Westinghouse Programs in Pulsed Homopolar Power Supplies

D. C. Litz
E. Mullan
Westinghouse R&D Center
Pittsburgh, PA

Disc Type Homopolar Machine

The disc type homopolar machine shown in Figure 1 is the simplest form of an electrical machine. The machine consists of a disc rotating in an axial field provided by an electric coil positioned at the disc outside diameter. If brushes are placed on the disc OD and ID a voltage will be generated if a prime mover is provided for the disc for continuous power generation. The machine is a simple turn configuration and therefore generates a very low voltage. This low voltage requires a large current for reasonable machine horsepower. The development of these machines has been limited because of the massive current collection systems required to transfer the current from the rotor to the stator. Advances in high current density current collectors and the need for high power density power supplies have resulted in increased interest in homopolar machines. In pulsed applications, the disc is accelerated to speed, thus acting as an energy storage flywheel. If the leads are connected to a load the mechanical energy stored in the disc will be converted to electrical power and delivered to the load as the disc decelerates. Since the voltage is generated in the same element that stores the energy, there are no transient torques as would be encountered in flywheel-generator combinations. The deceleration force on the energy storage disc introduces shear stresses in the disc during the energy conversion phase. For normal configurations these shear stresses are usually very low as compared with shaft shear stresses in a flywheel-generator combination.

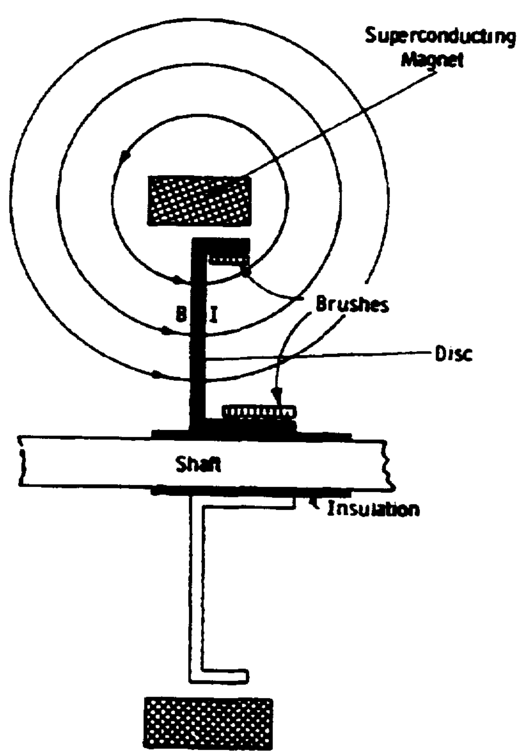

Figure 1

Drum Type Homopolar Machine

An alternate form of this concept is a drum machine shown in Figure 2. A drum or cylinder rotates in a radial magnetic field produced by two opposed solenoid coils. If brushes are placed on the cylinder surface as shown power will be generated as was the case with the disc machine. The drum machine can also act as an inertia storage device.

