

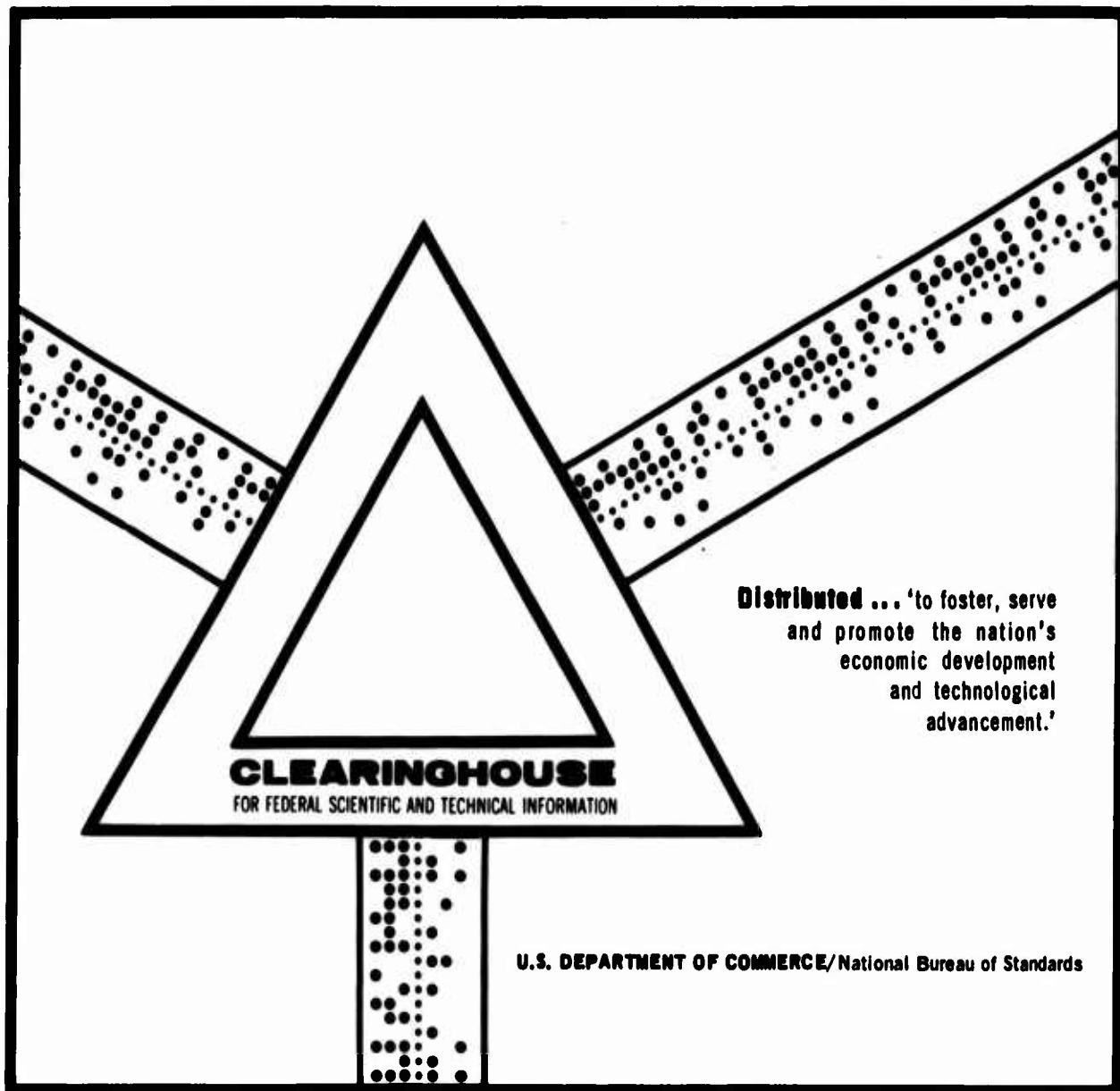
AD 700 799

**THE MAGNETIC FIELD IN SUPERCONDUCTING
SHIELDED SYNCHRONOUS MACHINES**

A. I. Bertinov, et al

Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

25 November 1969



This document has been approved for public release and sale.

