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A LOW SPEED DIRECT CURRENT SUPERCONDUCTING HETERPOLAR MOTOR.(U)
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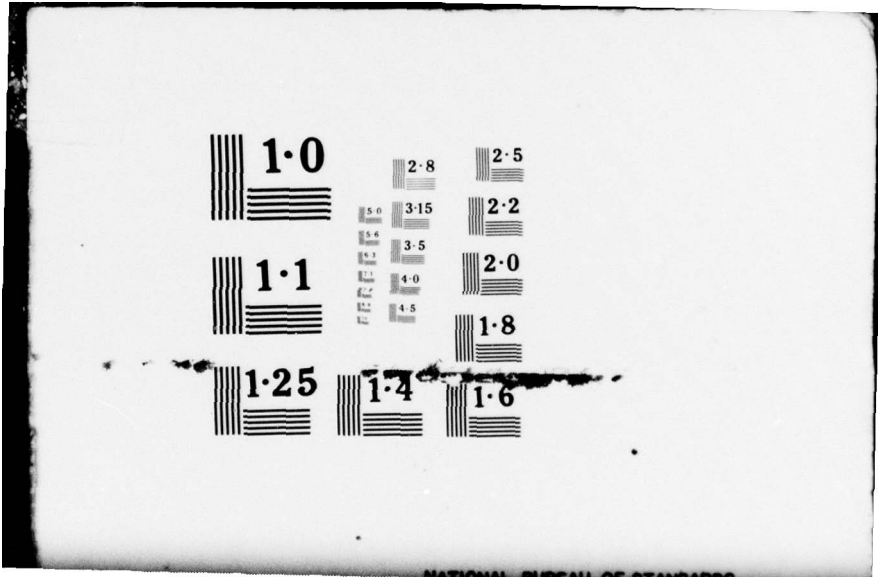
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SUPERCONDUCTING ELECTRICAL MACHINERY SYSTEMS
RESEARCH AND DEVELOPMENT CENTER

Churchill Borough
Pittsburgh, PA 15235

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A LOW SPEED DIRECT CURRENT SUPERCONDUCTING

HETEROPOLAR MOTOR

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- Inherent take-home capability on batteries, AC ship's service, or emergency diesel without cryogenic refrigeration.
- Improved subdivision of propulsion spaces and volume.
- Utilization of existing technologies which are compatible with safety requirements of submarines.
- Silent operation on batteries at high horsepower.

ABSTRACT



2.0 SUMMARY

Important progress in assessing the limits of ratings for new concept electrical machines for ship propulsion applications has been achieved.

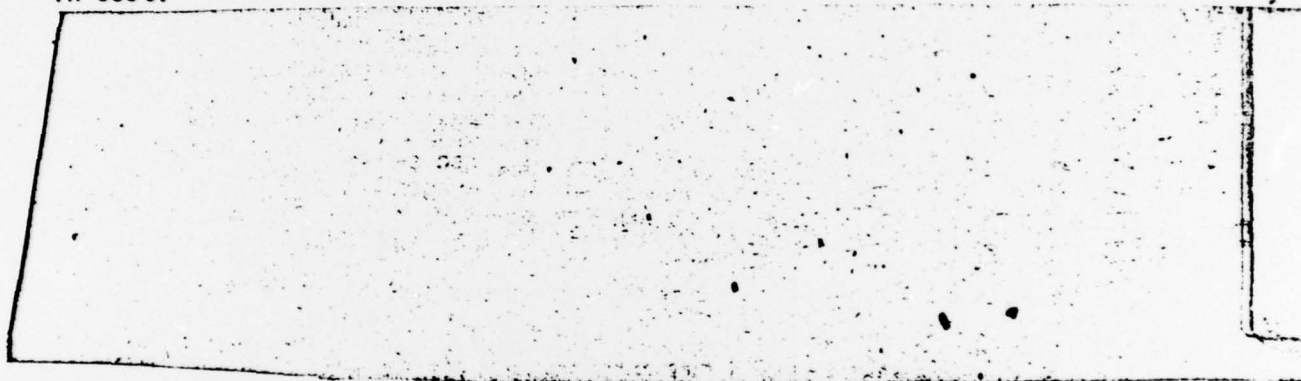
The superconducting heteropolar motor has been identified as the most promising machine concept for slow speed, high power use. Maximum utilization of the drum homopolar machine is limited by transmission line current ratings, and may be greatly improved if an in-line drive is required, and thus allowing the use of the homopolar torque converter. The magnetic disc homopolar motor with water cooling appears to be the preferred concept for low speed homopolar motor applications.

