HOMOPOLAR MOTOR-GENERATOR FOR INEXPENSIVE INERTIAL ENERGY STORAGE

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This period of activity was dominated by actual test runs on the 0.7 M.J. machine which has now exceeded the design goals of 10,000 amperes generation at 6000 RPM. From these test data we have designed a 5 M.J. machine to be built during the next six months for evaluation of a number of scaling factors in order that we may move with confidence to designs of larger machines of the 2000 M.J. class. In addition to these activities, a brush test machine has been designed and built, a dynamic stress analysis of the Tokamak coil retaining bolts was made and several new design concepts were introduced for inertial energy storage.

Bench Model

Design Changes

The design changes made on the current bench model in the last 6 months are, with the exception of the S.C.R. power supplies and magnetic thrust bearing, essentially detail improvements and a general clean up of the generator and its peripheral equipment. Nevertheless, these improvements have more than doubled the peak current output of the machine.

Most detail improvements centered around the rotor brush actuating mechanism and the brush leads. The individual brushes were articulated on the brush holders to allow them to conform more closely to the rotor. The individual air lines to the air cylinders were replaced with a more compact manifold system. This eliminated the interference between the air lines and brush holders. The stranded copper leads connecting the individual brushes to the outer aluminum ring were replaced first with heavier stranded copper leads with crimped terminals, then with flat braided, tinned copper leads with silver soldered terminals. This last step resulted in dropping the individual brush lead resistance from 17 milliohms/lead to 2 milliohms/lead. Furthermore, the internal resistance of the machine was reduced from 0.69 milliohms to 0.23 milliohms in the generate mode.

Externally, the replacement of the batteries with the SCR power supply allowed much of the former switching gear to be eliminated. The large vacuum break disconnect switch was retained, but used only to short the shaft and rotor brushes in the generate mode. All external leads for both the armature power supply and the entire generate circuit were upgraded to four parallel lengths of 4/0 neoprene insulated welding cable. These changes reduced the resistance of the external generate circuit from 1.65 milliohms to 0.49 milliohms.

Electrical Characteristics

Briefly, the operation of the homopolar motor-generator as a pulsed power source involves supplying an axial magnetic field through the rotor while passing a radial current through the armature to first motor slowly (about 100 sec) to a predetermined speed. At this point the rotor has stored kinetic energy which can be removed as electrical energy by disconnecting the power supply and switching in the load. The machine rapidly discharges ($\sim$1 - 10 sec) and generates a large current pulse (10^4 Amperes) whose shape and magnitude is set by the machine Faraday voltage and the load resistance and inductance. All of the results described in this section were obtained when operating in the pulsed mode.

Motor Mode

The torque generated in the homopolar machine is given by $T=J(d\omega/dt)+T_{f\omega}=K_f i_f i_a$ where J is the rotor moment of inertia, ω is the speed, $T_{f\omega}$ is the friction and windage torque, K_f the machine torque constant, i_f the field current, and i_a the armature current. When i_a is externally supplied, the rotor accelerates to a speed ω limited only by friction and windage. At the same time a Faraday voltage, $e_a= K_f\omega i_f$, is generated as the rotor cuts the lines of magnetic flux. This flux is produced by a set of 6 coils of 24 turns each. The magnetic curcuit is made up of a large iron yoke surrounding the coils, the rotor, and two small air gaps. We produce a field of 15 kG with 300 Amperes in the coils. The latter are excited with two SCR constant-current, constant-voltage power supplies having a full convertor bridge with invertor type SCRs. Measurements of $\underline{B}$ with Hall sensors placed on the yoke wall at various radial positions show $\underline{B}$ to be constant across the face of the rotor. The armature current is supplied by a single 150 kW SCR power supply giving an i_a of about 1500 Amp. The voltage at the machine terminals is $V_a = i_a R_a + e_a$ where R_a is the armature resistance including that of the brushes and their leads and is $4 \times 10^{-4}\ \Omega$. The principal contribution to R_a is from current constriction in the rotor at the brush contact points. This has been verified by measurements of voltage drop between adjacent brushes. The theoretical minimum R_a assuming a completely uniform current distribution in the rotor is $5 \times 10^{-6}\ \Omega$.