662002DV

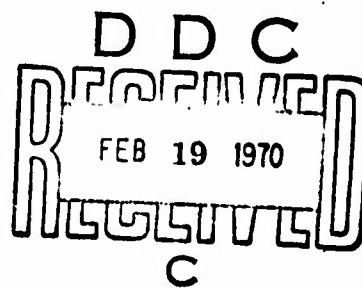
FOREIGN TECHNOLOGY DIVISION



THE MAGNETIC FIELD IN SUPERCONDUCTING SHIELDED SYNCHRONOUS MACHINES

by

A. I. Bertinov, A. V. Golovkin, et al.



Distribution of this document is unlimited. It may be released to the Clearinghouse, Department of Commerce, for sale to the general public.

Reproduced by the
CLEARINGHOUSE
for Federal Scientific & Technical
Information Springfield Va. 22151

EDITED TRANSLATION

THE MAGNETIC FIELD IN SUPERCONDUCTING SHIELDED SYNCHRONOUS MACHINES

By: A. I. Bertinov, A. V. Golovkin, et al.

English pages: 10

Source: AN SSSR. Izvestiya. Energetika i
Transport (Academy of Sciences of
the USSR. News. Power Engineering
and Transportation). No. 2, 1969,
pp. 96-101.

Translated by: W. Pearson/TDBRS-3

THIS TRANSLATION IS A RENDITION OF THE ORIGINAL FOREIGN TEXT WITHOUT ANY ANALYTICAL OR EDITORIAL COMMENT. STATEMENTS OR THEORIES ADVOCATED OR IMPLIED ARE THOSE OF THE SOURCE AND DO NOT NECESSARILY REFLECT THE POSITION OR OPINION OF THE FOREIGN TECHNOLOGY DIVISION.

PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

THE MAGNETIC FIELD IN SUPERCONDUCTING SHIELDED SYNCHRONOUS MACHINES

A. I. Bertinov, A. V. Golovkin, G. A. Zhemchugov,
and O. M. Mironov
(Moscow)

The magnetic field of the superconducting winding of a shielded synchronous machine is investigated, expressions for components of magnetic field strength are obtained, and the shape factor of the field of a synchronous machine with ferromagnetic and superconducting shields is determined.

Graphic dependences are given for the distribution of the components of magnetic field strength along the radius for various numbers of pairs of poles, and the relationship of geometrical dimensions of a superconducting winding and shield is shown.

In work [1] a superconducting synchronous machine without ferromagnetic parts was discussed. In such a construction of a superconducting synchronous machine the external magnetic fields reach great values, which can have a negative influence on the working of certain electrotechnical equipment situated near the machine. In connection with this the problem arises of shielding the magnetic field of the working area of a superconducting synchronous machine from the space around it with the aid of a ferromagnetic or superconducting shield.

This article presents results of the investigation of the magnetic field of a superconducting field winding of a machine with

ferromagnetic and superconducted shields; the equations obtained are also valid for nonsuperconducting machines of similar construction.

Let us examine a magnetic system with a fixed superconducting field winding located inside the shield (Fig. 1) in a cylindrical coordinate system. We make the following assumptions:

the magnetic field is plane-parallel;

the magnetic permeability of the field winding material is constant and equal to μ_0 . When the field winding is powered by a source with an automatic current-control system the superconducting material works with fields close to critical and, besides, when the winding is made of a superconductor stabilized with a normal metal the space factor is equal to, approximately, 0.1:

magnetic permeability of the shield is constant and equal to μ_0

Let us write the following relationships for the vector potential and field strength:

$$\begin{aligned} A &= \frac{\mu_0}{4\pi} \int \frac{j dv}{a}; \\ H &= \frac{1}{\mu_0} \text{rot} A. \end{aligned} \quad (1)$$

