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ABSTRACT

All information now available concerning fast discharge homopolar machines is only theoretical. No such machine has ever been built and existing electrical machines do not approach the extremely severe conditions required for a fast discharge machine. The Energy Storage Group at the University of Texas at Austin has designed and is in an advanced stage of building a very fast discharge experimental homopolar machine which will explore fundamental mechanical and electromagnetic limitations to discharge times.

The FDX is a fully compensated, pulsed field homopolar generator with two counterrotating rotors. It will discharge in 1.03 milliseconds when short circuited. The applied field averages 4 Tesla and the equivalent capacitance is 16.64 F. When discharged from full speed into a load having 0.275 μH inductance and 60 μΩ resistance, the discharge time will increase to 3.075 milliseconds and the efficiency of the discharge will approach 80 percent.

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Introduction

Fast discharge homopolar machines appear to be a way of economically storing and rapidly transferring large amounts of energy. The pulsed power requirements (1 to 10 GJ., 1 to 100 millisecond discharge time) of many of the fusion experiments being considered are met by this type of homopolar machine. The RTPR (Reference Theta Pinch Reactor), LTPHR (Linear Theta Pinch Hybrid Reactor) and the SFTR (Scyllac Fusion Test Reactor) anticipate using fast discharge homopolar power supplies. Some of the reactor schemes involve circulating power levels greater than the net reactor output (i.e. Theta Pinch Compression or Tokamak Toroidal Field and Ohmic Heating) making the natural, high efficiency ringing of a homopolar machine, which models as a capacitor, a unique source of the required pulsed power. Because homopolar machines are comparatively inexpensive to build and are inherently reliable, the cost savings over scaled up capacitor banks or conventional a.c. generators has been shown to be substantial.

In the spring of 1974, the Energy Storage Group (ESG) at the University of Texas at Austin began a theoretical investigation into the fundamental limitations governing fast discharge homopolar machines. All information currently available concerning this type of machine is only theoretical. No such machine has ever been built and existing electrical machines do not approach the extremely severe conditions of a fast discharge homopolar machine.

The ESG has designed and is in the advanced stages of assembling the mechanical portion of a very fast discharge, experimental homopolar machine. The FDX (Fast Discharge Experiment) is a fully compensated, pulsed field homopolar generator. Using two, counterrotating rotors shaped to minimize their inertia, the machine stores .36 Mj at an angular velocity of 3000 rad/sec (28,650 RPM). It will discharge in 1.03 milliseconds when short-circuited. The applied field will average 4 Tesla in the active portion of the rotors, corresponding to a machine voltage of 208 V.

This machine will explore the theoretically determined limitations to discharge times of homopolar machines resulting in more realistic design information in the future. In addition, it will investigate and verify analysis relating to high current density, high surface velocity current collection systems in high magnetic fields, dynamic rotor and bearing response, and magnetic field or armature current diffusion into the machine.

Theory of fast discharging homopolar machines

When a homopolar machine is connected to an inductive store, a field coil, or a fusion device it forms an R,L,C circuit in which the machine is a capacitor. Assuming that all the kinetic energy stored is converted electromagnetically

$$\tfrac{1}{2} I\omega^2 = \tfrac{1}{2} CV^2$$

and because the voltage (V) is always related to the angular speed (ω) and the flux (ϕ) in the active portion of the rotor by

$$V = \frac{\omega\phi}{2\pi}$$

then the capacitance is

$$C = 4\pi^2 I/\phi^2$$

The discharge time is, in the first approximation, set by the R,L,C parameters. However, mechanical losses and magnetic diffusion alter the above approach, the equivalent circuit actually being a complex one.

From the point of view of electromechanical energy conversion (1) the ideal case of a piece of material of unit volume, of density (γ), moving with velocity (V), moving in a magnetic field (B), is characterized by the discharge time

$$T_d = k_T \frac{\gamma V}{BJ}$$

(where J is current density and k_T is a constant) and by per unit losses

$$\lambda = k_\lambda \frac{\rho J}{BV}$$

(where ρ is resistivity and k_λ a constant). Their product

$$T_d \lambda \cong \frac{\rho \gamma}{B^2}$$

shows that a fast discharge with high efficiency is limited by the maximum attainable flux density and by the material which has the smallest $\rho\gamma$. This material, aluminum, is used in the rotors of FDX.

This approach is elementary and incomplete. It does not take into account:

(1) The fact that different parts of the rotor are in very different electromagnetic conditions and store different amounts of energy.

(2) The current penetration and field diffusion into conductive parts of the machine.

(3) The compensation of the armature reaction which affects the internal inductance of the machine and consequently, the discharge time.