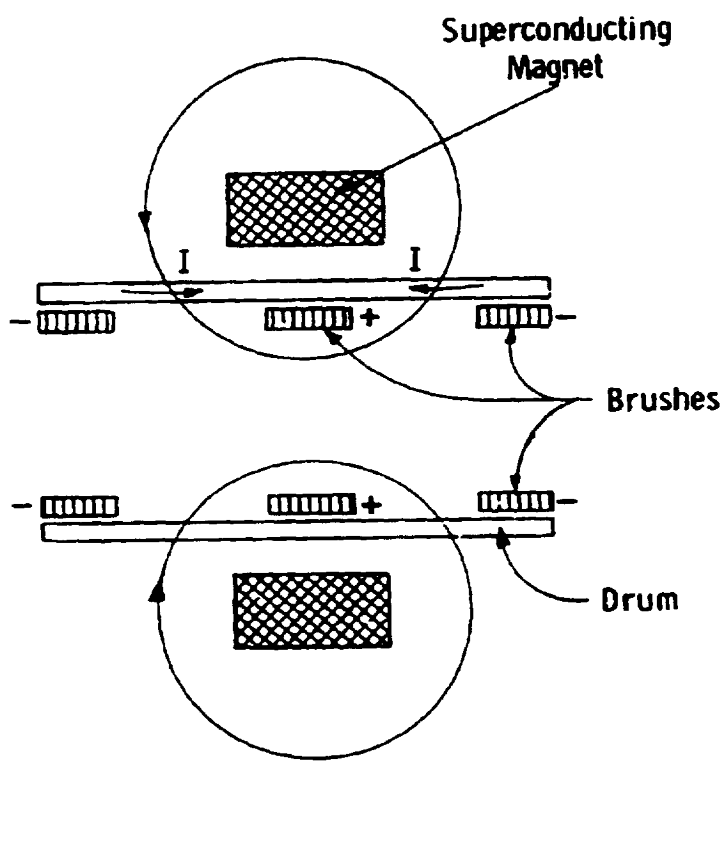

Figure 2

Pulsed Homopolar Characteristics

Homopolar machines are inherently low voltage, high current machines. When used as a pulsed power supply, they behave as a large mechanical capacitor with an extremely low internal inductance and resistance. The integral flywheel generator concept provides a high power density pulsed power supply. From a mechanical standpoint the machine is inexpensive, simple and rugged with uncomplicated dynamic components. The only area requiring a higher level of technology is the current collection system. These characteristics are summarized in Figure 3.

Pulsed Homopolar Characteristics

- Mechanical Capacitor

$$C = \frac{2E}{V^2}$$

C = Capacitance
E = Energy stored
V = Generated voltage

- Voltage Generated

$$V = \beta v l$$

β = Flux density
v = Tip speed
l = Machine active length

- Low resistance and inductance
- Rugged design
- Simple
- Current collection dominates the design

Figure 3

Westinghouse Homopolar Machine Experience

Westinghouse experience with homopolar machines started in 1929 with most of the work being done in the 1970's and 80's as shown in Figure 4. These included steady state DC power supplies, current collection test machines and pulsed power sources. The development of these machines required establishing expertise in support technologies including: current collection, both solid brush and liquid metal, rotor stability, AC losses, system integration, innovative cooling concepts and machine design.

1929	Homopolar Welding Power Supply
1972	Liquid Metal Homopolar
1974	Homopolar Energy Transfer System
1978	Machine Environment Brush Tester
1982	Rail Gun Homopolar Generator
1983	Artillery Rail Gun Homopolar Generator
1983	Space Borne Homopolar Generator

Figure 4

Westinghouse Welding Power Supply

In 1929 Westinghouse shipped a homopolar generator, shown in Figure 5, to Youngstown Sheet and Tube as a power supply for welding seamed tubing. This unit was capable of producing up to 100,000 amps at a terminal voltage of 10 volts. The machine is a modified drum design with axial bars imbedded in a ferromagnetic rotor core. The excitation was provided by a copper field coil operating at room temperature. The generator was dominated by current collection since the technology of that era dictated brush current densities of about 60-100 amps/in^2. This machine operated until the late 1970's when the pipe mill was retired.