The method of electromagnetic images is used for solving the problem. The strength of the magnetic field at any point of space included within the shield is determined by the real current of the superconducting field winding and by the fictitious current at distance of $r' = r_0^2/r$ beyond the edge of the shield [2]. The magnitude of the fictitious current is related to the real current by the coefficient

$$k_p = \frac{1 - \mu_0}{1 + \mu_0},$$

where

$$\mu_0 = \frac{\mu_0}{\mu_0}.$$

The components of the magnetic field strength are written in the following form:

$$\begin{aligned} H_{\phi} &= H_{\phi} + H_{\phi}'; \\ H_{\theta} &= H_{\theta} + H_{\theta}'. \end{aligned} \quad (2)$$

The values of the radial and tangential components of the magnetic field strength, H_ρ and H_φ , caused by the real current, are found from familiar formulas [1]. The values of H_ρ' and H_φ' are defined in terms of the vector potential of the magnetic field:

$$\begin{aligned} H_\rho' &= \frac{1}{\mu_0 \rho} \frac{\partial A'}{\partial \varphi}; \\ H_\varphi' &= -\frac{1}{\mu_0} \frac{\partial A'}{\partial \rho}. \end{aligned} \quad (3)$$

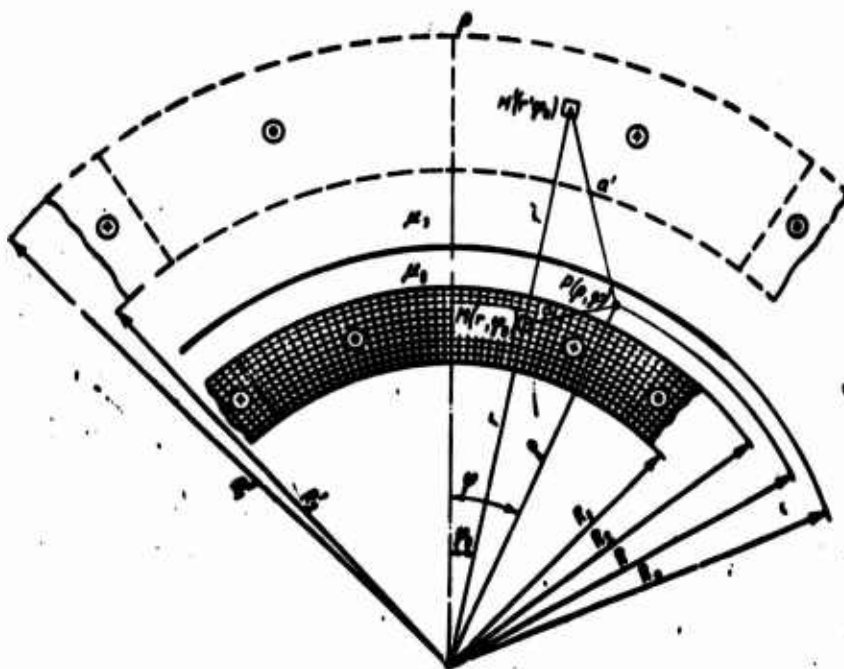


Fig. 1. Field winding of a shielded superconducting synchronous machine.

The axial component of the vector potential function at point P (ρ , φ) is equal to:

$$A' = \frac{\mu_0}{2\pi} \int_S j' r' dr' d\varphi_0 \ln a'. \quad (4)$$

where S' is the area occupied by conductors with a fictitious current;

$$\begin{aligned} j' &= j_{cp} k_p \left(\frac{r_0}{r'} \right)^k; \\ a' &= \sqrt{\rho^2 + r'^2 - 2\rho r' \cos(\varphi - \varphi_0)}; \end{aligned}$$

j and j_{cp} are respectively the fictitious and the real current density. Let us write the vector potential in the form of a Fourier series:

$$A' = \frac{j_0}{2\pi} \int_0^{2\pi} j' r' dr' d\varphi_0 \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{\rho}{r'}\right)^{np} \cos np(\varphi - \varphi_0). \quad (5)$$

