THE DESIGN, FABRICATION, AND TESTING OF A FIVE MEGAJOULE HOMOPOLAR MOTOR- GENERATOR

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ABSTRACT

The current and future generations of controlled thermonuclear fusion experiments require large amounts of pulsed energy for heating and confinement of plasma. Kinetic energy storage with direct conversion to electrical power (i.e. homopolar machines) seems to be the most economically attractive solution for meeting these requirements.

The University of Texas at Austin has a program intended to develop a design technology for homopolar machines to meet a broad spectrum of performance requirements in terms of stored energy and discharge times. The Energy Storage Group at the University of Texas at Austin has in the past ten months designed, fabricated, assembled and begun a thorough testing program on a second generation homopolar machine with a storage capacity of five megajoules. This machine, using room temperature field coils, solid electrical brushes, and hydrostatic bearings has been designed to deliver 42 volt pulses at current levels in excess of 150,000 amperes. The machine has been designed as a laboratory device with extremely stiff bearings, variable brush area as well as variable brush contact force, variable field strength for pulse shaping, and minicomputer controlled data acquisition, real time signature analysis and on line experiment control. A continuing program studying discharge characteristics, brush and rotor dynamics, machine losses, and system efficiencies is already underway and is currently funded through June, 1975. Funding for the project has been provided by the Atomic Energy Commission, the Texas Atomic Energy Research Foundation, and the Electric Power Research Institute.

INTRODUCTION

The next generation of thermonuclear fusion experiments currently under consideration requires large quantities of electric power for confinement and/or heating of the plasma. It is not feasible to take this energy directly from the electric power lines, and not economically feasible to construct new power generation or transmission facilities since the power is required only for short periods of time.

The last fact, however makes the use of energy storage systems which can slowly store energy from existing electrical distribution facilities and then deliver it to the experiment as rapidly as required, a practical alternative. In the past, both battery and capacitor banks have been used for this purpose, but the cost per joule of stored energy is rather high (\$0.20 to \$1.00 per joule). Additionally, as the size of either system increases, the complexity of the safety interlocks and switching gear required for safe operation increases substantially.

Several types of inertial energy storage devices have been proposed or constructed, but they usually consist of a separate motor, generator, and flywheel arranged along a shaft. In machines of this configuration minimum discharge time is determined by the

maximum torque which the shaft is capable of transmitting. Additionally, the individual motor and generator are fairly expensive, especially since they are usually conventional units originally designed for continuous duty. The generator in this arrangement is often an alternator, thus requiring a high current rectification system to deliver direct current to the experiment. The cost of such units has been in excess of \$0.20 per joule.

The Faraday Disc or homopolar machine in the conventional configuration (axial magnetic field and radial current flow, see Fig. 1.) can conveniently serve

Fig. 1. Faraday Disc

as both motor and direct current generator while the armature of the machine also serves as the inertial store. Thus, the forces which occur during motoring and discharge are generated within the flywheel itself, essentially at the same point where the energy is stored, eliminating the shaft torque limitation previously mentioned. The rotor itself is a right circular cylinder of electrically conductive material, and the magnetic field coil is simply a solenoid. Such units have been built at the University of Texas at Austin for less than \$0.01 per joule in half megajoule and five megajoule sizes and several design studies show that larger units can be built for somewhat less than this figure.

Prior to undertaking the five megajoule homopolar machine project, the Energy Storage Group at the University of Texas at Austin had successfully completed the design, fabrication, and testing of a half megajoule homopolar motor generator. This unit exceeded its design goals by motoring to 6000 RPM in 100 seconds with a current of 1200 amperes and discharging in 7 seconds with a peak current of over 14,000 amperes.

The Energy Storage Group has also completed design studies on homopolar machines ranging in size from 50 to 2000 megajoules.

DESIGN PHILOSOPHY

Although the homopolar machine is simple in concept, many past examples have employed extremely complicated solutions (such as liquid metal brushes and super-conducting field coils) in attempting to overcome basic limitations. The design philosophy of the Energy Storage Group has been to strive for simplicity and reliability; using conventional technology in the development of the homopolar machine as a practical, low cost pulsed power supply.

