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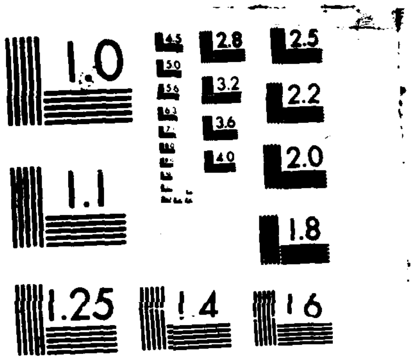

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STATIC MULTIPLE-POLE HOMOPOLAR GENERATOR WITH A SUPERCONDUCTING SCREEN

by

V.P. Kartsev, and I.M. Yegorov

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EDITED TRANSLATION

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О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

GRAPHICS DISCLAIMER

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V. P. Kartsev, and I. M. Yegorov

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INTRODUCTION

Large superconducting systems can be used in magnetic plasma traps, installations for magnetic separation of isotopes, charged particle accelerators, magnetohydrodynamic exciters and conventional generators, etc. A tendency noted in the development of such systems is the use of ever higher currents, flowing over a superconducting winding. The generation of these currents outside of a cryostat and their subsequent transfer to a Dewar flask with liquid helim, where the superconducting devices are contained, is a serious problem [1]. In this connection serious attention is merited by devices which make it possible to generate strong currents immediately in the area with the liquid helium.

Among the devices which can be used for excitation of a strong direct current in superconducting short-circuited circuits, a special place is occupied by the static homopolar generator-converter with a superconducting screen [2, 3]. It differs favorably from the Volger-Admiral generator [4] by the absence of any mechanical changes of position during operation, and from the numerous transformer circuits - by the absence of commutating elements and electronic coordination circuits.

This generator combines in one machine both a synchro drive and a homopolar generator of special construction. As a result of the combining of two machines in one it was found out that for the operation of such a motor-generator installation there is no necessity to drive it into rotation, since this rotation can be replaced by the equivalent rotation of the magnetic field along the periphery of the stator.

Static homopolar generators with a superconducting screen can be used for excitation of a self-sustained current of any magnitude in superconducting closed circuits for the creation of a "magnetic vacuum" in any area of space. It should be noted that regulation of the field and the current with the help of a superconducting homopolar generator can be done in the case of a calculation suitable for it with an extremely high degree of accuracy.

OPERATING PRINCIPLE OF THE GENERATOR

It is convenient to begin the analysis of the operating principle with Figure 1. In the drawing the superconducting tape is depicted in the form of the letter U, connected to a superconducting solenoid. The superconductors, of which the solenoid and tape are made, are different and are selected in such a manner that the tape leaves the condition of superconductivity under the influence of a much weaker field than the solenoid. Let us assume that the tape leaves the state of superconductivity in the case of a field of 500 Oe, and the solenoid and its leads - with 50,000 Oe.

If now we take a small bar magnet, creating near the pole a field, let us say, of 1000 Oe, and we pass it from right to left over the surface of the tape, as shown in the drawing, then in those points of the tape which at the given moment are found under the magnet the superconductivity is disrupted and the film loses its diamagnetic properties, thus becoming a "hole" for the magnetic force lines (designated in the drawing by the black spot).

Moving the magnet from right to left, we finally reach the point when the flux of the magnet turns out to be coupled with the superconducting circuit G (Fig. 1,a,b). Remarkable in this entire operation is that following introduction of the flux into circuit G in the latter no current flows, which would be the reaction to the

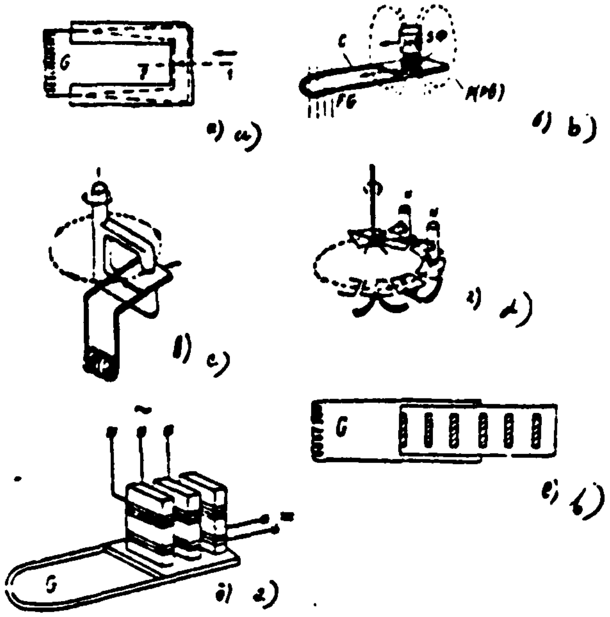

Figure 1. Operating principle of the generator.