After integration over every section occupied by conductors with fictitious current, substitution in equations (3), and introduction (for convenience of further calculations and the construction of graphic dependences) of the relative dimensions

$$\dot{R}_1 = R_1/R_2, \dot{R} = R/R_2^{np}, \dot{R}_0 = R_0/R_2,$$

we get

$$H_\rho' = j_0 \frac{R_2}{4\pi} K_\rho' \cos np\varphi;$$

$$H_\varphi' = -j_0 \frac{R_2}{4\pi} K_\varphi' \sin np\varphi,$$

where

$$K_\rho' = K_\varphi' = k_p \sum_{n=1}^{\infty} \frac{8}{n(np+2)} \frac{1 - \dot{R}_1^{np+2}}{\dot{R}_0^{2np}} \dot{R}^{np-1}. \quad (6)$$

For a ferromagnetic shield we assume $\mu_2 = \infty$ and $k_\mu = 1$. Then with one member of the series ($n = 1$) expression (6) will have the form:

$$K_{\rho 1}' = \frac{8\dot{R}^{p-1}\dot{R}_0^{2p}}{2+p} (1 - \dot{R}_1^{p+1}). \quad (7)$$

The dependences of $K_{\rho 1}'$ on R and R_1 for p equal to 1, 2, 3 and 4 are illustrated in Figs. 2-5. From the graphs in these figures it follows that the components of the magnetic field strength that are proportional to the coefficient K_ρ' have their greatest value on the inner surface of the ferromagnetic shield and are equal, in absolute magnitude, to the values of the strength at these points in the absence of a ferromagnetic shield. The total radial strength component in this case doubles, while the total tangential component becomes zero.

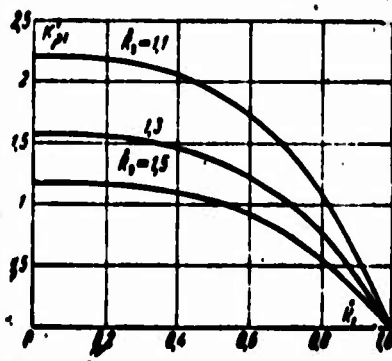


Fig. 2. Dependence of K_{p1}' on $j(R_1)$ for $p = 1$.

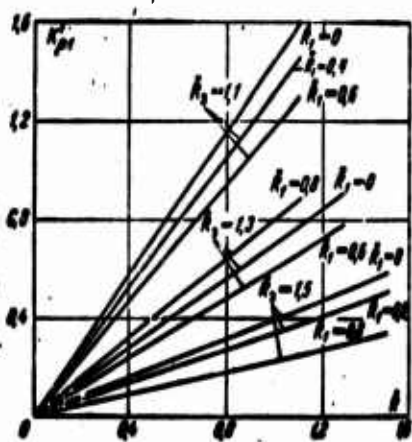


Fig. 3. Dependence $K_{p1}' = f(\bar{R})$ for $p = 2$.

Distribution of the total radial magnetic field strength component along the radius is shown in Fig. 6.

Thus, an almost two-fold increase in strength in the region occupied by the armature coil leads to the growth of the emf induced in it. For machines with a superconductive shield $k_\mu = -1$. The strength component H_ρ' in relation to H_ρ has a negative sign, with the result that the total radial strength component is less than H_ρ , and on the inner surface of the shield it acquires a value of zero (Fig. 7).

