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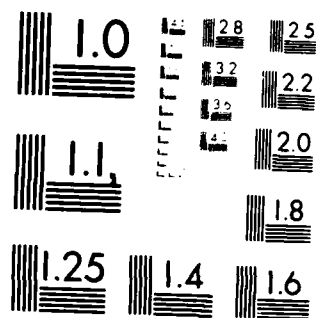
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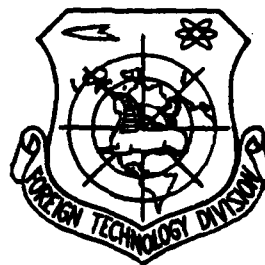
FOREIGN TECHNOLOGY DIVISION



UNIPOLAR MACHINE WITH SUPERCONDUCTIVE EXCITATION WINDING

by

W. Paszek, A. Rozycki, and Z. Pawelec



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UNIPOLAR MACHINE WITH SUPERCONDUCTIVE EXCITATION WINDING

Wladyslaw Paszek, Adam Rozycki, and Zbigniew Pawelec

The article presents the problem of building unipolar machines with superconductive excitation winding. Methods for increasing the unit power and unit voltage of these machines by increasing the induction of the excitation field are discussed. A survey of structural designs in which an increase in the rated voltage of unipolar machines was obtained is presented.

Utilization of Superconductors in Electric Machine Building

Superconductivity phenomena have created new possibilities in the striving to design electric machines with high rated powers and highest efficiency.

The article presents several remarks on the topic of building unipolar machines with a superconductive excitation winding, based on the experiences of some foreign companies (IRD Co. in Great Britain, Laboratoire Centrale des Industries Electriques in France, and others).

A superconductive material is predominantly a metal or alloy which exhibits, for all practical purposes, a zero resistance inside the region P (Fig. 1) in the coordinates J_{exc} , H , T -- current density, external magnetic field strength, temperature, respectively. The relation $H_c = f(T)$ for $J_{exc} = \text{const}$

can be described by the approximate relation

$$H_c = H_0 \left[1 - \left(\frac{T}{T_c} \right)^4 \right] \quad (1)$$

Superconductors are classified into superconductors types I and II. From an operating standpoint, the basic difference between them are the values of the critical parameters and the dependence of the magnetic induction B in the volume of the superconductor on the magnetic field strength H (these relations are illustrated in Fig. 2).

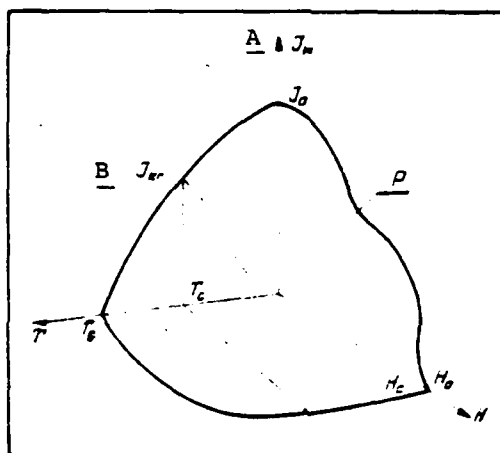


Fig. 1. Critical parameters of superconductor

Key: A. J_{exc} B. J_{cr}

From the graph it follows that in a variable magnetic field, superconductor type II exhibits hysteresis losses (similarly as ferromagnetics), which are increasing with the amplitude of the changes in the field and the frequency.

In the range of intensities from H_{c1} to H_{c2} , superconductors type II are in the so-called mixed state characterized by the existence of normal state regions (domains) in the volume of the superconductor.