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change of the flux linkage of circuit G.

For proof of this position turn again to Figure 1a. In the case of the position of the magnet in point 1 the G circuit has a flux linkage equal to zero. When the magnet intersects the right broken contour current does not develop in the solenoid, since the inner broken contour is preserved, thus observing equality to zero of the flux linkage of circuit G, closed by the inner broken line.

When the magnet intersects the inner broken line current still cannot develop in the solenoid, since in circuit G, closed now by the right broken line, a constancy of flux linkage Φ should be observed. All the reactive currents, emerging following the introduction of the magnet through the band into circuit G, were closed on the contours, similar to the broken contour in the band, and did not infringe on the main circuit G, which turned out to be connected with flux linkage Φ without development of a reactive current in it. However, with withdrawal of the magnet from contour G not through the band, but on any other route, a reactive current develops in contour G, since in this case the flux linkage of the contour is reduced from the magnitude Φ to zero. The cycle can be repeated an infinite number of times, and the current of the solenoid will increase by portions until the strength of the field of the solenoid reaches a critical magnitude. This circumstance makes it possible to use such a type of device for power supply of superconducting circuits, in which current of such a magnitude should flow that the transfer of it to a superconducting circuit from devices operating at a temperature of the surrounding air causes considerable difficulties.

The first effective generator operating on this principle was proposed by Volger and Admiraal [4]. One of the modifications of such a generator, proposed by Betterton [5], is depicted in Fig. 1c. In the model there is a magnet, executing rotational movement over a film in one direction. Figure 1d depicts an analogous system used by Wipf [6]. In it several magnets are used simultaneously. Such a system makes it possible to increase the rate of build-up of current in the solenoid.

However, in order to shift the magnetic field along the band there is no need to use a mechanically moving magnet. For shifting of the "hole" in one direction it is possible to use a three-phase system of a traveling magnetic field (Fig. 1e). However, such a field always creates two "holes," made in the superconducting film by magnetic fields of a different sign. It is evident that, abandoning both holes, we obtain an alternating current in circuit G. In order to eliminate "holes" of an unnecessary direction, on the traveling field it is necessary to apply a constant field, coinciding in direction with the traveling field, creating the "necessary holes." In this case, without any mechanical shiftings in the medium with liquid helium the current in circuit G begins to increase.

When a three-phase voltage of industrial frequency is used the described static model possesses the shortcoming that the hole moves too rapidly. In the case of rapid movement of a nonsuperconducting "hole" in it thermal losses caused by Foucault currents develop. The result of this is that the band does not "manage" to switch from a normal state into superconducting, and the efficiency of the generator is reduced sharply.

In order that this doesn't happen it is advisable to use multi-

-pole generators with a traveling field, as, for example, the twelve-pole [generator] (this corresponds to six "holes" or "normal zones") investigated by the authors. As is known, the linear rate of movement of the poles of a traveling field are inversely proportional to the number of poles. Therefore, in a twelve-pole model the rate of movement of the field was six times less than it would be in an analogous two-pole model, and during its testing no serious effects of "erosion" of the normal zone due to eddy currents were noted.

EXPERIMENTAL MODEL OF A TWELVE-POLE GENERATOR

The source of the multiple-pole traveling field was the winding of the stator of a synchro micromachine with a number of poles 2p=12. For increasing magnetic conductivity a fixed "rotor" 3 was inserted in the stator (see Figure 2).

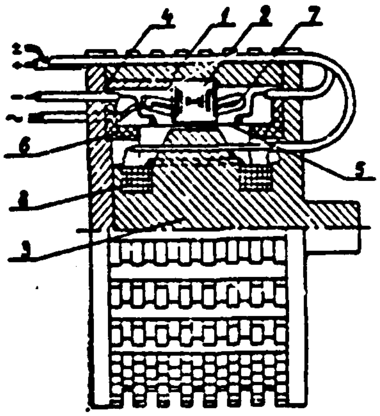

Figure 2. Longitudinal and transverse section of a static homopolar converter with a superconducting diamagnetic screen. 1. Generator housing. 2. Stator core. 3. "Rotor" with end shield. 4. End shield. 5. Superconducting screen. 6. Insulation sleeve. 7. Stator winding. 8. Homopolar winding.