In Fig. 1 we see recorder traces of V_a, i_a, and ω for a complete cycle of operation. The traces show values of V_a=7 V and ω = 300 sec^{-1} before discharge. In other runs we have achieved our design speed of ω = 628 sec^{-1} developing a voltage of 16 volts. In the latter case 227 sec was required to reach this ω compared with a value of 100 sec calculated from the torque equation. The difference is due to friction losses primarily coming from the thrust bearing and the brushes. From the ω and V_a curves and the value of i_f we calculate K_f to be 5×10^{-5} which agrees within 20% of the theoretical value. The power supplied to the machine during runup is given by $P_i = \overline{V}_a i_a + V_f i_f$ where $\overline{V}_a$ is the average voltage obtained from the recorder traces. For the case given in Fig.1 we obtain a P_i = 11 kW where V_f = 20 V and i_f = 250 A.

Generator Mode

Once we have reached the desired speed, the armature supply is disconnected and the load switched in. A current pulse is produced whose peak value is $i_{max} = V_a/(R_L + R_a)$ where R_L is the load resistance. In Fig.1 we see the record of the discharge pulse through a "short circuit" showing an i_{max} = 8.8 kA. For V_a = 7 V, this gives $R = R_L + R_c = 8 \times 10^{-4}\ \Omega$. Since $R_c = 4 \times 10^{-4}\ \Omega$ we observe that the limiting current we could hope to achieve under these conditions is about 16 kA. (For the case of ω = 628 sec^{-1} and V_a = 16 V, this would produce an i_{max} = 35 kA.) Although the rise time of the current cannot be measured from this curve, we have determined that it is less than 25 ms indicating an armature circuit inductance of less than 10^{-5}H. The decay curve closely approximates an exponential and has an e-folding time of about 3.8 sec. We can model the homopolar machine as a capacitor with an equivalent capacitance of 4.4 x 10^3 f. If the inductance is negligible in the resulting RLC curcuit, the time constant is approximately given by τ = RC. For our case RC = 3.5 sec which agrees well with the observed time. In addition this means that the non-electromagnetic torque components are negligible for pulse discharges on this time scale. If they were not the decay time would be less than RC. We also note that the RC time constant gives the minimum time the rotor can stop regardless of mechanical considerations. In our case this would be when R = R_a or τ = R_a C = 1.8 sec. Finally, the peak power output for this run is given by $V_D = i_{max} V_a$ and is about 55 kW. Thus a five-fold increase in power was achieved in this run.

Armature Resistance

As we see from above the homopolar machine delivers a large current pulse in times less than 1 sec and has a large power gain (greater than 5). These results provide evidence toward substantiating our claim regarding the usefulness of this machine in powering the large electromagnets of CTR experiments. The two principal problems to be overcome are the high armature resistance and the friction losses in motoring the machine. Since the former limits the discharge time and the maximum current, it is necessary to reduce R_a substantially. Because high R_a is due to current constriction at the rotor surface, it will be necessary to cover as much of this surface with brushes during discharge as possible. At present only 1% of the surface is covered.

This will be increased by at least a factor of 10 in the next machine. Mechanical resistance due to brush and bearing friction is discussed with the test results in the next section.

Electromagnetic Thrust Bearing

Besides the brushes, the principal source of friction appears to be the loading of the thrust bearing due to electromagnetic forces acting on the rotor. This axial force occurs when the rotor is not exactly in the magnetic center of the machine tending to move the rotor toward the yoke wall. The presence of this force is clearly observed by noting the increase of the rotor starting torque required as the field increases. Existence of this force results from the unbalance of the field lines in the two air gaps. This means that an axial displacement of the rotor causes an increase in the magnetic intensity in the region where the gap is shortened and a decrease in the gap that is lengthened. The net effect is a negative spring constant which leads to instability. A possible method of stabilizing the system is to adjust the ampereturns differentially to compensate for changes in air gaps which should generate a net negative spring constant yielding a restoring force for small displacements from the magnetic center.

Thrust-Force Calculation

The system to be analyzed is shown in Fig. 2. We divide the field coil into two equal banks and excite each with its own power supply. To compute the force we calculate the magnetic co-energy, $W_m'(\Delta i, z)$, in the gap regions assuming a small displacement $z \ll g$ and a small increment of current $1/2\ \Delta i \ll i_{fo}$. The fields, $\underline{H}_1$, and $\underline{H}_2$, are determined from Ampere's law and $\nabla \cdot \underline{B} = 0$. Once W_m' is calculated, the force is given by $F = \partial W_m'/\partial z$ which is to first order in z and Δi,

$$F = \frac{\mu_o \pi \left(R_o{}^2 - R_i{}^2\right) N^2 i_{fo}}{g^2} Q\left[\frac{2z}{g} - \frac{\Delta i}{i_{fo}}\right]$$