Heat losses to eddycurrents occur in these regions during the flow of alternating current and in a variable magnetic field. These properties

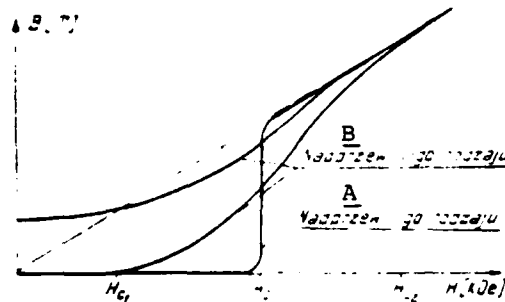


Fig. 2. Graphs of $B = f(H)$ for superconductors types I and II

Key: A. Superconductor type I
B. Superconductor type II

determine the applications of superconductors.

1. Superconductors type I (lead, tin), so-called soft superconductors, are characterized by comparatively low critical values (H_c is on the order of magnitude 1 kOe , $T_0 < 10^\circ\text{K}$).

Hence they are not suitable as a material for windings for strong magnetic fields; however, they are suitable as a material for diamagnetic shields, structural elements of jet pumps, cryotrons, etc., since they exhibit much smaller losses in a variable magnetic field than superconductors type II.

2. Superconductors type II (Nb-Ti, Nb_3Sn , Nb-Zr, and others) have much greater critical parameters: I_0 to 10^5 A/mm^2 , $T \leq 20\text{K}$, H is on the order of magnitude of hundreds of kOe , however, they cannot operate cost-efficiently in equipment in which the frequency of magnetic field changes exceeds 1 Hz .

From the above discussion it follows that one obvious application of superconductivity will be unipolar machines because of the high constancy over time of the magnetic field in the excitation winding region. In

multipolar direct-current machines with a superconductive excitation winding, effects that are difficult to surmount would occur, for example:

- effect of variable field of a commutator coil;
- variable magnetic field caused by magnetic permeance changes in the axis of the poles during movement of the grooved rotor with respect to the stator;

- considerable effect of electromagnetic shields (due to high current density which is close to the effects from surge short-circuit currents) between windings of individual poles;

- difficulties involving appropriate configuration of the field in the transverse axis of the machine for obtaining correct commutation;

Structure of Unipolar Machines with Superconductive Excitation Winding

The unit electromagnetic power (power per unit) of any electric machine, including a unipolar machine, is

$$p_E \sim B \cdot J \cdot n \text{ [W/m}^2\text{]} \quad (2)$$

where:

B is magnetic induction inside the armature

J is armature current density

n is rotational speed.

As a result of the application of a superconductive excitation winding, the resistance losses in the excitation circuit are practically zero.

Therefore, without fears about proper operation, temperature rises in the winding and its insulation, one can increase the current density to the magnitude $J_{exc cr}$, which depends on the material of the superconductor and the geometry of the winding.

Efficient current densities on the order of magnitude 100 A/mm^2 and greater are attained in this way. This fact also implies that the induction B of the

magnetic circuit of the machine can also be increased considerably. In a unipolar machine, induction up to 7 T $\overline{[1]}$ is attained.

In ferromagnetic magnetic circuits with a winding from a normal conductor, the upper induction limit is 2 T because of heat losses in the winding, its limited dimensions, and the ferromagnetic saturation phenomenon.

From Fig. 3 it follows that in the case of a superconductive winding with high excitation density, an increase in magnetic induction by the magnetizing inductance M in the ferromagnetic saturation state is generally not great. Hence it follows that a ferromagnetic is not needed and only a magnetic-air circuit need to be used. This provides great design freedom.

It allows one to use elements compensating the armature reaction flux in the armature; it improves cooling of the machine; and most importantly, it allows one to make the armature from a material which is a good conductor of electricity, for example, Cu and Al).

Consequently, a possibility exists to increase the admissible armature current density, which in view of relation (2) allows one to further increase the unit power.

Despite indisputable advantages (simplicity of design, great rated currents), unipolar direct-current machines are not widely used because of the difficulties involved in draining great currents through slip contacts and low rated voltages.

An increase in the induction alone does not ensure sufficiently high voltages. The rated voltage can also not be increased by building so-called multicoil machines and by the armature configuration shown in Fig. 4.