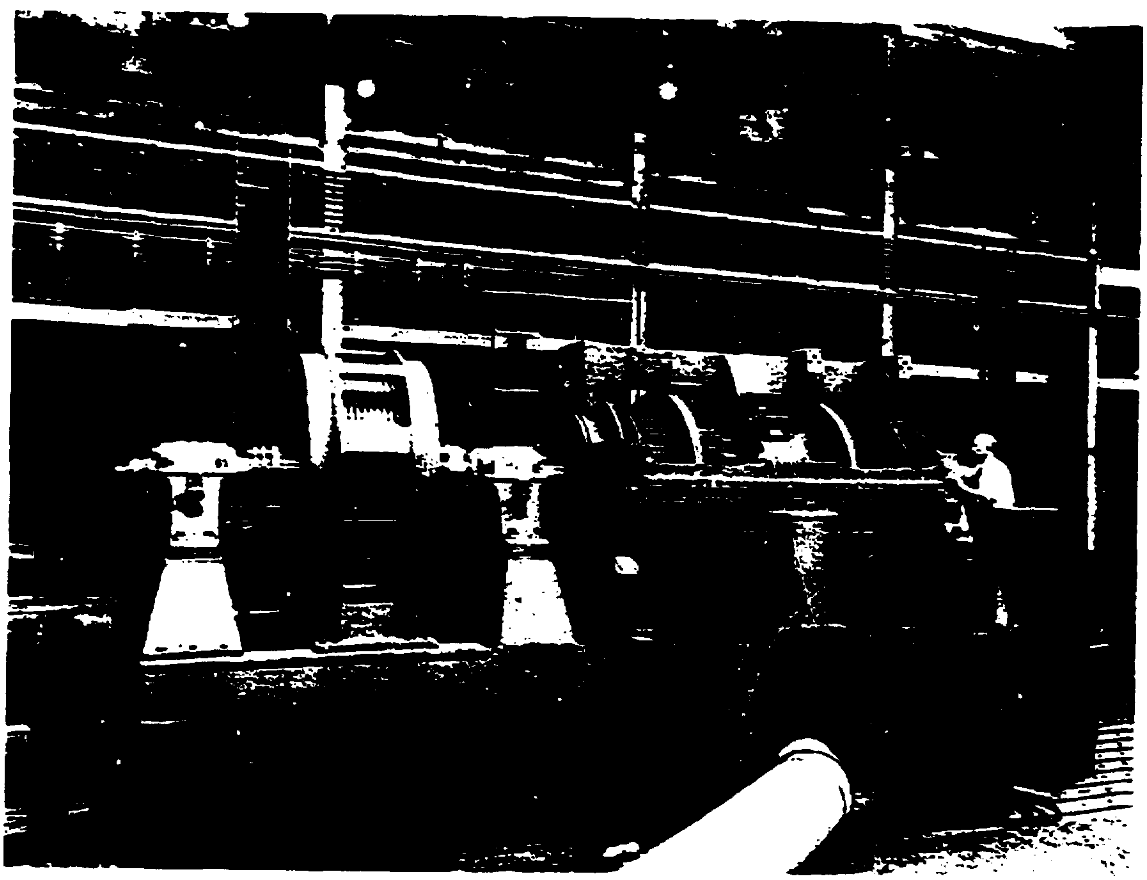

Figure 5

Liquid Metal Homopolar Generator

In the early 1970's interest in homopolar machines as ship's propulsion motors and generators increased. The major disadvantage of the machine was its low power density due to the low current density of available current collection systems. One current collection system, using liquid metal instead of solid brushes, showed a potential for current collection current densities as high as 25,000 amps/in^2. A program [1] was undertaken at the Westinghouse R&D Center to investigate homopolars with liquid metal current collectors. As a result of this program a 3000 HP machine shown in Figure 6 was designed, built and tested. The machine which used NaK in the current collection system produced 100,000 amps at 20 volts DC. The study also evaluated gallium indium. The liquid metal was maintained in the current collection zone by viscous and centrifugal forces due to the rotation of the rotor. The behavior of liquid metal current collectors is very complex. Westinghouse, as part of this study performed an experimental program to develop the operating characteristics of the collector. Analytical and experimental work was completed on magneto hydrodynamics, liquid metal wetting, environmental control, viscous losses and current carrying capabilities. The results of this program, coupled with advances in solid brush current collection, showed the advantages of high current density liquid metal collectors were offset by their complex operating requirements and auxiliary support systems.