In the gap between the stator and the "rotor" there is a superconducting band (Fig. 1f), twisted into cylinder 5. The stator winding is made from a copper conductor, and the stator from transformer steel with low losses, sheet thickness 0.2 mm. Core 2 is secured in the housing and retained by end shield 4. The fixed "rotor" 3 is made from steel with low specific losses on alternating current. On the "rotor," just as on the frame, two superconducting coils 8 are wound. They are made from 65BT wire and create a homopolar field.

Superconducting cylinder 5 is a layer of lead 5 μm thick, applied by the electrolytic method on a nickel backing 100 μm thick. The cylinder is secured on insulation sleeve 6. Terminals made from superconducting wire from 65BT alloy 0.25 mm in diameter are spot welded to the edges of the cylinder. The cylindrical screen and the terminals were coated with a layer of bakelite varnish to prevent oxidation of the lead.

Contact between the terminal ends and the terminals of the load solenoid was realized with the help of clamping of both ends in a niobium-tin tube with a niobium wedge-shaped rod.

METHOD OF ELECTROMAGNETIC CALCULATION

Figures 3, 4, 5 show the distribution of intensity of the rotating magnetic field in the air gap along the double pole pitch of the periphery of the generator stator. If on this sinusoidal field a field of magnetization H_{yH} of constant direction (homopolar field) is applied, then the sinusoid of intensity of the resulting field is shifted along the axis or ordinates.

In Figures 3, 4, 5 the thin lines depict the magnitude of the critical strength of the field $\pm H_{\kappa p}$ of the material of the superconducting film of the cylinder, situated in the gap between the stator and the "rotor." If the intensity of the resulting field in certain areas of the screen turns out to be higher than the critical intensity of the field of the material of the superconductor, then in these areas the screen loses its superconducting properties (it acquires a finite electrical resistance and becomes permeable for magnetic flux). In Figures 3, 4, 5 these areas are limited by the coordinates (x_1-x_2) and (x_3-x_4). In the remaining areas the screen remains superconducting, i.e., it possesses zero resistance, and since it is made out of a superconductor of the 1st order - lead, then on the force of the Meissner effect it is absolutely diamagnetic, i.e., impermeable for magnetic flux. Thus the magnetic flux can pass through the screen only in "normal" or "active" zones (x_1-x_2) and (x_3-x_4), as this is shown in Figures 3, 4, 5. Since the "normal" or "active" zones were formed under the joint influence on the screen of the traveling (i.e., moving in space) and magnetizing field, the "normal" (active) zones are also shifted on the periphery of the cylinder at the rate of the traveling field.

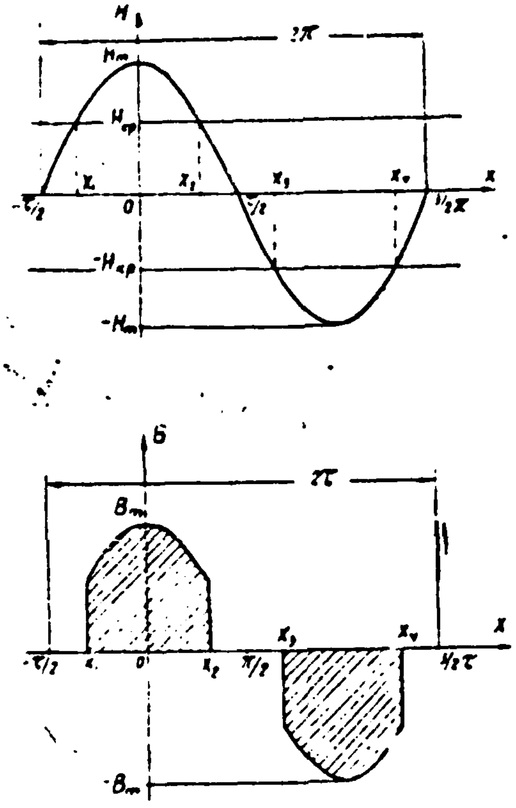

Figure 3.