Technical progress in the conceptual configuration of the superconducting heteropolar machine is presented together with a report on progress on the solution of commutation problems in such machines.

ABSTRACT

3.0 CONCLUSIONS

The superconducting heteropolar motor has considerable promise as a ship propulsion motor for high power and low propeller speed applications, such as high speed nuclear submarines and destroyers. The machine is very small in size, very efficient, very quiet, and low in cost.



4.0 MACHINE RATING LIMITS

All electrical machine types have limits imposed on maximum achievable ratings at various speeds. These limits are peculiar to specific machine types and must be considered in the selection of machines for any specific application. The limits on the ratings of advanced concept machines are similar in nature to those imposed on conventional machines of similar types.

The advanced machine concepts now undergoing study and/or development include two classes of machines:

- Flux limited concepts.
- Current limited concepts.

Flux limited machines include those which have armature windings which are AC and where performance is limited by armature reactance. These include superconducting synchronous machines and superconducting heteropolar DC machines.

Current limited machines are essentially all homopolar machines which have no armature reaction or other magnetic load effects.

The principal machine concepts currently under consideration for ship propulsion applications include the following types:

- Superconducting AC synchronous.
- Superconducting DC heteropolar.
- Superconducting drum homopolar.
- Water cooled drum homopolar.
- Water cooled magnetic conductor disc homopolar.
- Water cooled homopolar torque converter.

Most machines are designed to produce their maximum output within thermal limitations on insulating and structural materials, and/or mechanical stress limitations. Almost all high speed machines are operated close to the stress limited state.

Synchronous machines are constructed in very large ratings over a wide range of speeds. These machines are rugged and have large operating

1.0 INTRODUCTION

This brief document reports on progress on the DC Heteropolar motor concept study being conducted by Westinghouse, and the complimenting study on commutation problems being supported by U.S. Navy, Office of Naval Research Code 473, Contract N0004-72-C-0432.

The DC Heteropolar motor concept shows considerable promise as a low speed propulsion motor for high power ratings. The machine uses a superconducting field winding to allow the use of an air gap armature winding, which results in considerable improvements in commutation technology. The high field together with other important innovations will further improve commutation of the machine, and this allows considerable increases in the machine ratings.

Many developments are proceeding in advanced electrical machines, particularly superconducting machines. One major area of application is ship propulsion, where a wide range of ratings and speeds are required for a variety of ship concepts. It has become apparent that no single machine system concept may be valid for all ship applications, and therefore that a variety of machine types will be required in the future. This follows historical experience with conventional machines.

A study has been conducted to identify the machine rating limits for a variety of machine concepts, and also to select machine concepts for the required applications. This study has revealed that several machine concepts will be required for effective across-the-board utilization of superconducting electrical machines for ship propulsion systems.

Among the many advantages of the superconducting AC generator - superconducting heteropolar DC motor propulsion systems for submarines are:

- Large initial and life cycle cost savings over alternative transmission systems.
- Reduced weight and volume of cables, structural members, and life support equipment.
- Design flexibility of submarine internals.
- Increased systems reliability and redundancy.
- Higher system efficiencies due to high voltage cables, optional control of motor field, and superconducting machine efficiencies.

air gaps. The superconducting version has been built with very large power densities at high speed with few poles. However, where slow operating speeds and therefore large numbers of poles are required, such as required in ship propulsion, very poor magnetic coupling is achieved, and the weight, volume, and efficiency advantages are somewhat diminished.

The use of very high magnetic fields in superconducting heteropolar DC machines substantially increases the machine rating, and at the same time greatly reduces commutation problems which have a major effect on machine rating. Since this machine is essentially a slow speed machine very large ratings are obtainable at very slow speeds. However, the performance at high speed is severely limited.

