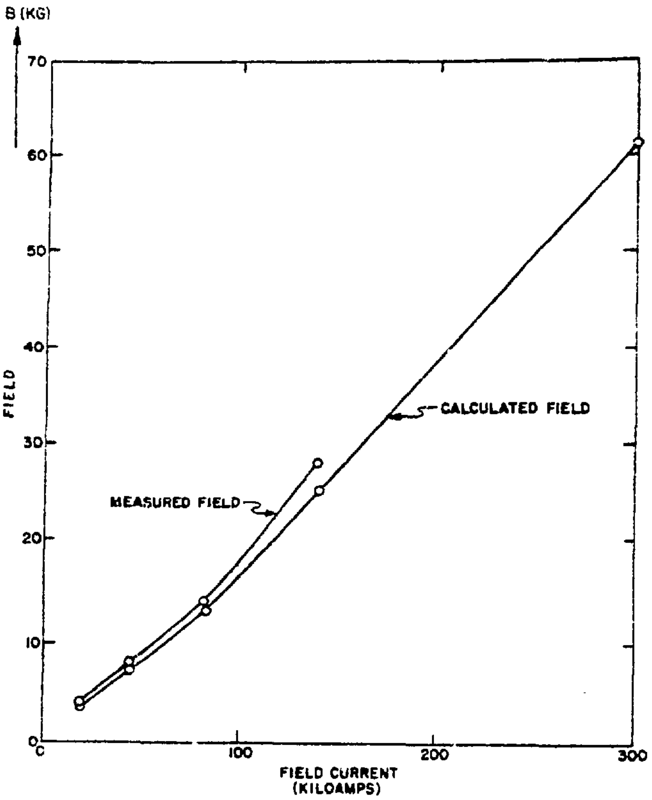

Figure 7. FDX Field Coil Levels.

Discharging FDX involves several distinct steps, each of which must be carefully timed. A digital mini-computer has been implemented to control the experiment of sequence. The 5 MJ machine is discharged into the FDX field coil. At peak field, the FDX brushes are actuated. After contact is verified by a voltage check, the making switches are fired as soon as possible to limit the frictional brush losses. Extensive testing of this system was required due to its critical part in the experiment. Spurious voltage spikes and ground loops were eliminated in the control circuit.

An initial short-circuit discharge test has been conducted. The field coil power supply (the CEM 5 MJ homopolar machine) generated 140,000 A into the FDX copper field coil. An average magnetic field of 2.44 T was observed inside the bore of the coil. Both FDX rotors were spinning at approximately 3000 r/min upon closing the current initiation switches. This speed and magnetic field corresponded to an FDX machine voltage of 19 V. From 3000 r/min the rotors stopped in 2.5 ms and the machine generated approximately 260,000 A. This was the fastest discharge of a homopolar machine to date. It was predicted that the machine would discharge an order of magnitude faster. The discrepancy is probably due to a higher than anticipated internal resistance which is caused by bolted connections. This condition will be remedied and the experiment repeated. Further testing and adjustment will continue in the effort to achieve a one ms discharge.

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References

[1] Paul Wildi, John Gully, "A Metallic Contact, Fast-Closing, High Current Switch," Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, Knoxville, Tennessee, October 24-28, 1977.