It is clear from Figure 4 that the increase in the intensity of the homopolar field leads to an increase in the width of one active zone (x_1-x_2) and a reduction of the dimensions of the other active zone (x_3-x_4). As a result of this the resulting magnetic flux on the double pole pitch turns out to be equal not to zero, as in ordinary electrical machines, but to a certain magnitude $\Delta\Phi$. Under the other pairs of poles there is an analogous picture.

The intensity of the resulting magnetic field in point x for a specific moment of time is expressed in the following manner:

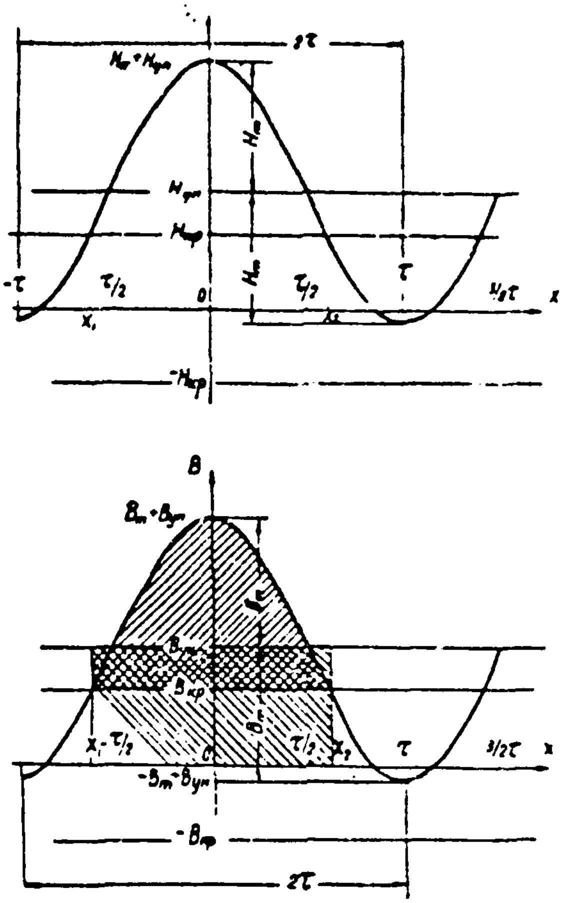

Figure 4.

$$H_x = H_m \cos\left(\frac{\pi}{\tau}\cdot x\right) + H_{ym} \qquad (1)$$

where τ - pole pitch;

H_{yk} - intensity of permanent field of magnetization;

H_m - amplitude value of intensity of traveling field.

Let us isolate in the active zone the elementary site ds=ldx (l - length of stator), for which intensity can be considered constant. Then the elementary flux through this site can be expressed as

$$d\Phi = \mu H_x \cdot l \cdot dx.$$

For determination of the total magnetic flux, passing from the

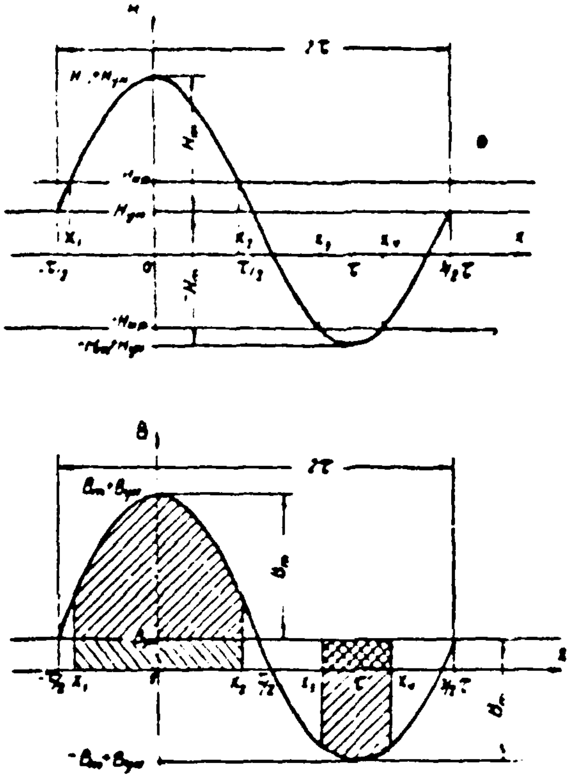

Figure 5.