GENERAL LAYOUT

The general layout of the five megajoule homopolar motor-generator is shown in

Figs. 2 and 3. The 0.610 meter diameter, 0.279 meter thick steel rotor is shrunk onto

Fig. 2. 5 mj Homopolar Motor Generator

Fig. 3. 5 mj Homopolar Machine Cross Section

a 0.127 meter diameter, non-magnetic shaft. This shaft is supported both axially and radially by hydrostatic bearings which combine high stiffness and relatively low frictional losses. The bearing housings are attached to the magnetic yoke which also serves as a return path for the axial magnetic field generated by the field coil. The yoke is designed to uniformly distribute the magnetic field across the faces of the rotor.

ROTOR AND BEARINGS

The moment of inertia of the 0.610 meter diameter, 0.279 meter thick steel rotor is given by:

$$I = \frac{\pi R_o^4 m a}{2} = 29.707 \text{ kg-m}^2 \quad (1)$$

At a design speed of 584 radians per second the stored energy is:

$$KE = \frac{1}{2} I \omega^2 = 5.07 \times 10^6 \text{ joules} \quad (2)$$

The stress at the periphery of the hole in the center of the rotor is the critical factor which limits rotor speed. The tangential and radial stresses due to spin and shrink fit of 0.002 m/m are as follows:

$$\sigma_{\theta} = \frac{(3 + \nu) m \omega^2}{8} \left[R_o^2 - \left(\frac{1 + 3\nu}{3 + \nu} \right) R_i^2 \right] + \frac{E \delta}{2} \left(\frac{R_o^2 + R_i^2}{R_o^2} \right) \quad (3)$$

$$\sigma_r = \frac{(3 + \nu) m \omega^2}{8} \left(R_o^2 - R_i^2 \right) - \frac{E \delta}{2} \left(\frac{R_o^2 - R_i^2}{R_o^2} \right) \quad (4)$$

Combining these equations gives the effective stress at any speed.

$$\sigma_{\text{eff}} = \sigma_{\theta} = \sigma_r = \frac{m \omega^2}{4} (1 - \nu) R_i^2 + E \delta \quad (5)$$

$$(\sigma_{\text{eff}})_{\omega=0} = 4.14 \times 10^8 \text{ nt/m}^2$$

$$(\sigma_{\text{eff}})_{\omega=584} = 4.16 \times 10^8 \text{ nt/m}^2$$

Thus the operating stress can be seen to be nearly independent of rotational speed. The limiting speed is reached when $\sigma_r = 0$, i.e., when the slip fit is overcome by rotational strain. Setting Eq. 4 equal to zero and solving for ω gives:

$$\omega_{\text{max}} = \pm 2 \left[\frac{E\delta}{(3+\nu)R_o^2 m} \right]^{1/2} = 1174 \text{ rad/sec} \quad (6)$$

The shrink fit of the disc on the rotor can be seen to have a factor of safety of two in terms of limiting speed vs. maximum operating speed and it should be noted that this represents a factor of safety of four in terms of energy stored in the rotor assembly.

The radial bearings are four-pocket orifice compensated hydrostatic bearings supplied with oil at $4.14 \times 10^6 \text{ nt/m}^2$. The stiffness of each bearing is in excess of $7.88 \times 10^8 \text{ nt/m}$. Bearing stiffness is kept high in order to maintain all natural frequencies of the rotor-shaft-bearing system above the maximum operating speed of 584 radians/second. Analysis of the shaft indicates that it may be considered to be rigid in comparison to the bearings. For a worst case assumption, the upper and lower bearing housings may be assumed to be held together by two 19 mm diameter by 7.62 cm long bolts and two 19 mm diameter by 15.24 cm long bolts. This assumption gives an effective housing spring constant of $2.32 \times 10^9 \text{ nt/m}$. The effective spring constant is:

$$K_{\text{eff}} = \frac{k_B k_h}{k_B + k_h} = 5.88 \times 10^8 \text{ nt/m} \quad (7)$$

The first critical frequency can be calculated by

$$\omega_{c1} = \left[\frac{2k_{\text{eff}}}{M_T} \right]^{1/2} = 1273 \text{ rad/sec} \quad (8)$$