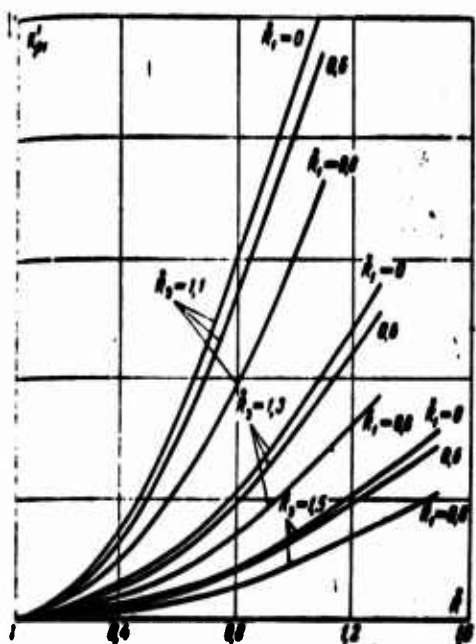


Fig. 4. Dependence $K_{\rho 1}' = f(\tilde{R})$ for $p = 3$.

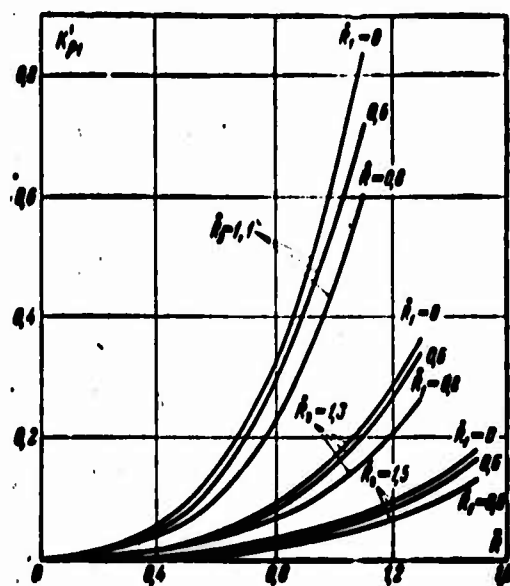


Fig. 5. Dependence $K_{\rho 1}' = f(\tilde{R})$ for $p = 4$.

If the machine has a ferromagnetic or a superconducting shield the field shape factor is expressed as follows:

$$k_{10} = \frac{H_{\rho 10}}{H_{\rho 0}} = \frac{H_{\rho 1} + H_{\rho 1}'}{H_{\rho 0} + H_{\rho 1}'} \quad (8)$$

The above-obtained expression for H_ρ' is presented in the form of an infinite series necessary for defining $H_{\rho 1}'$. The expression for H_ρ' can also be realized in finite form.

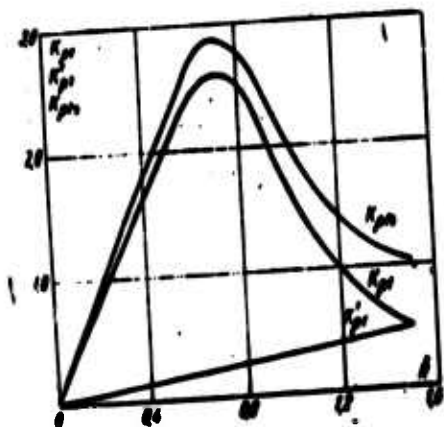


Fig. 6. Dependences of K_{p1} , K_{p1}' , $K_{p1\theta}$ on R for $p = 2$, $R_{\theta}^* = 1.5$, $\mu_{\theta} = \infty$.

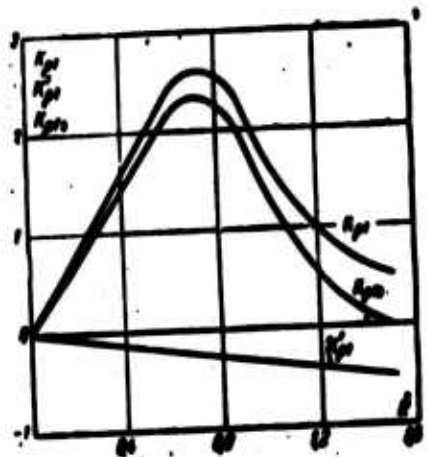


Fig. 7. Dependences of K_{p1} , K_{p1}' , $K_{p1\theta}$ on R for $p = 2$, $R_1 = 0.6$, $R_{\theta}^* = 1.5$, $\mu_{\theta} = 0$.