stator into the "rotor" through the active zones on the double pole pitch, we integrate the value $d\Phi$ within the limits (x_1-x_2) and (x_3-x_4)

$$\Delta\Phi = \mu_0 l \left[\int_{x_1}^{x_2} \left(H_m \cdot \cos \frac{\pi}{\tau} \cdot x + H_{ym} \, dx + \int_{x_3}^{x_4} \left(H_m \cos \frac{\pi}{\tau} \cdot x + H_{ym} \right) dx \right] . \qquad (2)$$

The total magnetic flux, passing from the stator into the "rotor" on the total length of the periphery of the screen, will correspondingly be equal to

$$\Sigma\Delta\Phi = p\Delta\Phi .$$

where p - number of pairs of poles of the generator.

From evident physical considerations it is clear that $\Sigma\Delta\Phi$ is that elementary flux, which after each cycle of feeding three-phase voltage gives the corresponding increase of magnetic flux and energy of the circuit G. In our case circuit G consists of superconducting sectors of the screen with the superconducting terminals and the load superconducting solenoid.

Coordinates x_1, x_2, x_3 and x_4 can be found from the following evident correlations:

$$H_m \cos\frac{\pi}{\tau} x_{1,2} + H_{\text{ун}} = H_{\text{кр}}$$

and

$$H_m \cos\frac{\pi}{\tau} x_{3,4} + H_{\text{ун}} = -H_{\text{кр}},$$

from which

$$x_{1,2} = \arccos\frac{H_{\text{кр}} - H_{\text{ун}}}{H_m}$$

and

$$x_{3,4} = \arccos\frac{-H_{\text{кр}} - H_{\text{ун}}}{H_m}. \qquad (3)$$

It follows from formulas (2 and 3) that for a generator with a known geometry and selected material of the superconductor the coordinates $x_{1,2}$ and $x_{3,4}$, and consequently $\Delta\Phi$, are determined easily.

For finding the rate of change of the field or the emf it is sufficient to calculate the intensity of the traveling and homopolar fields. The solution of these problems is known, however, introduction of the diamagnetic into the gap of the generator causes a certain complication of the calculation of magnetic conductivities and reactances.

Electromagnetic calculation of the investigated generator can be made in the following phases.

1. Based on the critical intensity of the magnetic field $H_{\text{кр}}$ the variables H_m and $H_{\text{ун}}$ are selected. The selection of these variables is made stemming from the following considerations:

a) For preventing the screen from leaving the state of superconductivity in the case of disruption of power supply of the three-phase winding, $H_{\text{ун}}$ should be less than $H_{\text{кр}}$ ($H_{\text{ун}} < H_{\text{кр}}$). In the opposite case when $H_{\text{ун}} > H_{\text{кр}}$ and in the case of absence of power supply of the three-phase winding, the resulting magnetic field on the entire length of the periphery of the screen turns out to be equal to H_{yH}, which entails the exit of the entire screen form superconductivity.

The superconducting contour of the screen-solenoid turns out to be disrupted. Such a phenomenon induces the conversion of the energy of the magnetic field, which is accumulated in the solenoid, into thermal energy, which leads to excessive heating or melting of the screen. The greater the inductance of the solenoid and the greater the energy accumulated in it, then the more dangerous is such a phenomenon. Thus from considerations of reliability of the device we select $H_{yH} < H_{Kp}$.

For the investigated model H_{Kp}=550 Oe, and H_{yH} is accepted equal to 500 Oe.

b) In the optimal construction it is necessary to realize the greatest rate of increase of the field in the solenoid $\left(\frac{\Delta\Phi}{\Delta t}\right)$. Since $\Delta\Phi$ increases with an increase in the width of one zone and a decrease of the other, then with the total disappearance of one of the zones $\Delta\Phi$ with the selected H_{yH} will evidently be greatest. For this the maximum of the negative half-wave of intensity of the resulting magnetic field should not exceed H_{Kp}. This will take place in the case of $-H_m+H_{yH} \geqslant -H_{Kp}$, from which $H_m \leqslant H_{Kp}+H_{yH}$. Based on what was said, in the calculation it was accepted that H_m=1000 Oe.

c) If there is no fear of emergence of the shield from the state of superconductivity in the case of disruption of power supply of the three-phase winding, then it becomes possible to increase H_{yH} up to values close to H_{Kp}. In this case the greatest rate of increase of the field will be achieved with a width of the active zone close to 2τ. Considering the possibility of fluctuation of the magnitude of intensity of the resulting magnetic field, it is advisable to select the width of the active zone 5-10% less than 2τ*.