$$= -K_1 z - K_2 \Delta i \quad (K_1 < 0 \text{ and } K_2 > 0) \qquad (1)$$

where Q is a dimensionless quantity dependent on the geometry, and N the number of turns in each bank of coils (assumed equal). Further, it can be seen from Eq. (1) that $K_1/K_2 = -2i_{fo}/g$. For $i_{fo} = 250$ A and $g = 1.6 \times 10^{-2}$ m which are characteristic of the system this ratio is 3.16×10^4. Now if we can relate Δi to z as $\Delta i = Cz$ then Eq. (1) becomes

$$F = -K_2\left[\left(\frac{K_1}{K_2}\right) + C\right] z = -Kz$$

Stability can be achieved when $K > 0$ or $|C| > |K_1/K_2|$. For a minimum value of $C = 3.2 \times 10^4$, we need a Δi of at least 32 Amps for a z of 1×10^{-3} m. Therefore power supply one (Fig. 3) would decrease to 234 Amps while power supply two would increase to 266 Amps to stabilize the system. We note from this analysis two important facts: (1) a large gain is required when converting the displacement to a field current change, and (2) only relatively small displacements in the rotor position are tolerated. The limits on z are determined by the maximum voltage of the power supplies as we shall see.

Method of Stabilization

To bring about stability we must relate Δi to z. This is accomplished by sensing the position of the rotor with a photoelectronic device and sending the resulting voltage into the control circuit of the power supplies to close the loop as shown in Fig. 3. Sufficient amplification is required to generate the necessary current as well as production of a differential voltage to feed the two supplies. We can now write circuit equations which connect z and Δi for each bank of coils and combine them to get

$$L \frac{d\Delta i}{dt} + R\Delta i = -2K_3 z \tag{3}$$

Here, $L = L_{1,2} - M_{12}$ where $L_{1,2}$ are the self-inductances of the two coils and to a good approximation are equal, M_{12} is the mutual inductance between the coils, $R = R_c + \beta$ where R_c is the coil resistance and β is the effective resistance of the constant-current power supply (determined from the power supplies' I-V characteristic for a given regulation percentage), and K_3 is the gain of the control system. The maximum voltage, $2K_3 z$, is 400 volts which limits the value of z once we have set K_3. Typical values are $L_{1,2} = 2 \times 10^{-3}$H, $M_{12} = 1.5 \times 10^{-3}$H, $R_c = 11$ mΩ, and $\beta = 5\Omega$ (for 20% regulation). Combining Eq. (3) with the equation of motion obtained from Eq. (1)

$$F = m \frac{d^2 z}{dt^2} = -K_1 z - K_2 \Delta i \tag{4}$$

we get a third-order system. However, since $L/R \lll 1$, this reduces to a second-order system of the form

$$\frac{d^2 z}{dt^2} + \frac{K_2}{m}\left[\frac{K_1}{K_2} - \frac{2K_3}{R}\right] z = 0. \tag{5}$$

Stability occurs when the coefficient of z is > 0. For the values listed above we get $K_3 = -8 \times 10^4$. From Eq. (2) we can get an approximate value for Δi since $L \ll R$. This is $\Delta i = -2K_3 z/R$ or $\Delta i = 32$ A for $z = 1 \times 10^{-3}$ which is what we obtained earlier. In addition solution of Eq. (5) shows that the quarter period, $1/4\ T_R$, is on the order of 500 ms for the parameter values given above.

Implementation

The above control system is implemented by the circuitry shown in Fig. 2. The position sensor consists of a narrow beam angle LED and phototransistor. The output of the latter is amplified by a two-stage variable gain amplifier and then converted to $\pm V_{out}$ using a balanced output combination of operational amplifiers. Each power supply receives one of the two output voltages into the current portion of the SCR control circuit (Vectrol 1001). We have modified the latter to be able to null out the voltage from the position sensor at the equilibrium point. Therefore, only changes from $z = 0$ will cause a change in i_f. Both power supplies have a common control to set the steady state current, i_{fo}.

To make this system operate correctly it is necessary to insure that the time response of the power supply control circuit and of changes in the machine's magnetic field is much faster than 1/4 T_R as determined by Eq. (5). We are presently modifying the SCR control circuit to satisfy the first condition. With regard to the latter, we have performed measurements of the time response of the magnetic field by applying a current step to the field coils. By monitoring the current rise in the coils and the rise in flux with a Hall element we measured rise times of less than 60 ms for the current and 100 ms for the field. The difference represents the diffusion of the magnetic flux through the rotor. In either case these rise times are fast enough to satisfy our requirements.