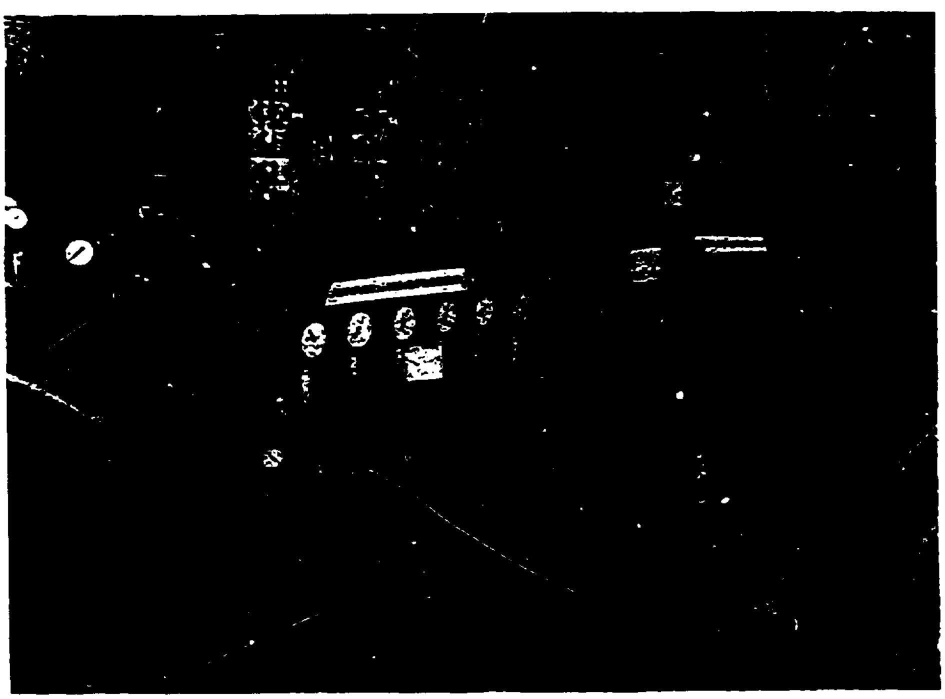

Figure 6

Homopolar Energy Transfer System (HETS)

The emergence of fusion reactors as a viable power supply triggered interest in homopolar machines as pulsed energy sources. The pulsed energy source design objective was to deliver to, accept from and store energy at high efficiency for the fusion reactor. Westinghouse performed a study[2] to develop an engineering design for a homopolar machine to perform this function. A conceptual design, shown in Figure 7, was developed as part of this study. The machine delivered 1.3 GJ of energy in 30 millisec, using eight counter-rotating energy storage rotors. The peak current was 12.25 megamps at a peak terminal voltage of 11 kilovolts. The machine has 13 meters of rotor active length with a 2-meter-diameter rotor spinning at a tip speed of 277 m/sec. The machine used a superconducting field excitation coil with a maximum field of 8 tesla. An iron flux return path was provided to limit stray fields. The machine overall diameter was 7 meters, the overall length was 20.5 meters and the energy transfer efficiency was 95%.