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* In those cases when in the solenoid a considerable current should be circulating, it follows to watch that the density of the current in the superconducting "bridges" of the screen does not exceed critical (determined for lead, being a superconductor of the 1st order, by the Silsbee rule).

2. The following phase of electromagnetic calculation is the determination of the magnetizing current.

For this in respect to the selected variables H_{π} and H_{yH} the coordinates $x_{1,2}$ and $x_{3,4}$ are calculated using formulas (3). This makes it possible to determine the magnitude of magnetic flux of the field of the stator, penetrating into the "rotor."

$$\Phi_1 = \mu_0 l \left[\int_{x_1}^{x_2} H_m \cos \frac{\pi}{\tau} x \cdot dx - \int_{x_3}^{x_4} H_m \cos \frac{\pi}{\tau} x \cdot dx \right].$$

For the specific case being considered the variable $\Phi_1 = 5.06 \quad {}^{\cdot 6}$ Wb.

Knowing the magnitude of the flux and the paths for closing it, it is possible to calculate the average magnitude of induction on different sections of the magnetic circuit. In connection with the insignificant magnitude of critical intensity of the field of semiconductors of the 1st order, the induction in the gap between the stator and the "rotor", numerically equal to the intensity of the field in the gap, cannot reach values which are found in conventional electrical machines. Consequently, the magnetic circuit of a static generator with a superconducting screen cannot be saturated on even one sector, which is of decisive importance from the point of view of isolation of thermal energy in a magnetic circuit which is found in a medium of liquid helium. In the narrowest sector of the magnetic circuit (teeth of the stator) the calculated induction in the test model $B_z \approx 2500$ G.

On the magnetization curves it is possible to determine the intensity of the field for each sector of the circuit, and from expression $\Sigma H \cdot l = I_{\mu} \cdot w$, to obtain the magnitude of the magnetizing current I_{μ}.

When there is only one active zone on the double pole pitch it follows to take into account the ampere-turns, corresponding to only one pole, since the magnetizing force (n.s.) of the second pole does not take part in the conducting of magnetic flux. In the calculation for this case the magnitude $I_{\mu} = 0.8$ A is obtained.

3. The following phase of the calculation is determination of the magnetizing current of the homopolar circuit I_{yH}. The magnitude

of the homopolar magnetic flux is determined from the expression

$$\Phi_{y\text{н}} = \mu_0 l \left[\int_{x_1}^{x_1} H_{y\text{н}} \cdot dx + \int_{x_1}^{x_2} H_{y\text{н}} \cdot dx \right].$$

In this case the calculation is made with a certain approximation due to the disregard of the influence of flux Φ_1 on the magnetic resistance of the circuit. However, in view of the operation of the device in a mode far from saturation such a simplification has virtually no influence on the results of the calculations. Subsequent calculation of I_{yH} is done by the method indicated earlier. For the case under consideration $I_{yH}=1.13$ A.

4. On the basis of the data obtained it is possible to determine the rate of growth of the field $\frac{\Delta\Phi_\rho}{\Delta t}$, where $\Delta\Phi_\rho$ - total magnitude of flux of all the poles, closed on the path of the homopolar flux. $\Delta\Phi$ for the pair of poles is determined using expression (2).

In the calculation of the test model a magnitude of $\Delta\Phi_\rho=53.5\cdot10^{-6}$ W was obtained. Since $\Delta\Phi_\rho$ causes correspondingly an increase of energy in the magnetic field of the solenoid, then the rate of growth of the field can be obtained by dividing the resulting value of $\Delta\Phi_\rho$ by the time of one period of three-phase voltage. Knowing the inductance and constant of the solenoid $\left(\frac{H}{I}\right)$, it is possible from the variable $\frac{\Delta\Phi_\rho}{\Delta t}$ to convert to the variable $\frac{\Delta H}{\Delta t}$. For the investigated model L=0.3 H, $\frac{H}{I}$ 1.2 kOe/A and $\frac{\Delta H}{\Delta t}=1.78$ Oe/s. From the test with operation in the calculated mode the variable $\frac{\Delta H}{\Delta t}=1.45$ Oe/s was obtained.