Gyroscopic effects cause a conical whirl whose frequency is given by

$$\omega_{cw} = \left[\frac{k_{\text{eff}} L^2}{2(I + I')} \right]^{1/2} = 1113 \text{ rad/sec} \quad (9)$$

The thrust bearing is also a hydrostatic unit but is compensated by the use of flow control valves. It is designed to have a stiffness of $4.38 \times 10^8 \text{ nt/m}$. Any misalignment in the bearing surfaces will produce a one cycle per revolution forcing function. The natural frequency of the rotor-shaft-bearing system in this mode is given by:

$$\omega_{ca} = \left[\frac{K_t}{M_t} \right]^{1/2} = 777 \text{ rad/sec} \quad (10)$$

This critical frequency is only 33% above the maximum operating speed of the machine but detailed analysis as well as past experience with high flow rate hydrostatic bearings indicates that the internal damping is such that this will not be a severe vibration mode, even in the event that it is reached.

MAGNETIC CIRCUIT

The magnetic circuit of the five megajoule homopolar machine is designed to operate at a nominal flux density of 1.61 wb/m^2 . This is the highest field attainable with

moderate power losses in the field coil. The air gap at each end of the rotor is 0.0245 m. The number of ampere turns required to give the required flux density in the air gap is given by:

$$(Ni_{fc})_{air} = \frac{2gB}{\mu_o} = 65085 \text{ ampere turns} \quad (11)$$

Additionally, the number of ampere turns required to produce the same flux density in the steel portion of the magnetic circuit (nominal length of $L_m = 1.7$ meters) is given by:

$$(Ni_{fc})_{steel} = L_m \cdot \bar{H} = 5950 \text{ ampere turns} \quad (12)$$

$\bar{H}$ is determined from the magnetization curve for steel shown in Fig. 4. The total ampere turns required in the field coil are:

$$(Ni_{fc})_{tot} = (Ni_{fc})_{air} + (Ni_{fc})_{steel} = 71035 \text{ ampere turns} \quad (13)$$

Thus for a field coil of 260 turns, the current required is 273.2 amperes.

Fig. 4. Magnetization Curve for Steel

The field coil is wound of round copper tubing of 12.7 mm outer diameter and 1.24 mm wall thickness. Although electrolytic tough pitch copper is desirable because of its low electrical resistivity ($\rho=1.71$ microhm-cm); deoxidized, high residual phosphorus copper ($\rho=2.03$ microhm-cm) was used because of its ready availability. The nominal length of the coil is 762 meters. The resistance is given by:

$$R_{fc} = \frac{\rho L_{fc}}{A_t} = 0.343 \text{ ohms} \quad (14)$$

Thus, the coil voltage and power requirements are:

$$P_{fc} = (i_{fc})_{tot}^2 R_{fc} = 25.6 \text{ kilowatts} \quad (15)$$

$$V_{fc} = (i_{fc})_{tot} R_{fc} = 93.7 \text{ volts} \quad (16)$$

The field coil is divided into ten segments of 26 turns each and cooling water is supplied to each segment at 2.5 liters/min. and 20° C. The average exit temperature of the water is given by:

$$T_{out} = T_{in} + \frac{tP_{fc}}{C_p Q_m} = 34^\circ \text{ C} \quad (17)$$

This is certainly a conservative coil design in terms of temperature rise.

The 10 coils of the field winding of the machine can be connected in two groups of 5 coils, fed from two separate SCR power supplies and differentially controlled to serve as an electromagnetic thrust bearing. In this mode, the rotor is stabilized in the magnetic center of the machine against the axial electromagnetic forces tending to move the rotor towards the yoke wall. Previous experiments, made with the 0.5 mj. machine, led to a stable feedback system, controlling the two power supplies differentially in such a manner that the total ampere-turns remain constant. The position sensor has low inertia and strong derivative feedback to overcome the delay due to the relatively slow penetration of the magnetic field into the rotor.

This feedback system effectively controls the homopolar machine in the motoring mode. In the generating regime, (in the time of discharge) the feedback system remains connected. However, the rotor tends to be stabilized by the high currents in the compensating plates which, for the short time of discharge, play the role of a levitation system keeping the rotor carrying the high discharge current in the center of the air gap.