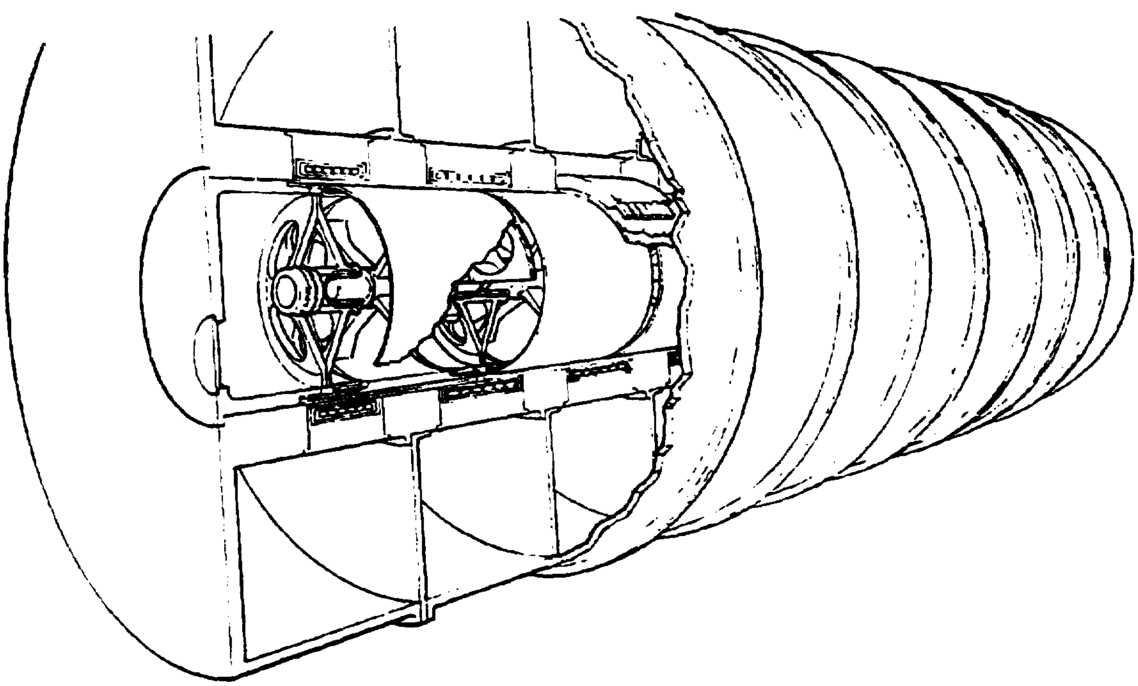

Figure 7

HETS Engineering Demonstration Model

The development of the HETS concept required the design of a demonstration unit to evaluate machine performance characteristics and to test the current collection system in the machine environment. Westinghouse developed an engineering design for such a prototype. This machine, shown in Figure 8, was designed to evaluate all machine technologies used in the large 1.3 GJ homopolar generator. The machine is a drive homopolar with two counter-rotating rotors, each storing 5 MJ. The rotor drums rotating it at a tip speed of 277 m/sec were fabricated from high strength aluminum and supported from a central shaft with constant strength discs. The machine incorporated the current collection system used in the larger machine. Field excitation was provided by a Niobium-Tin (Nb_3Sn) superconducting field winding. Counter-rotating design was used to eliminate the large torque reaction on the machine base.

Figure 8

Homopolar Pulsed Current Collection Testing

The implementation of the HETS concept required the development of a current collection system that would operate at a high current density and tip speed with low losses in a high (6 T) magnetic field. These design requirements are far beyond the state of the art for current collection systems that had been developed. Achievement of these design objectives requires a new concept in solid brush system design. The design adopted [2] was a segmented brush with a pneumatic actuator. A prototype current collection system was designed, built and tested on the test rig shown in Figure 9. The te-t rig used two brush box modes on a 14-inch-diameter wheel rotating with a tip speed of up to 277 m/sec. A pulsed power supply provided an electric current that flowed into one brush to the rotor and into the other brush to complete the circuit. An air actuator system was provided to lower the brush onto the rotor. The current collection system was tested with a brush current density of 12000 amps/in^2 at a tip speed of 277 m/sec with a discharge time of up to 80 millisec. This exceeded the design requirement for the HETS application.

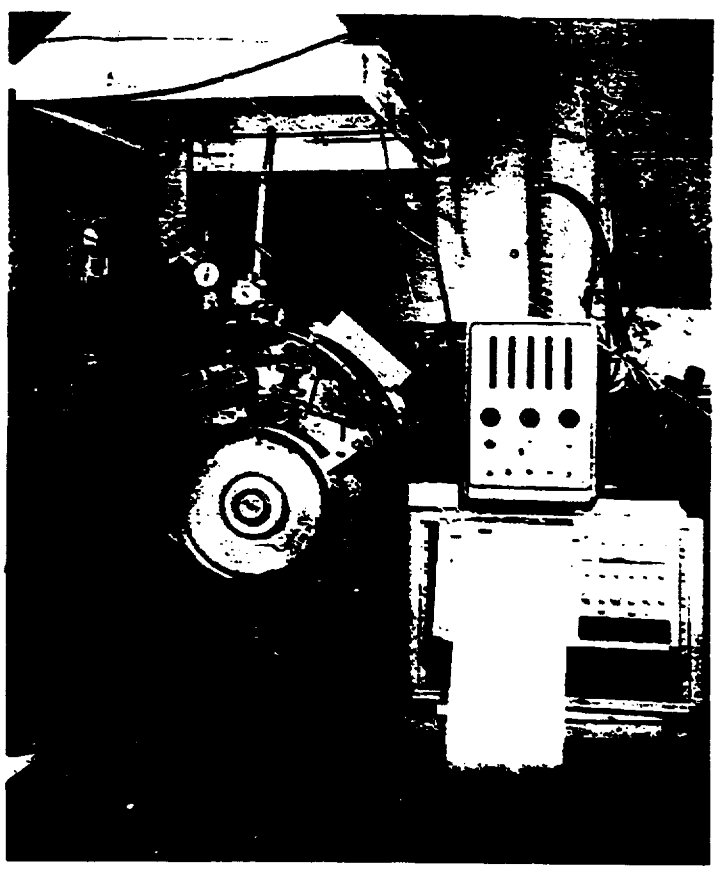

Figure 9

ORIGINAL PAGE IS OF POOR QUALITY

Prototype Homopolar Pulsed Power Supply

The testing required to qualify the HETS current collection system required development of a power supply to deliver energy to the test rig. The power supply consisted of a homopolar generator and pulse shaping inductor shown in Figure 10. In addition to its primary function as a power source, the homopolar generator also acted as a test rig to study the stability of parallel brushes on a common slip ring. Current sharing of high current density multiple parallel brushes had not been studied to date. The machine produced 20,000 amperes at .8 volts and was driven by a variable speed DC machine. Each brush system had 23 parallel brushes operating at a current density of 10000 amps/in^2. In order to limit the rotor losses, a unique water cooling system was provided for the rotor. The machine was successfully operated in conjunction with the test rig demonstrating that high current density multiple brushes can operate stably during pulse loading duty cycles.