Discussion of Electrical Design Improvements

The successful implementation of the electromagnetic thrust bearing described above will substantially reduce the friction forces acting on the rotor during the motor phase. In addition to this we are also designing a control system to regulate the speed, hence the current, during the discharge pulse. This method will also require variation of i_f for the two coil banks but this time in tandem instead of differentially. The importance of this operation is based on the need to achieve a relatively flat current pulse so that the confinement field will be constant during the course of the fusion experiment.

For a feasibility experiment this "flat-top" time is about 10-20 sec. The control problem in this case is analytically more difficult than in the stability case because the transfer function between i_a and i_f is exponential in form. We are presently attacking this problem by computer simulation.

Experimental Results

Initially, experiments were made to determine the optimum number of brushes and brush load to be used in the motoring and generate modes. With the standard 1972 General Motors starter motor brushes, acceleration in the motoring mode is maximized using two tracks of eight brushes per track on the rotor and all shaft brushes at a brush load of 2 pounds/brush or about 10 psi. Best results have been obtained in the generate mode with all available brushes loaded at maximum pressure (approx. 25 psi).

Once this information was obtained a series of runs was made as follows:

1. Motor Up - Coast Down, with field on and motoring brushes down
2. Motor Up - Coast Down with field on and no brushes down
3. Motor Up - Coast Down with field off and no brushes down
4. Motor Up - Coast Down with field on and generate brushes down

Data collected during these runs allowed the determination of drag due to the magnetic field, the motoring brushes, the generating brushes, windage, and hydrostatic bearing losses as well as determination of machine efficiency in the motoring and generating modes.

A sample data set is shown in Fig.4 which was used to obtain motoring and generating efficiency. Motoring efficiency is simply the ratio of the kinetic energy stored in the rotor to the electrical energy put into the machine to get up to speed. For this run the motoring efficiency is 5.9%.

Generating efficiency is the ratio of the electrical energy output during generating (measured at the machine's terminals) to the kinetic energy stored in the rotor. For the run shown in Figure 4, this value is 69%.

The net efficiency is the ratio of the electrical energy generated by the machine to the electrical energy put into the machine. It is numerically equal to the product of the motoring efficiency and the generating efficiency. For our example run, the net efficiency is 4%.

New Investigations

Brush Test Machine

Due to many unresolved questions in the area and the general lack of applicable information on the subject; a test fixture is being constructed to run electrical brushes under varying conditions of current, mechanical loading and surface speed. The test fixture consists of an AISI 4340 steel rotor mounted on hydrostatic bearings and driven by a variable speed air turbine. Two brushes can be forced against the rotor 90° apart by air cylinders. Current for the tests is to be supplied by a 750 ampere DC motor-generator set.

Provision is made to monitor current through the brushes, voltage drop across the brushes, normal force on the brushes, frictional force on the brushes, rotor surface speed, and brush wear. Results of these tests will dictate the brush material to be used on the next homopolar generators.

Coil Assembly Stress Analysis

In order to generate the magnetic field necessary to contain the plasma, the Texas Tokamak utilizes a series of coil assemblies arranged in a circle. Each coil assembly consists of several flat copper washers stacked and insulated to form a helical coil. This coil is held together by two aluminum plates bound together with 5/16-inch stainless steel bolts. During the transient period while the magnetic flux is building up, the reaction of the field with the plates puts a large load (force) on the connecting bolts.

A stress analysis of the plates and bolts was completed along with laboratory tests of the bolt-insulator assembly. The ultimate strength of the bolt-insulator assembly was 6800 pounds. Plastic deformation occurs at 4000 pounds. Since the calculated maximum loading on the bolts is 2090 pounds, there is some margin of safety. However, due to the dynamic nature of this load and the stress concentration in the bolt threads the design is considered marginal and should be checked with actual stress measurements before full loading is applied.

Design Configurations for New Machine

Before beginning the design of the 5 mj homopolar machine a brief study and analysis was made of possible alternate configurations including some new concepts not previously discussed. A brief review of the advantages and disadvantages is instructive.

The single rotor machine with axial magnetic field and radial current flow (our bench model) is mechanically the simplest configuration and thus the least expensive. It is also the configuration with which we have the most experience. However, since it gives only one pass through the magnetic field it must be either a relatively low voltage machine or have a very large diameter rotor, which causes stability problems. In addition it shares one problem with all axial magnetic field machines; it is magnetically unstable.

The single rotor machine of the General Electric Co. type (Radial Magnetic field, axial current flow) is magnetically stable and simple. Unfortunately the long, small diameter rotor is inefficient for inertial energy storage and the machine also produces low voltages.