The homopolar machine is essentially a low voltage, high current machine. Very high power density machines must utilize liquid metal current collection systems in order to carry the very high DC current across the machine air gap. With optimum conductor cooled drum machines extremely high currents may be achieved, in orders of 80,000 amperes per foot of diameter, yielding very high power densities.

The problems related to transmitting very large currents in ships are very severe. Very large, heavy and inefficient transmission systems are necessary, and where the transmission lines are long the weight, volume and losses may severely detract from the overall system performance. In order to minimize the transmission problems it is necessary to limit the current of homopolar machines to a level far below the thermal capability of the advanced homopolar machine concepts.

One way to fully utilize the current carrying capability of homopolar machines is to integrate a generator and motor into one unit and obtain a torque converter. With this approach the transmission system is contained in the torque converter and has a very large current carrying capacity.

One new homopolar motor concept is the multiple disc machine using magnetic disc conductors, which combine current carrying capacity with flux carrying capability. This concept allows much lower current ratings than in drum machines, and therefore larger ratings within specific current limitations.

Machine designs which have inherently small gaps between the rotating and stator members are limited in physical size due to rotor movements resulting from distortion, thermal, and bearing movements. Historically the induction motor required for slow speed use has been severely limited in rating by this problem. In some machines this problem is more severe due to unbalanced magnetic forces.

The homopolar machine requires very small gaps between the stationary and rotating current collector components, and small air gaps between

the rotor and stator when iron cores are used. This requirement for small air gaps results in severe limitations on the physical size, and on rating of the machine for low speed use.

Figure 1 illustrates the approximate limits on the ratings for direct current machines. The drum homopolar machine is limited in physical size and transmission current at low speed by mechanical stresses. Using a torque converter machine configuration the current and rating may be increased by a factor of $2\frac{1}{2}$ -3 in proportion to the increased current achieved on the same physical size as the size limited homopolar motor.

The magnetic disc machine has far more capability than the simple drum motor within a given physical size, for the 100,000 ampere arbitrary current level.

The DC Heteropolar motor limited by commutation, has the highest working flux density of all the machine concepts, and the magnetic coupling between the field and armature windings is very good due to the few poles used. This results in an extremely small slow speed machine.

There are no rating limits relating to superconducting AC machines within the given range of rating and speed in Fig. 1. However, the diameter will be quite large on slow speed machines with many poles, in order to obtain reasonable magnetic coupling and performance.

The superconducting DC heteropolar motor is the only suitable DC machine for high power ratings at very slow speed.