The electromotive force is summed algebraically in the armature sections, giving between the current collectors A, B a voltage equal to e , regardless of

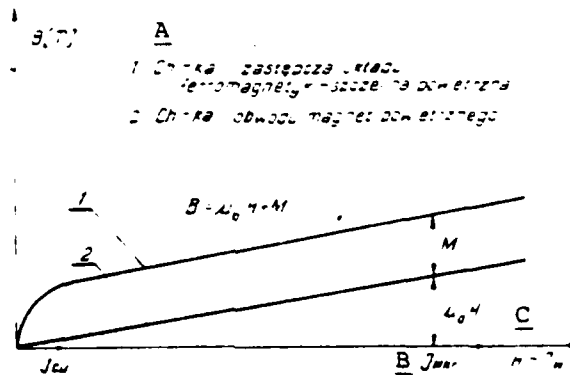


Fig. 3. Graph of characteristics $B = f(J_{exc})$
for ferromagnetic and magnetic-air circuits

Key: A. 1. Equivalent characteristic of ferro-
magnetic-air gap system
2. Characteristic of magnet-air circuit
B. J_{exc} cr
C. J_{exc}

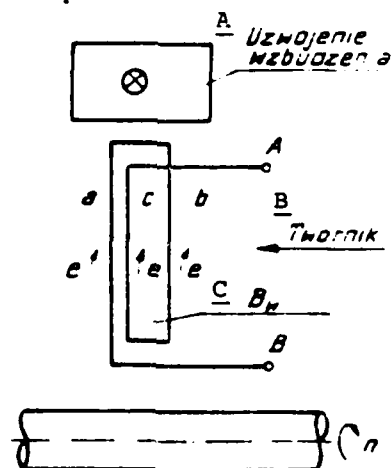


Fig. 4. Unipolar "multiwinding" machine

Key: A. Excitation winding B. Armature
C. B_{exc}

the number of armature elements. Only the concept of inactivating the element b makes it possible for a multiple of the section voltage to appear at the output terminals.

Inactivation of the section b and its connection by means of slip contacts to active sections a and c constitute the basis of a design with a sectional armature.

This method involves subdividing a cast rotor into $2N$ shaped, electrically insulated active sections. These sections are connected in series by means of a static system of N passive sections (Fig. 5). The number of active sections is two times greater; as a result, instantaneous short-circuiting occurs in the intermediate position of the current collector. A 450 V voltage (rated power $P_N = 2420$ kW) is attained in this manner in the motor manufactured by the British IRD Company. However, this connection has a disadvantageous property, namely, that almost the entire machine voltage $\Delta U = (N - 1)e$ is in the intermediate brush contact position between the sections 1-1' (Fig. 5). This effect can be eliminated by subdividing the rotor into two sections connected in series and connecting both groups in parallel. The maximum voltage between sections in this system is equal to the voltage on a single section.

Thanks to the appropriate configuration of passive sections (Fig. 5), the armature current flow is bifilar. The latter brings about:

- nearly complete elimination of the armature reaction flow of that portion of the armature which consists of active sections;

- thanks to this design, the electromagnetic moment of the reaction is not transmitted over the excitation winding (with weakened strength characteristics), but over the static disk, consisting of passive sections, which is fastened to the base.

In a practical design the passive sections have a characteristic shape: within the range of the radius R_2 (Fig. 5) they have a sector in which the current flows in the circumferential direction. The total effect from the

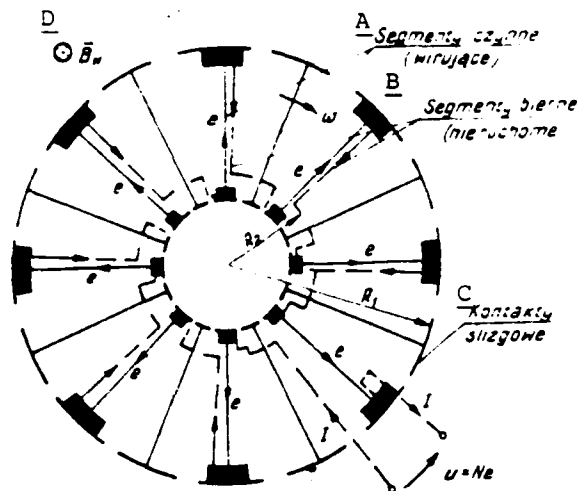


Fig. 5. Schematic diagram of sectional armature

- Key: A. Active sections (revolving)
 B. Passive sections (immovable)
 C. Slip contact
 D. B exc