The single rotor machine (axial magnetic field, radial current flow) using a central rotor for energy storage and multiple plates as current carrying members (See Fig. 5) obtains much higher voltages by making multiple passes through the magnetic field. Unfortunately the narrow plates severely restrict the number of brushes which can be used to carry current especially on the inner edge of the plates. The brush connections and operating mechanism become very complex. Cooling the inner plates is very difficult and differential expansion between the plates and rotor due to thermal and centrifugal loading must be dealt with. Again this configuration is magnetically unstable.

A single split rotor with axial magnetic field and radial current flow also offers higher voltage than the current single rotor machine, but securely joining the two rotor halves presents definite problems.

A drum type rotor with a radial magnetic field and axial current flow offers the advantage that all magnetic flux is cut at maximum peripheral speed thus offering some voltage increase. However the drum shape is inherently a low speed device due to structural instabilities.

A spool shaped rotor in a bidirectional magnetic field (See Fig. 6) using an axial magnetic field with radial current flow, although still magnetically unstable, offers the advantage of two passes through the magnetic field with half the number of brush-rotor contacts required by the other multiple pass schemes. This is made possible by the elimination of the shaft brushes. This is quite significant since the brush-rotor contact is responsible for a major portion of the voltage drop in the circuit.

A slightly more complicated rotor configuration will allow 4 passes through the field with the same advantages. After careful consideration the decision was made not to pursue this configuration on the 5 mj machine due to the added cost of the double coil and yoke, but this should become less significant on a larger machine, especially in view of the increased output voltage and 50% reduction in internal voltage drop.

Brief consideration has been given to liquid metal brushes because of their popularity on other machines of this type. Mercury, the most obvious choice for liquid metal brushes has a resistivity of around 10 x 10^{-6} ohm-cm as compared to copper at 1.72 x 10^{-6} ohm-cm. Thus the required brush area would need to be increased by a factor of 58 to maintain the same voltage drop. The more common alloys like Na-K have lower resistivity on the order of 6 to 8 times higher than copper but must be heated slightly to become liquid. This of course greatly complicates start up procedures. Also both of the above compounds are highly toxic and require considerable care in handling. Additionally the Na-K alloy is highly unstable.

When these disadvantages are viewed in the light of the fact that we have run solid brushes at current densities of 4600 Amperes/square inch without experiencing any difficulties, the reasoning behind our choice of solid brushes seems justified.

In the larger machines the use of a hydrogen atmosphere becomes advantageous for three reasons. First, hydrogen has an absolute viscosity approximately one-half that of air, so that, using the coefficients from the Locheed windage equation.

$$\text{REDUCTION IN WINDAGE LOSS} = \left[1 - \frac{(.022)^{.2}}{(.047)^{.2}}\right] 100 = 14\%$$

Additionally the specific heat of hydrogen is more than 14 times greater than that of air, so this will greatly aid in cooling of machine parts during cyclic cooling. Dr. Schobert, Vice President of Technology for Stackpole Carbon Company also tells us that the hydrogen atmosphere will reduce contact drop and improve brush life.

Design of a 5 Megajoule Homopolar Generator

After a review of the various proposed designs discussed in the last chapter and a review of the current and future funding situations; the decision was made to pursue the design of a 5 megajoule single rotor model as shown in Fig. 7. This unit will incorporate the improvement suggested during the past year spent running the existing model. It will be capable of running with the existing power supplies and has been sized to be constructed from "off-the-shelf" materials using machine tools readily available to us. Construction time is estimated at 6 months.

The rotor will be forged of AISI 4340 steel for reasons previously discussed. It will be 24 inches in diameter, 11 inches thick and will be shrunk onto a 5 inch diameter 304 stainless steel shaft. The shaft will be supported by hydrostatic journal bearings in stainless steel housings attached directly to the magnetic yoke. Provision has been made for using either a hydrostatic thrust bearing or a mechanical safety stop for use with the magnetic thrust bearing.

The magnetic yoke consists of a 53 inch outside diameter, 3 inch thick rolled mild steel ring 14 inches long welded between two 6 inch thick end plates which also form the base of the machine. The end plates have been designed for uniform flux density across the face of the rotor.

The magnetic field coil consists of 2600 feet of 1/2 inch outside diameter, 0.049 inch wall copper tubing wound and epoxy potted to form a coil 20 turns wide by 13 turns deep. With this coil and yoke, a field current of 250 amperes will give a magnetic field of 1.61 webers/square meter. This coil having a resistance of 0.282 ohm will operate at 70.5 volts with a power consumption of 17.6 kw--well within the capabilities of the present power supplies. The field coil will be split to facilitate use as a magnetic thrust bearing.