The magnetic yoke is designed so that the 1.61 wb/m^2 flux density in the air gap is maintained throughout the magnetic circuit. The manner in which this is accomplished may be seen more clearly by referring to Fig. 5. The area of the rotor penetrated by the uniform magnetic field in the air gap is determined as follows:

$$A_1 = \pi(R_o^2 - R_{im}^2) = 0.259 \text{ m}^2 \quad (18)$$

The area of the yoke end plate penetrated by the total flux is

$$A_2 = 2\pi R_o t \quad (19)$$

and in the outer ring the area is

$$A_3 = (d^2 + 2R_{oy}d)\pi. \quad (20)$$

Fig. 5. Magnetic Circuit

But for uniform flux density:

$$A_1 = A_2 = A_3,$$

$$\text{or } t = \frac{A_1}{2\pi R_o} = 0.135\text{m} \quad (21)$$

and

$$d = \left[R_{oy}^2 \pm \left[R_{oy}^2 - \frac{A_1}{\pi} \right]^{1/2} \right] = 0.085 \text{ m} \quad (22)$$

where $R_{oy} = 0.673$ meters for the 5 mj. machine.

ELECTRICAL CHARACTERISTICS

If the magnetic flux density is assumed to be uniform across the faces of the rotor, the no load machine voltage is:

$$V_{nl} = \omega B \left[\frac{R_o^2 - R_{im}^2}{2} \right] = \frac{\omega \Phi}{2} \quad (23)$$

Hall probes placed radially along the rotor face indicate that the magnetic field in the air gap is uniform, even in the transient regime. At the maximum design speed of 584 rad/sec. and the rated magnetic flux density of 1.61 wb/m^2 , the no-load voltage is approximately 42 volts.

The actual voltage across the machine terminals differs slightly for the two modes of operation.

(a) In the motoring mode:

$$V_m = \omega B \left(\frac{R_o^2 - R_{im}^2}{2} \right) + r_{tm} i_m = \frac{\omega \Phi}{2\pi} + r_{tm} i_m \quad (24)$$

(b) In the generate mode:

$$V_g = \omega B \left(\frac{R_o^2 - R_{im}^2}{2} \right) - r_{tg} i_g - L_r \frac{di_g}{dt} = \frac{\omega \Phi}{2\pi} - r_{tg} i_g - L_r \frac{di_g}{dt} \quad (25)$$

The motoring current is almost constant. The discharge current is varying in time and the role of the internal inductance of the rotor circuit, L_r (corresponding to the magnetic energy stored in the air-gap, compensating plates, and in the ferromagnetic body of the rotor) may be important. The values of r_{tm} and r_{tg} are different because the motoring regime occurs with only a small portion of the brushes on the rotor while the discharge occurs with all the brushes in contact - the friction and the wear of the brushes for the short period of time involved being negligible in comparison with the improvement in the electrical efficiency of the discharge. The influence of the resistance of the brushes can be seen if we compare it with the resistance of the rotor and compensating plates.

The electrical resistance of the rotor:

$$R_{\text{rotor}} = \frac{\ln(R_o/R_i)}{2\pi\sigma_{st}a} = 0.173 \times 10^{-6} \text{ ohms} \quad (26)$$

The electrical resistance of the compensating plates

$$R_{c.p.} = \frac{\ln \frac{R_o}{R_i}}{4\pi\sigma d_{cp}} = 0.378 \times 10^{-6} \text{ ohms} \quad (27)$$

The total resistance of the machine (measured) is less than 100×10^{-6} ohms including the brush system, rotor, compensating plates and leads. It is obvious that, as expected, the resistance of the brush contacts accounts for almost the entire resistance of the machine. In the near future, the external load will be replaced with a switch having a resistance of less than 5×10^{-5} ohms. In this way, the total resistance of the path for the discharge current will be less than 1.5×10^{-4} ohms. Then, the maximum value of the discharge current will be approximately

$$I_{\max} = \frac{42 \text{ volts}}{1.5 \times 10^{-4} \text{ ohms}} = 280,000 \text{ amperes} \quad (28)$$

Usually, the homopolar machine is considered (and analytically approached) as the condenser in an R,L,C circuit. Since a large amount of kinetic energy is converted into electrical energy at a relatively low voltage, the capacitance is very high. For the 5 mj. machine:

$$1/2 CV^2 = 5 \times 10^6 \text{ joules or } C = 5750 \text{ farads} \quad (29)$$

The parameter which describes the behavior of R,L,C circuits:

$$\lambda = \frac{1}{R} \left[\frac{L}{C} \right]^{1/2} = 6 \times 10^{-3} \quad (30)$$

for the present circuit which indicates a highly damped circuit, while, for the improved discharge circuit λ will be only 0.02 when 0.5 is the value for the critically damped circuit.