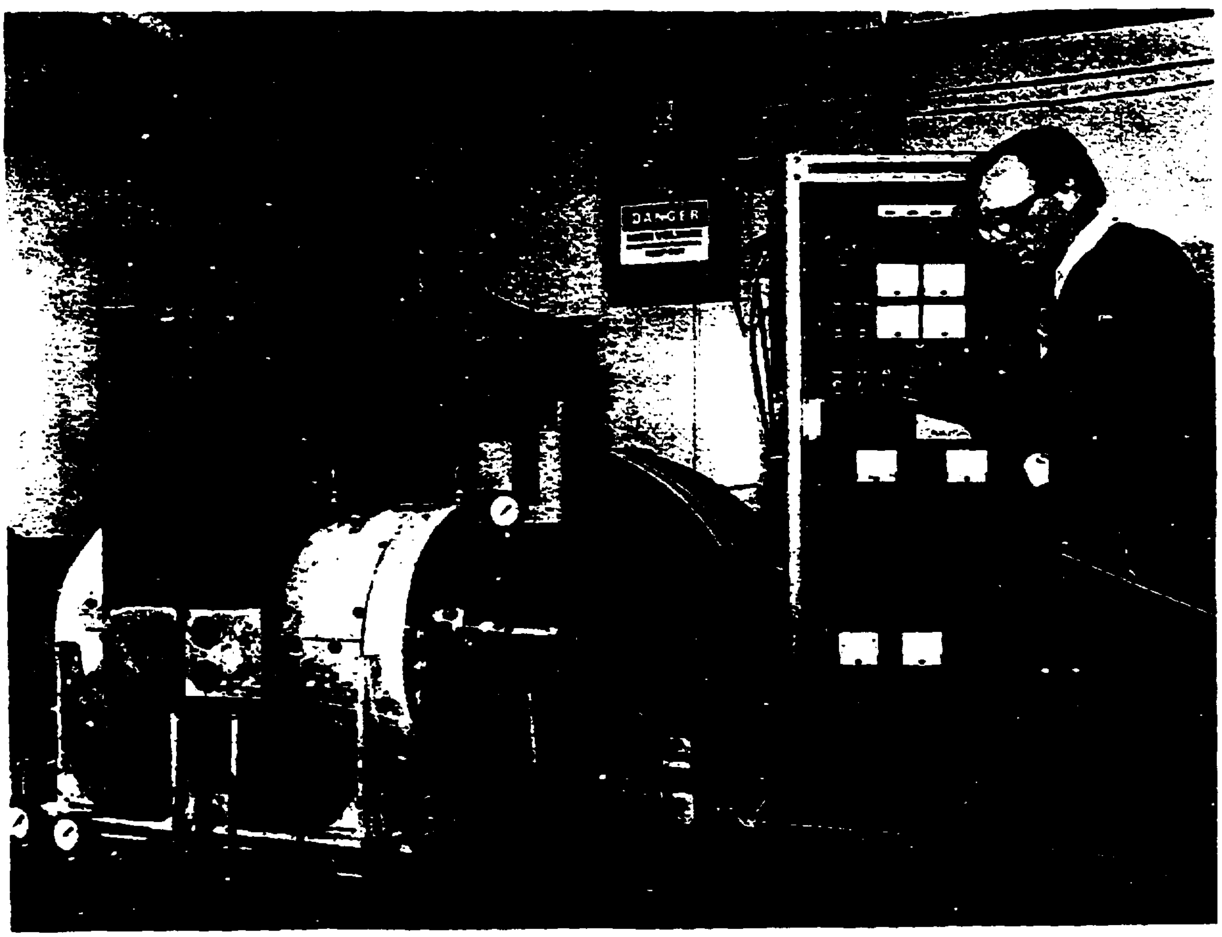

Figure 10

Naval Research Laboratory Self-Excited Homopolar

A novel new approach in pulsed homopolar machines was developed at NRL.[3] This machine shown in Figure 11 uses a series wound approach in that the armature and field coil are connected in series, thus eliminating the need for a separate excitation coil. The machine's constant stress counter-rotating rotor is accelerated to speed and the starting circuit is connected to introduce a starting current in the armature-field circuit shown in Figure 11. During acceleration the circuit breaker is closed. The starting circuit produces a low magnetic field that generates an EMF in the series connected rotors. This results in a current buildup in the circuit through the circuit breaker. When the desired current is reached, the circuit breaker is opened and the current is commutated into the load. Westinghouse participated in this program by providing a new concept current collection system using fiber brushes. These brushes were developed at the R&D Center for high current density during pulse loads.