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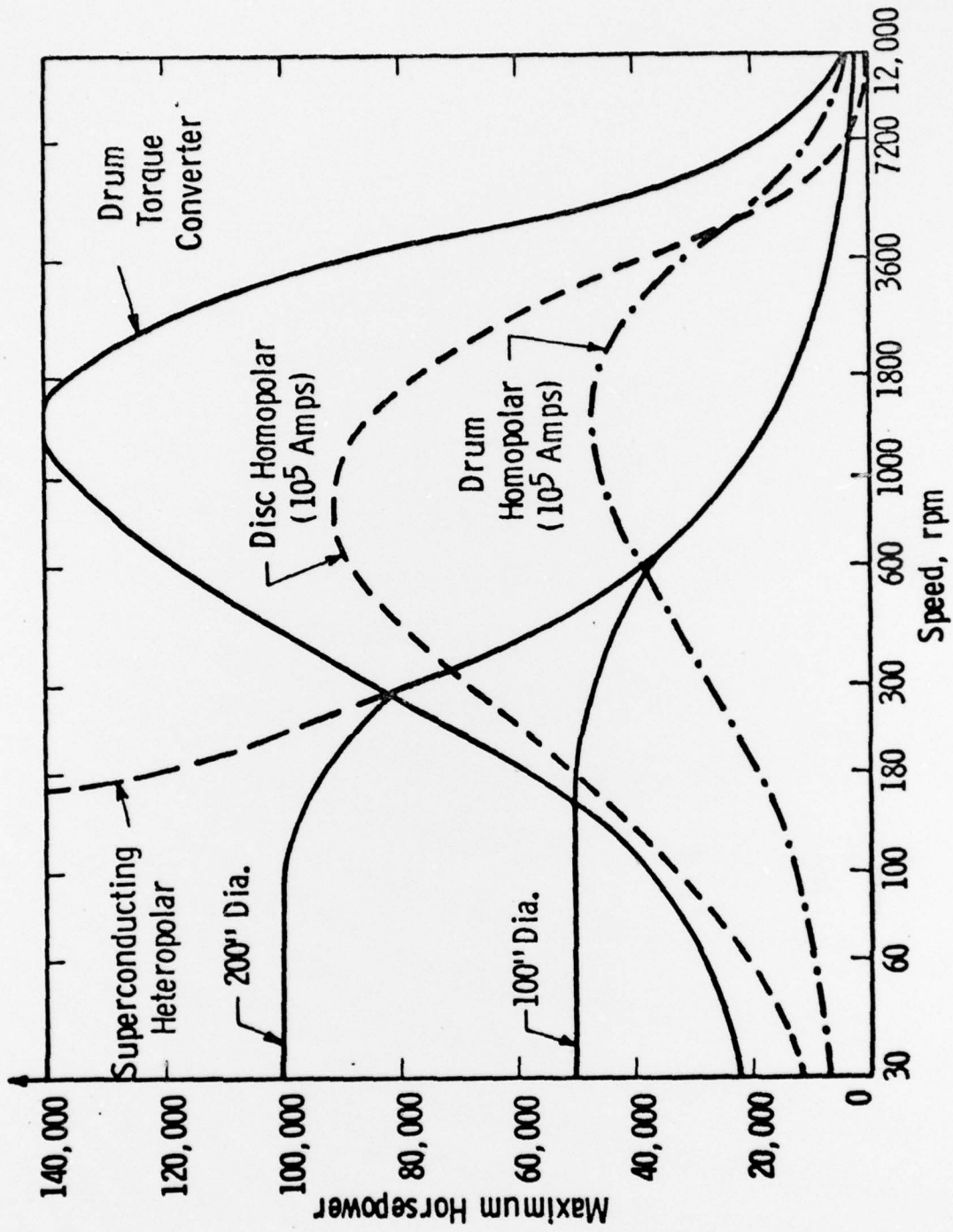


Fig. 1 -DC machine capability curves

5.0 TECHNICAL DISCUSSION

5.1 Low Speed, High Power Machine Constraints

The concept of a superconducting DC heteropolar machine overcomes the major problem areas associated with other machines in low speed propulsion systems. These low speed problem areas were identified for DC homopolar and AC machines.

- DC Homopolar Machines
 - Transmission Line - Transmission line currents upwards of 100,000 amps require severe size, weight and loss penalties in this area. As an illustration, a 100 ft line carrying 100,000 amps, water cooled, requires two 9 inch diameter conductors weighing 46,000 lbs with a 1% loss for a 50,000 HP motor.
 - Current Collector Gap - At the large diameters required for low speed machines, it becomes physically impossible to maintain the small collector gap required for reliable contact.
 - Liquid Metal Confinement - A satisfactory seal for speed reversals on machines with large diameter collectors is not presently available.
 - Losses - Collector losses are high in high voltage machines. Reducing the voltage and, in turn, the machine losses increases the transmission line losses.
- AC Machines
 - Magnetic Coupling - A large number of poles is required for low speed machines resulting in poor magnetic coupling unless the diameter is large or the machine has a dual-rotor configuration.
 - Speed Control - Speed variations require prime mover speed control since the motor and generator speeds are synchronously coupled.
 - Losses - Losses generated in the magnetic teeth are high unless the stator iron laminations are thin.

5.2 Shetpole Features

- Capability

Figure 1 illustrates the capability of DC machines in various ship applications. Areas below each curve are considered feasible regions of application. The homopolar machine capability is severely restricted in the low speed range by collector gap restrictions. In comparison, the capability of SHETPOLE increases as speed is reduced primarily because commutation improves at lower speeds.