The topology of the fast discharge machine has received an extensive treatment elsewhere [2]. The conclusions were that the "spool" configuration has a smaller equivalent capacitance, having a smaller moment of inertia, for a given flux linkage when compared with an equivalent drum configuration. As a result the "spool" machine has a smaller discharge time while the "drum" machine, for equivalent conditions, has higher efficiency of discharge. The FDX machine, which has two counter-rotating disks is topologically equivalent to a spool machine. FDX attempts to explore fundamental limitations, making fast discharge times more important than efficiency. In figure 1, which shows alternative topological configurations, variations b or c apply to FDX.

The current penetration is the limiting electromagnetic factor in fast discharge. The notion of steady-state diffusion does not apply to this situation. A finite element method for calculating the field diffusion was devised. The method is general and is outlined in a companion paper.

The important questions, attempted theoretically in (2) of the fundamental limitations to discharge times have never received a practical confirmation. The discharges performed with FDX will show how the theoretical results, for flux and current diffusion, topology and mechanical stresses fit the experimental data.

Design of FDX

FDX was designed to investigate homopolar machine limitations. Therefore, many parameters, such as mechanical stresses, brush current densities, and interface speeds will be at their predicted performance limits. It is a low cost, high performance model of a spool type homopolar machine.

The FDX, shown in figure 2, consists of two counterrotating rotors, each representing ½ of a spool type rotor. The FDX rotors are supported by hydrostatic journal and thrust bearings, used for their low loss, high stiffness characteristics. It is powered by two gas turbines, modified to run on compressed air. A room temperature, pulsed copper coil supplies the magnetic field. A glass reinforced epoxy structure which withstands the thrust forces, torques and electrically insulates the machine as well as supporting the components, is mounted inside of a 1.97 cm. thick steel magnetic shield.

The two, 12 inch O.D. rotors and integral shafts are made of a 7050 aluminum alloy. The shafts and thrust bearings surfaces were hard anodized, providing a hard insulated bearing surface. In order to achieve the fastest discharge possible, the rotors are tapered, decreasing the moment of inertia and the effective capacitance of the machine.

Solid copper-graphite brushes will be used on FDX. The proportions and geometry of the brush material as well as the rotor surface on which they will slide, is being determined by brush test facilities at the University of Texas.

Switching will be accomplished by magnetically forming an aluminum ring over the ends of coaxial transmission lines. Five microsecond switching times with no chatter are anticipated.

Final assembly of the bearings, rotors, turbines and the coil in their housing is completed. During testing of these components, the electrical part of the machine will be built.

Predicted performance

The FDX field coil is pulsed by the existing 5 MJ, 5600 RPM, 42 V homopolar machine which is at the University of Texas. The coil has inductance of 8.2 μH when pulsed inside of the iron shield. The 5 MJ discharge results in a 4 Tesla average field across the active portion of the rotors. This will be obtained for a current in the field coil of 360,000 A and will occur at 0.22 seconds after the 5 Mj discharge begins.

The FDX will be discharged from only half of the rated speed, 1500 rad/sec, to avoid exaggerated mechanical stress and current density levels. The discharge time will be 1.033 milliseconds and the discharge current will reach 1.88 million amps. At full speed, 3000 rad/sec, the FDX is a 208 V machine.

Average values for the parameters of the short circuit are 2.5×10^{-8} H inductance, 1.55×10^{-5} Ω resistance and 16.64 F capacitance of the machine. Assuming a load having 0.275 μH inductance three cases have been considered:

(a) the load is superconductor;

(b) the resistance of the circuit is 30 μΩ;

(c) the resistance of the circuit is 60 μΩ.

The maximum currents will be respectively 1.42 MA, 1.305 MA, 1.138 MA and the discharge times, 3.38 m/sec., 3.27 m/sec., 3.075 m/sec.

	MAGNETIC ENERGY IN THE LOAD	MAGNETIC ENERGY IN THE MACHINE	JOULE LOSSES IN THE LOAD	JOULE LOSSES IN THE MACHINE
a)	0.273 MJ	0.0248 MJ	0 MJ	0.0622 MJ
b)	0.234 MJ	0.0213 MJ	0.0506 MJ	0.054 MJ
c)	0.178 MJ	0.0162 MJ	0.123 MJ	0.0428 MJ

If, in the figures for efficiency only the magnetic energy delivered to the load is considered then the efficiency for each of the three cases is respectively 76%, 65%, and 50%. If the joule heating energy deposited in the load is taken into account, the figures become 76%, 80%, and 84% respectively.