Westinghouse is also evaluating the self-excited homopolar concept as a lightweight alternative to iron cored machines.

LAYOUT AND ELECTRICAL CIRCUIT OF NRL 10 MJ HOMOPOLAR MACHINE

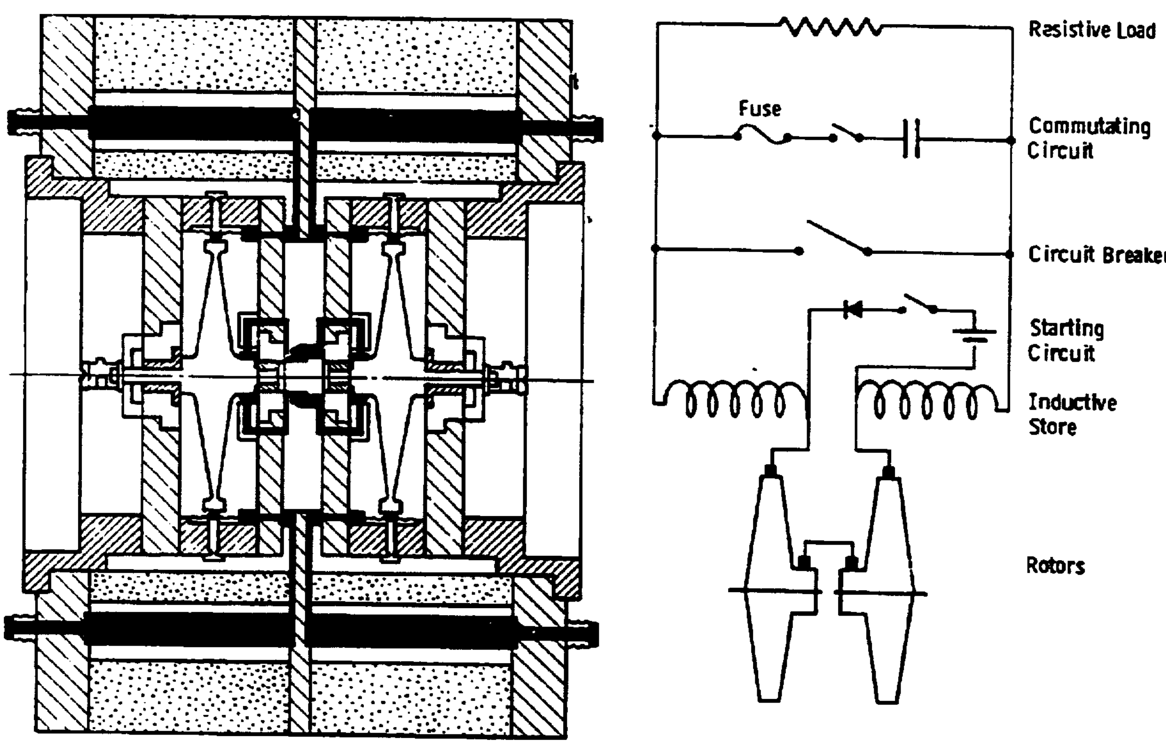

Figure 11

Electromagnetic Launcher Homopolar Supply

Westinghouse has designed, built and tested an Electromagnetic Launcher (EML)[4] for the U.S. Army that uses a pulsed homopolar[5] as the primary power supply. This machine, shown in Figure 12, is designed to deliver 17.5 MJ of energy to the system in 120 millisec with a peak current of 2.16 megamps and peak voltage of 108 volts. The current collection system for the machine is a modified HETS design that operated at a brush current density of 13000 $amps/in^2$ and on a rotor surface moving at 225 m/sec. The machine rotor is 24.5 inches in diameter and 24 inches long, while the overall machine is 48 inches in diameter and 37 inches long. The machine was tested as a part of the overall EML system at the R&D Center. The system has subsequently been installed at a U.S. Army Laboratory at Picatinny Arsenal where it is being used for laboratory experiments on EML programs.