entire set of passive sections is approximately the same as from a single winding situated on the radius R_2 ; a longitudinal armature reaction flow occurs. To eliminate this effect, a compensating coil was used, which was connected in series with the armature winding (Fig. 6 -- for simplification purposes, only passive sections are indicated).

Special stranding of active sections (Fig. 7) was used to improve commutation. Each armature section is subdivided into two parallel branches stranded with the branches of neighboring sections.

During commutation, a current decrease in section group "1" is accompanied by a current increase in group "2". Thanks to this improvement and the fact that the dissipation flux is confined in a nonferromagnetic medium, the rated currents are considerably smaller than those at which sparking of contacts occurs.

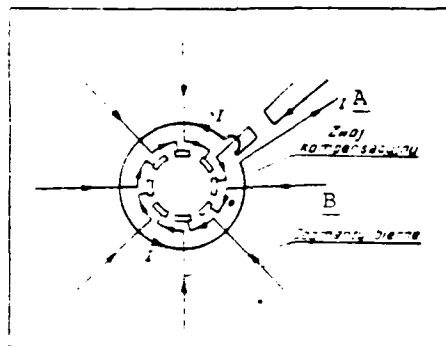


Fig. 6. Schematic diagram of compensating coil connection

Key: A. Compensating coil
B. Passive sections

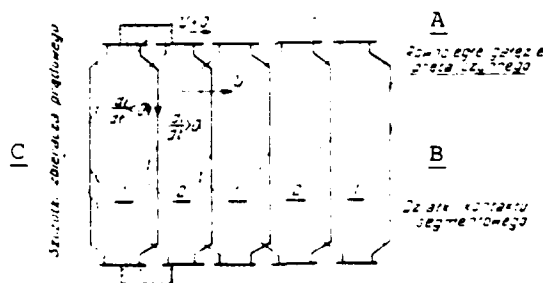


Fig. 7. Schematic diagram of transposition of active armature sections

Key: A. Parallel branches of active section
B. Sectional contact graduation
C. Current collector brushes

The structure of a unipolar machine with a sectional armature excludes the possibility of using liquid metal slip contacts. However, great progress has also been made in the area of designing solid contacts (metal-graphite

contacts with a fibrous structure), and the parameters that were obtained were about two times better than those obtained so far in building direct-current machines.

The limiting powers of unipolar machines with a sectional armature can attain 200 MW [1], compared with the 10 MW power limit for direct-current machines built at the present time.

Another way of increasing the rotor voltage involves building a so-called multidisk machine (Fig. 8) with liquid-metal contacts filling the space between active and passive disks.

Liquid-metal contacts are characterized by high admissible current densities on the order of magnitude 100 A/mm^2 and peripheral speed (to 150 m/s). As a result of this, the unit power of multidisk machines may be very high (according to [8], to 500 MW per 1 m^3 armature volume).

The liquid metal is formed by a thin film in turbulent or laminar motion, bringing about efficient cooling of the armature. At the same time, it is also a source of relatively large magnetohydrodynamic losses. Machines of this type are characterized by high armature current constancy over time and high rated currents.

The shortcoming of the methods described above for increasing the rated armature voltage is the decrease (by more than a factor of 2) of the rated power obtained from the given dimensions of the machine compared with designs without passive elements. This is the result of the existence of passive elements and insulation which do not contribute to generation of the electromagnetic moment.