The RC time constant, for the improved discharge circuit is:

$$\tau = 0.8625 \text{ seconds.} \quad (31)$$

The expected variation in time of the discharge current is given in Fig. 6.

Fig. 6. Discharge Current As A Function of Time

The electromagnetic torque is given by the formula

$$T = \frac{\Phi i}{2\pi} \quad (32)$$

assuming again that the magnetic flux density is uniform across the rotor. Then, for instance, the maximum braking torque occurring in the discharge time is

$$T_{\max} = \frac{\Phi i_{\max}}{2\pi} = 20,050 \text{ nt-m} \quad (33)$$

BRUSHES

This machine uses solid brushes made of copper-graphite, chosen after intensive testing; because of their low voltage drop. Also friction, heating and wear of the brushes and the rotor were important considerations in our tests and our choice.

Cyclic D.C. machines have energy stored in the commutating coils which must be dissipated in the commutation period and leads to severe arcing. Homopolar machines do not experience this difficulty so that, for this reason, the current density at the brush contact can be increased to relatively high values while the operating conditions remain satisfactory. In the previous machine (0.5 mj.) discharge current densities exceeding 750 amps/cm² were regularly reached without difficulties. In the 5 mj. machine, the contact area of the brushes is such that at the highest expected discharge current, the current density will be approximately 450 amps/cm² on the rotor and 1200 amps/cm² for the shaft brushes.

The arrangement of the rotor brushes comprises 6 separate tracks, each of them having 18 brushes of 6.45 cm² contact area. The shaft brush arrangement consists of 6 tracks of 6 brushes each. The contact force and number of brushes which make contact during either mode of operation can be pre-selected. The brushes are air retracted/spring extended such that in the event of a loss of air pressure all brushes will be lowered onto the rotor and shaft with full spring load.

CONTROL AND DATA ACQUISITION

The rapid response and large amount of energy involved in experiments with the five megajoule homopolar machine dictate the use of an automatic control system rather than the manual controls used on the half megajoule system. A small digital computer has been purchased to handle data acquisition and reduction as well as control and safety functions. The control duties assigned to the computer will be: (1) switching from motor to generate mode, (2) terminating an experiment in the event of a malfunction, (3) controlling the electromagnetic thrust bearing, and (4) shaping the discharge pulse by field and brush control. The computer is equipped with eight channels of analog to digital conversion and eight channels of digital to analog conversion to facilitate interfacing it with the machine.

Additionally, the computer will monitor and record the required data during the course of an experiment, perform the required data reduction, and plot the results in whatever form may be desired. It will also generate a permanent record of machine performance parameters after each run.

FABRICATION AND ASSEMBLY

The five megajoule homopolar machine was fabricated and assembled in a period of less than eight months. In order to do this, every effort was made to utilize readily available parts and materials wherever overall machine quality and performance would not be sacrificed by doing so.

be sacrificed by doing so.

The rotor was machined in the Mechanical Engineering Shop at The University of Texas at Austin from a billet of A.I.S.I. 4340 vacuum remelt steel.* Before final machining the rotor was shrunk onto a shaft of type 304 stainless steel. The radial bearings were rough machined from stainless steel tubing and then babbitt liners were cast in place before the final machining.

Due to the unavailability of large stainless steel billets, the bearing housings were built up from three 7.6 cm thick stainless steel plates. These also were fabricated in the University's Mechanical Engineering Shop.

The magnetic yoke assembly, due to its large size, was the only part of the machine not fabricated at the University of Texas. The assembly was welded up from two 15.24 cm thick hot rolled steel end plates and a central ring rolled from 7.62 cm thick steel plate.** Next, bolted to the yoke and align bored as an assembly to assure proper bearing alignment.