- Transmission Line

The transmission line is considerably smaller than that required for homopolar machine systems. Analysis of a new commutator design has indicated that a terminal voltage up to 4000 volts is feasible. Line currents are at least 20 times lower than in homopolar machine systems of the same power rating. With the sharp decrease in line size and weight, the added complication and weight of water-cooled lines are avoided.

- Power Density

Magnetic coupling is good since fewer poles are required than in AC machines. The number of poles and the coupling are independent of the design speed. As a result, power density is consistently high at any speed within the application range.

- Losses

Losses are inherently very low. Most of the losses are produced by ohmic loss in the armature winding. Rotor core losses and conductor eddy current losses are much lower than in AC machines since the rotor field frequency is less than 60 HZ.

- Current Collection

Solid brush current collection provides the reliability and safety required in naval applications. In addition, the high terminal voltage and the resulting low currents in relation to homopolar machines avoids the problems of a high current density collector.

- Speed Control

Speed is controlled by terminal voltage and field current. Prime-mover speed remains constant or is set to its most efficient operating speed. Speed reversal is accomplished effectively and quickly by switching operations.

- Superconducting Field Winding

The simple stationary support structure for this winding requires restraint of conductor motion against the force produced by torque reaction. Centrifugal forces are not present as in the AC machine case.

- System Costs

System costs compare favorably with other advanced AC and DC machine systems. Although this system requires rectifiers, this extra cost is compensated by the lower cost of SHETPOLE and lower transmission costs.

- Noise

No magnetic teeth are present in SHETPOLE. As a result, the noise component produced by teeth vibration and by magnetic field pulsations caused by teeth are avoided.

- Air Gap Control

The gap between the stator and rotor is *not critical* as in the homopolar machine collector gap. A reasonably large air gap is possible from the magnetic circuit standpoint so that some rotor eccentricity, present in all large diameter machines, can be tolerated.

- Configuration

The arrangement of components and their external requirements are uncomplicated in relation to other advanced machines. The promise of the AC machine for low speed applications lies in a complicated, dual-rotor concept. The homopolar machine is complicated by the numerous pipes and the large leads penetrating the small collector region.

5.3 DC Heteropolar Machine Constraints

Conventional heteropolar machines are constrained to relatively low-power applications. The SHETPOLE concept comprising a superconducting field winding,

- Maximum Power Rating

The conventional machine limit of 12,000 HP maximum is increased to a rating greater than 100,000 HP by:

- A sharp reduction in commutation reactance obtainable from an air gap armature winding.
- An increased armature current loading.

The first improvement would not be possible without the large mmf possible from a superconducting field winding.

- Commutation Voltage Compensation

In theory, the average reactance voltage of commutation is compensated by interpole windings so that the commutation process takes place smoothly without brush arcing. In practice, magnetic and electrical discontinuities in the air gap and on the commutator surface produce voltage pulses in the commutated coils causing brush arcing and deterioration. In SHETPOLE, cylindrical magnetic surfaces of the rotor and stator eliminate pulses due to magnetic discontinuities and the low diameter commutator provides a smoother commutator surface. By reducing spurious voltages this way, commutation becomes more reliable and, more important, predictable by simulation.

- Field Form Distortion

Distortion of the main field by armature reaction limits commutator bar voltages to avoid flashover in the region of peak magnetic fields. SHETPOLE virtually eliminates this problem since the armature mmf is small in relation to the superconducting field mmf. A compensating winding to compensate armature reaction is not required as in conventional machines.

- Air Gap

The small air gap between the stator and rotor of conventional machines is not required in SHETPOLE. A large gap can be provided for physical clearance since the extra mmf required from the superconducting field winding is small in relation to the total mmf.

- Commutator and Brush Maintenance

Two factors contribute to an improvement by SHETPOLE in this area:

- Fewer poles and, as a result, fewer brush assemblies are required.

- Rotor Frequency

Impractically fine armature stranding and thin rotor laminations are not required since the rotor frequency is low and eddy current and hysteresis losses are minimal.

- Low Cost

The cost of a SHETPOLE system is comparable to the low cost of other advanced high speed propulsion systems and considerably lower in cost than comparable direct drive gear systems.