Figure 12

Westinghouse Pulsed HPG Programs

Westinghouse has studied several applications for homopolar machines. These applications all required short bursts of energy in the several to ten's of megajoule range. In single discharge machines the rotor must be sized to deliver the energy required at the voltage and machine capacitance to provide the pulse shape necessary. The prime movers for this application are small since the time required to accelerate the rotor to speed is arbitrary. The homopolar machines for this application are simple and straightforward, with the machine losses being absorbed by temperature rises in the machine parts. At present these systems are primarily research tools to study the technology of pulsed power systems in specific experiments. As these power supplies move from the laboratory to the field, the duty cycle becomes more stringent which is reflected in the machine design. The repetitive discharge is a repeat of the single discharge with several seconds between pulses. In recent studies at Westinghouse, these systems require a large prime mover such as a gas turbine, since the average power required is larger. The homopolar machine also is more complex since the disposition of losses is more important. For a short number of cycles, the losses can be absorbed in the machine mass by contracting the losses. As the number of cycles increases, cooling systems within the machine are required to maintain machine temperatures within acceptable limits. The extended rapid discharge duty cycle remains the most challenging to the designer. In this system it is not practical to store the mission total energy in the rotating mass of the system. In this application the power is furnished by a H_2 turbine with the machine rotor supplying sufficient stored energy to stabilize the voltage between bursts. The homopolar machine for this application requires strict control of losses and exotic cooling systems to survive. The characteristics of these applications are shown in Figure 13.

Inertia Storage System Studies

1. Single Discharge
   - Accelerate rotor to speed
   - Discharge into load
   - Extended reconfiguration (minute to hours)

2. Repetitive Discharge
   - Accelerate rotor to speed
   - Discharge into load
   - Reconfigure and re-accelerate (several seconds)
   - Discharge

3. Extended Rapid Discharge
   - Accelerate rotor to speed
   - Series of discharges (milliseconds between cycles)

Figure 13

Summary

Westinghouse has been associated with homopolar machines since 1929 with the major effort occurring in the early 1970's to the present. The effort has enabled Westinghouse to develop expertise in the technology required for the design, fabrication and testing of such machines. This includes (Figure 14) electrical design, electromagnetic analysis, current collection, mechanical design, advanced cooling, stress analysis, transient rotor performance, bearing analysis and seal technology. Westinghouse is using this capability to explore the use of homopolar machines as pulsed power supplies for future systems in both military and commercial applications.

Westinghouse Homopolar Technology

- Electrical Design
- Electromagnetic Analysis
- Current Collection
- Mechanical Design
- Advanced Cooling
- Stress Analysis
- Transient Rotor Performance
- Bearing Analysis
- Seal Technology

Figure 14

References

1. Design and Development of a Segmented Magnet Homopolar Torque Converter, Final Report; Department of Defense, Advanced Research Projects Agency, Contract No. DAHC 15-72-C-0229, September 1976.

2. Conceptual Engineering Design of a One GJ Fast Discharging Homopolar for the Reference Theta Pinch Reactor, EPRI ER-246, August 1976.

3. Robson, A. E., et al., (1976): An Inductive Energy Storage System Based on a Self-Excited Homopolar Generator, 6th Symposium on Engineering Problems in Fusion Research, IEEE Pub. No. 75 CH 1097-5-NPS (1976), p. 298.

4. Deis, D. W. and McNab, I. R.: A Laboratory Demonstration Electromagnetic Launcher, IEEE, Transaction on Magnetics, Vol. 18, No. 1.

5. Proceedings of the 1983 International Current Collection Conference. David Taylor Naval Research Facility, October 18-20, 1983.