The field coils were wound from 12.7 mm outside diameter copper tubing covered with a braided fiberglass sleeve. The ten segments of the final coil were then individually potted in glass reinforced epoxy. The winding and potting operations were carried out by undergraduate engineering students under the supervision of project personnel.

Electrical brushes were manufactured from a sintered copper-graphite material.*** The brushes are 2.54 cm square and 1.0 cm thick and are contoured to fit the rotor or shaft on which they run. They are silver soldered to 2.54 cm by 1.6 mm thick copper straps which act as electrical conductors and brush locating members. The brushes are forced down onto the moving surface by stainless steel coil springs. The brushes are lifted and the contact interface pressure is modulated by pneumatic cylinders attached to the back of each brush. The shaft brushes are able to utilize standard commercial air cylinders, but due to space limitations the rotor brush cylinders had to be fabricated at the University.

Additional preparations required for the five megajoule homopolar machine program included a high pressure oil supply and scavenging system for the bearings and a pressurized emergency oil reservoir to provide bearing lubrication in the event of a main oil pump or power failure. A pneumatic control system, unaffected by high magnetic fields, allows selection of any desired combination of brushes for motoring and/or generating as well as selection of the desired brush interface pressure for either mode. Also because of the high magnetic fields present in the machine, a fluidic tachometer has been designed and fabricated, as well as fluidic axial and radial rotor position sensors. Due to the unavailability of a suitable switch, an armature shorting switch capable of sustaining a current of 320,000 amperes for one second has been designed and is being fabricated for testing the generator.

TESTING PROGRAM

An extensive, year long, testing program, intended to thoroughly evaluate the new 5.0 megajoule homopolar motor-generator is currently underway at the University of Texas at Austin. The objectives of the program are to:

- * provided by Cameron Iron Works, Inc., Houston, Texas
- ** Fabrication by Astec Industries, Inc., Chattanooga, Tennessee
- *** Morganite Corp. CM-1 S Homopolar Brush Material

- 1) experimentally verify the basic machine constants,
- 2) determine machine efficiency in various modes of operation,
- 3) separate, investigate and attempt to minimize the various sources of mechanical and electrical losses,
- 4) determine the magnetic field distribution in all parts of the machine, under both steady state and transient conditions,
- 5) implement a signature analysis program to optimize operational procedures and prevent failure conditions,
- 6) explore the operational limits of the various components of the machine and implement programs to extend those limits.

Shortly after completion of assembly of the 5.0 megajoule machine, a series of static tests were performed to verify certain design parameters. Oil flow rates and pressure drops in the radial and thrust bearings were verified. Radial bearing eccentricity was measured as was breakaway torque of the rotor. Breakaway torque was found to be higher than anticipated due to excessive drag from the thrust bearing oil seals. Provisions are now being made to relieve the pressure on those seals.

The magnetic field was measured with a radial array of Hall effect probes and the rise and decay times of the magnetic field were determined under various modes of switching. This information was required for the implementation of the magnetic thrust bearing control system as well as for several other schemes currently under investigation for switching the power output of the generator.

After the static tests, the machine ran satisfactorily the first time power was applied to the armature. A series of tests was then begun to generate data for the separation of losses calculations, classically known as a "retardation test". Essentially the machine is operated in four modes; first motoring up to a certain speed and then:

- 1) coasting down with all brushes retracted and magnetic field turned off (bearing and windage losses only)
- 2) coasting down with all brushes retracted and magnetic field on (introduces magnetic field induced losses.)
- 3) coasting down with motoring brushes down (brush losses.)
- 4) coasting down with generating brushes down (brush losses.)

The data generated in these tests allows the determination of the absolute as well as relative values of the various losses at all speeds, except those produced by eddy currents and electrical forces on the brush conductors. These tests have already been run up to 86% of full speed and they verify the aforementioned seal drag problem, but all other losses seem to be in order.

The machine has also generated at various speeds up to 86% of full speed, into a rather high resistance external load since the new shorting circuit is not yet completed. Even with the high resistance loading circuit, current levels exceeding 139,000 amperes have been reached.

CONCLUSIONS

Although the testing and evaluation program on the 5.0 megajoule homopolar machine is just beginning, the preliminary results indicate that this machine will exceed its original performance goals by a clear margin. For example, the measured internal resistance of the machine is well below the value originally anticipated and continues to decline as the brushes wear in.