The low internal inductance of the machine is due to the careful compensation of the armature reaction.

The FDX coil has begun a series of tests being pulsed with increasing currents from the 5 Mj machine. Good agreement between the predicted and measured values has been obtained.

References

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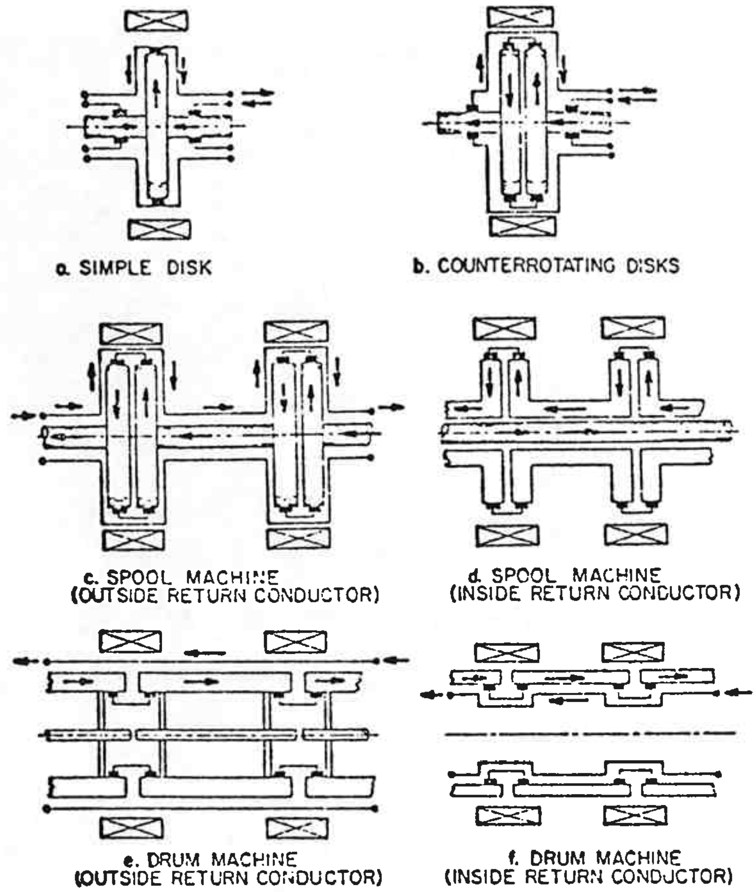

Figure 1: Topological configurations for fast-discharging homopolar machines

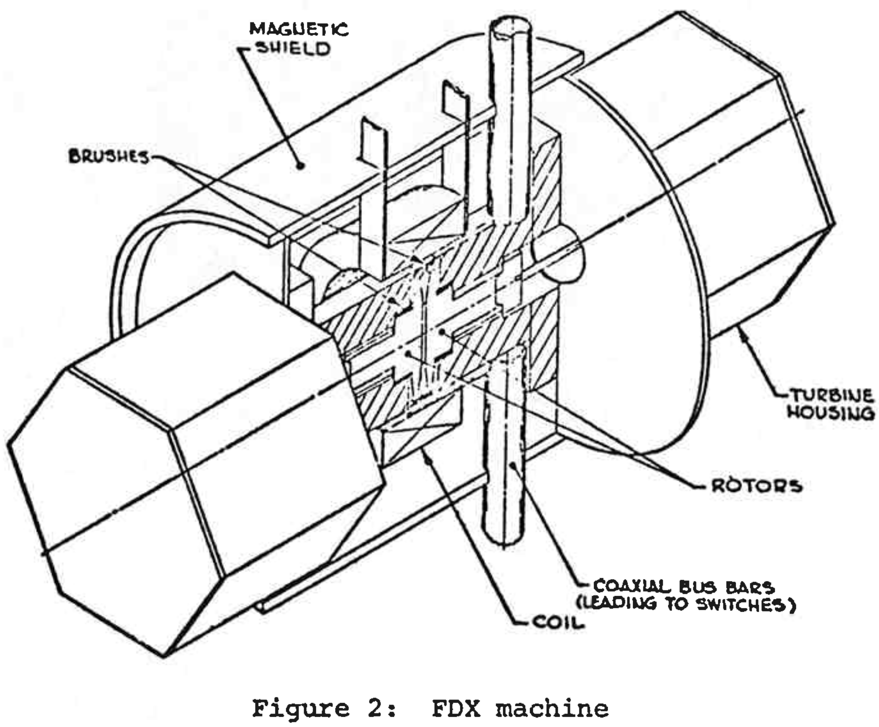

Figure 2: FDX machine