Excitation Winding in High-Power Unipolar Machines

The electromagnetic power of a unipolar machine can be described by the equation:

$$P_E = c_p D^2 B_{\max} q \cdot n \quad (3)$$

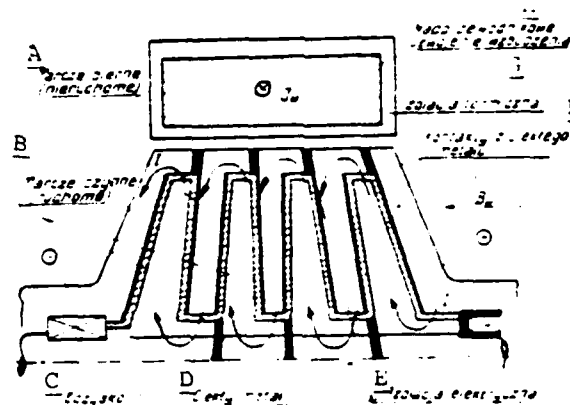


Fig. 8. Axial cross-section of unipolar multidisk machine

- Key: A. Passive (immovable) disks
 B. Active (moving) disks
 C. Bearing
 D. Liquid metal
 E. Electrical insulation
 F. Liquid-metal contact
 G. Thermal insulation
 H. Superconductive excitation winding

where:

- c_p is a coefficient depending on the geometry of the machine
 $B_{\max}$ is the maximum magnetic induction within the armature
 D_1 is the outer armature diameter
 q is the slip contact current density
 n is the rotational speed.

The magnitudes (in Eq. (3)) have an effect on the limiting power of the machine. The diameter D_1 depends on mechanical considerations. The maximum induction $B_{\max}$ is limited by the critical magnetic field magnitudes H_c and the critical current density J_c of the superconductor. The fact that these

parameters are much smaller for a winding than for small superconductor specimens must be taken into account in the design of the machine. For an Nb-Ti alloy this is illustrated in Fig. 9.

An essential component of the type of machines discussed is a superconductive excitation winding. It is designed as a so-called stabilized winding. A stabilized conduit is formed by a series of superconductive fibers fused into a material which is a good conductor of electricity (for example, copper). The stabilizing coating and the superconductor have an electric contact along the entire length of the winding. The energy densities collected in the superconductor are very high (several tens of J per cm^3 , according to $\sqrt[4]{4}$). Fast conversion of magnetic field energy to thermal energy in the event of loss of superconductivity could lead to destruction of the winding.

The stabilizing coating brings about a gradual occurrence of this process, since by way of electric and electromagnetic coupling, a portion of the current passes into the stabilizing base. Thanks to this, the current density in the superconductor can decrease below the critical value for the current (temporarily raised) temperature and thus create a chance of maintaining the superconductive state.

By appropriate selection of the number of superconductive windings, the degree of stabilization (ratio of the copper and superconductor volumes), capacitance and conductivity of thermal winding materials, and operating temperature, one can obtain a voltage drop on the winding as a function of the excitation current as shown in Fig. 10.

Such a graph of the winding characteristic can be used in systems protecting the winding from loss of superconductivity.

The properties of the excitation winding impose special systems for supply of the latter. In the case of a unipolar generator, a self-exciting characteristic cannot be obtained in a shunting system, since both the electric as well as the magnetic circuit are linear. Similarly as in modern drive systems with direct-current machines, thyristor switches, are most suitable for supplying the armature circuit in motors.

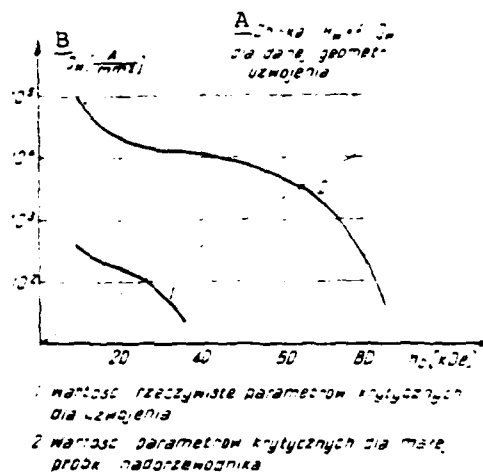


Fig. 9. Graphs of $J_{exc} = f(H)$ for winding and small superconductor specimen

Key: A. Characteristic $H_{exc} = f(J_{exc})$ for the given geometry of the winding