REACTANCES OF SCATTERING IN A GENERATOR WITH A SUPERCONDUCTING SCREEN

The calculation of reactive resistances of fluxes of scattering is complicated by the presence of the diamagnetic screen and requires certain simplifications. In view of the fact that groove scattering is determined by the conductivity of the air gap of the groove, in the case of an unsaturated magnetic circuit it is possible to consider reactive resistance x_n, corresponding to this form of scattering, independent of the presence of the diamagnetic screen. Such reasonings are also applicable to frontal scattering, the reactive resistance of which we designate x_{Λ}. The reactances of groove and frontal scattering can thas be determined using known formulas for ordinary electrical machines.

Calculation of these reactances for the investigated model gives the magnitudes x_n=0.2 ohms, x_{Λ}=0.083 ohms. In the calculation of auxiliary (differential) scattering x_{δ} one cannot disregard the influence of the diamagnetic screen on the conductivity of the "air" gap. In the first approximation it is possible to assume a proportionality between conductivity of the "air" gap and dimensions of the active zones $\lambda_{\delta} \equiv l\tau'$, where l - length of the active zone along the directrix of the cylinder, τ' - width of the active zone. With this assumption it is possible to determine differential scattering in this case using the method of calculation for rotating electrical machines, and then to multiply the resistances obtained by $\frac{\tau'}{2\tau}$, i.e., by the width τ' of the active zone, expressed in fractions of the double pole pitch. Following calculation with this method the magnitude of x_{δ} turned out to be equal to 0.024 ohms.

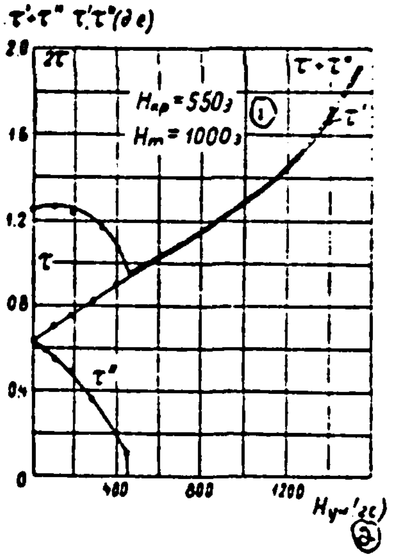

Figure 6.
Key: (1) Oe; (2) G.

The dependence of x_δ on τ' results in the fact that the magnitude of total reactive resistance $x=x_n+x_\lambda+x_\delta$ is a certain function of τ'. The width of the active zone in turn depends on the values of three-phase I_m and homopolar I_{yH} currents. In analyzing the expressions for $x_{1,2}$ and $x_{3,4}$ (3) it is possible to come to the conclusion that a change of τ' with a change of one of the currents will be determined by inverse trigonometric functions. Figure 6 illustrates the nature of change of τ', and consequently, x_δ depending on the magnitude of homopolar current I_{yH}. Measurements made in the process of the experiment showed that the nature of the calculated dependence is close to the actual picture.

CONCLUSIONS

The proposed method of calculation of static multiple-pole homopolar generators with a superconducting screen ~~(Figure~~ 7), being a modification of the calculation of synchro and homopolar electrical machines for the conditions considered, ensures a coincidence of experimental and calculated data which is satisfactory for the assumptions accepted. ([illegible] Ta[illegible])

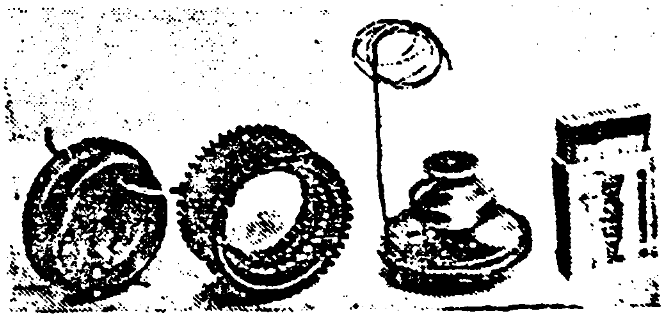

Figure 7.

In conclusion the authors consider it their duty to thank G. N. Petrov, corresponding member AS USSR, and also V. S. Sychev, V. B. Zenkevich and Yu. G. Kovalevskiy for comprehensive help.

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