The Energy Storage Group at the University of Texas at Austin has shown that the disc type homopolar machine is a practical approach to the development of low cost pulsed power supplies where relatively low voltage, high current power is required or can be

used. This type of system occupies less space, has a more flexible charge-discharge cycle, is less costly, and represents less of a safety hazard than competitive motor-generator, battery and capacitor systems. Investigations are now underway involving the application of this homopolar machine design technology to providing power for confinement systems of actual fusion experiments.

The Energy Storage Group wishes to express its gratitude to The U.S. Atomic Energy Commission, the Texas Atomic Energy Research Foundation, and the Electric Power Research Institute for this research.

LIST OF SYMBOLS

- A_t = cross sectional area of field coil conductor (cm^2)
 $A_{1,2,3}$ = cross sectional area of magnetic yoke (m^2) (see Fig. 5.)
 a = rotor thickness (m)
 $\bar{B}$ = magnetic flux density (wb/m^2)
 C_p = heat capacity of water ($\text{watts}/\text{kg}-^\circ\text{C}$)
 d_{cp} = thickness of compensating plate (cm)
 E = Young's modulus (nt/m^2) ($2.069 \times 10^{11} \text{ nt}/\text{m}^2$ for steel)
 g = air gap between end of rotor and magnetic yoke (m)
 $\bar{H}$ = magnetic field strength (amp-meters)
 I = moment of inertia of rotor about axis of rotation ($\text{kg}-\text{m}^2$)
 I' = moment of inertia of rotor perpendicular to axis of rotation ($\text{kg}-\text{m}^2$)
 i_a = armature current (amps)
 i_{fc} = current in field coil (amps)
 i_g = armature generating current (amps)
 i_m = armature motoring current (amps)
 K.E. = kinetic energy stored in rotor (joules)
 k_B = radial bearing spring constant (nt/m)
 k_{eff} = effective radial spring constant (nt/m)
 k_h = radial bearing housing spring constant (nt/m)
 k_t = thrust bearing spring constant (nt/m)
 L = distance between radial bearings (m)
 L_{fc} = length of field coil (m)
 L_m = effective length of magnetic circuit in steel (m)
 L_r = rotor inductance (henrys)

M_t = mass of rotor & shaft (kg)

m = mass density of rotor (kg/m^3) (7833 kg/m^3 for steel)

N = number of turns in field coil

P_{fc} = electrical power consumed in field coil (kw)

Q_m = total mass flow rate of field coil cooling water (kg/sec)

R_{fc} = resistance of field coil (ohms)

R_i = shaft radius (m)

R_{im} = radius of central hole in magnetic yoke (m)

R_o = outer radius of rotor (m)

r_{tg} = internal resistance of machine in generate mode (ohms)

r_{tm} = internal resistance of machine in motor mode (ohms)

T_{in} = inlet temperature of field coil cooling water ($^{\circ}\text{C}$)

T_{out} = outlet temperature of field coil cooling water ($^{\circ}\text{C}$)

t = time (sec)

V_{fc} = field coil voltage drop (volts)

v_{nl} = no load armature voltage (volts)

δ = shrink fit of rotor on shaft

μ_o = magnetic permeability of air (wb/amp-meter)

ν = Poisson's ratio (0.3 for steel)

ρ = electrical resistivity (ohm-cm)

σ_a = electrical conductivity of aluminum compensating plate (3.3×10^7 mhos/m)

σ_{eff} = effective combined stress at inner periphery of rotor (nt/m^2)

σ_r = radial stress at rotor inner diameter (nt/m^2)

σ_{st} = electrical conductivity of steel rotor (5×10^6 mhos/m)

σ_{θ} = tangential stress at rotor i.d. (nt/m^2)

Φ = magnetic flux (webers)

ω = rotor angular velocity (rad/sec)

ω_{ca} = axial critical frequency of rotor-shaft-bearing assembly (rad/sec)

ω_{cw} = critical whirl frequency of rotor-shaft-bearing assembly (rad/sec)

ω_{cl} = first critical frequency of rotor-shaft-bearing assembly (rad/sec)