1. Actual critical parameter values for winding
2. Critical parameter values for small superconductor specimen

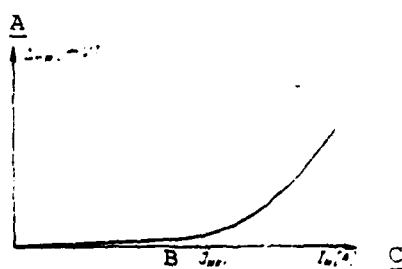


Fig. 10. Graph of characteristic $U_{exc} = f(I_{exc})$ of superconductive excitation winding

Systems supplying the excitation winding must meet a number of requirements that are typical for superconductive windings: they must provide the possibility of controlling the excitation current and protection from the effects of loss of superconductivity. Basically, such systems are subdivided into two groups:

- Systems in which the current source is a direct-current machine or an inverter system. In these systems the problem of protection is solved relatively easily: in a malfunctioning operating state the energy stored in the winding can be discharged in the system suppressing the field.

- Superconductive supply systems represent a futuristic design (superconductive rectifiers and especially, topological generators--jet pumps). The source and receiver may be situated in a common cryostat constituting an entirely superconductive circuit (which avoids the use of troublesome cryo-bushings in the system).

However, the problem of protecting the winding is difficult. In the event of loss of superconductivity, the only possibility seems to be to discharge the energy by way of coupling the superconductive winding with an auxiliary winding situated outside the cryostat, whose circuit contains a discharge resistance.

The decisive matter in the structure of the excitation winding is that it must be designed in such a way that the heat flux penetrating the cryostat is as small as possible.

If the inequality

$$\Delta P_k \frac{1}{\eta_{\text{refr}}} \leq \Delta P_{\text{exc}} \quad \text{holds} \quad (4)$$

where:

ΔP_k is the total thermal power drained from the cryostat by the refrigerating cycle

η_{refr} is the total efficiency of the refrigerating cycle

ΔP_{exc} are the power losses in the excitation winding of a machine whose structure is normal

roughly speaking, for the same rated power the superconductive machine will be more efficient.

The above requirement is satisfied for high-power machines (in the megawatt range). Whether this requirement is satisfied also depends to a considerable degree on the range of rotational speeds. The source of power losses ΔP_k are thermal losses which occur in the semiconductor and the stabilizing coating; the heat flowing from the surrounding environment is due to the imperfections of the thermal insulation of the winding and current leads.

Hence, building the excitation winding requires the solution of a number of complicated problems, for example:

1. building closed refrigerating cycles with the highest possible efficiency;
2. designing a winding insulation which will ensure the smallest heat input to the cryostat from the surrounding environment (use of cooling with many temperature levels, superinsulation);
3. suitable configurations of thermodynamic winding parameters, taking into account the low thermal capacity of helium and the properties of thermal stabilizing coatings at low temperatures (small thermal capacity, great thermal conductivity);
4. solution of the problem of great mechanical stresses in the winding (a copper coating operates at the plastic strain limit).

Conclusions

Wide-scale application of unipolar machines is envisioned, especially in the high-power range.

Here the following are taken into consideration:

1. large metallurgical drives;
2. hoisting machines and other reversible drives;
3. these types of generators may become irreplaceable in the chemical industry (chlorine and aluminum production), since according to preliminary calculations they are much cheaper than the transformer-rectifier systems used until now.
4. large generators are perfectly suitable as supply sources of magnets in strong magnetic field laboratories.

Mainly cost considerations will decide the wide-scale use of these machines, which appear to be advantageous for high-power machines (compared with classical designs).

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