Not expanding the vector potential function in a series, we select definite integral (4):

$$H_{\theta}' = \lim_{R \rightarrow \infty} \frac{R_{\theta}}{R} K_{\theta}'.$$

where

$$\begin{aligned} K_{\theta}' = & \sum_{n=1}^{\infty} (-1)^{n+1} k_n \left[\frac{1}{2R} \ln \frac{\dot{R}_0^4 + \dot{R}^2 - 2\dot{R}_0^2 \dot{R} \cos \alpha}{\dot{R}_0^4 + \dot{R}^2 - 2\dot{R}_0^2 \dot{R} \cos \beta} - \right. \\ & - \frac{\dot{R}_1}{2R} \ln \frac{\dot{R}_0^4 + \dot{R}_1^2 - 2\dot{R}_0^2 \dot{R}_1 \cos \alpha}{\dot{R}_0^4 + \dot{R}_1^2 - 2\dot{R}_0^2 \dot{R}_1 \cos \beta} - \\ & - \left(\frac{\dot{R}_0^4}{\dot{R}^2} \cos^2 \alpha - \frac{\dot{R}_0^4}{2\dot{R}^2} \right) \ln \frac{\dot{R}_0^4 + \dot{R}^2 - 2\dot{R}_0^2 \dot{R} \cos \alpha}{\dot{R}_0^4 + \dot{R}^2 - 2\dot{R}_0^2 \dot{R} \cos \beta} + \\ & + \left(\frac{\dot{R}_0^4}{\dot{R}^2} \cos^2 \beta - \frac{\dot{R}_0^4}{2\dot{R}^2} \right) \ln \frac{\dot{R}_0^4 + \dot{R}^2 - 2\dot{R}_0^2 \dot{R} \cos \beta}{\dot{R}_0^4 + \dot{R}^2 - 2\dot{R}_0^2 \dot{R} \cos \alpha} + \\ & + \frac{\dot{R}_0^4}{\dot{R}^2} (1 - \dot{R}_1) (\cos \beta - \cos \alpha) + \\ & + \frac{\dot{R}_0^4}{\dot{R}^2} \sin 2\alpha \left(\arctg \frac{\dot{R} - \dot{R}_0^2 \cos \alpha}{\dot{R}_0^2 \sin \alpha} - \arctg \frac{\dot{R} \dot{R}_1 - \dot{R}_0^2 \cos \alpha}{\dot{R}_0^2 \sin \alpha} \right) - \\ & - \frac{\dot{R}_0^4}{\dot{R}^2} \sin 2\beta \left(\arctg \frac{\dot{R} - \dot{R}_0^2 \cos \beta}{\dot{R}_0^2 \sin \beta} - \arctg \frac{\dot{R} \dot{R}_1 - \dot{R}_0^2 \cos \beta}{\dot{R}_0^2 \sin \beta} \right) \Big], \\ & \alpha = \varphi - \pi \left(\frac{n}{p} - \frac{1-Y}{2} \right); \quad \beta = \varphi - \pi \left(\frac{n-1}{p} + \frac{1-Y}{2} \right); \end{aligned} \quad (9)$$

γ — the ratio of the wound part of the pole to the entire polar section.

The maximum value of K_p' with $\varphi = 0$, $\gamma = 1$, and $\mu_\theta = \infty$ for various numbers of pairs of poles equals:

when $p = 1$

$$K_p' = \left(\frac{2}{R} - \frac{2\dot{R}_0^4}{\dot{R}^3} \right) \ln \frac{\dot{R}_0^3 + \dot{R}}{\dot{R}_0^3 - \dot{R}} - \left(\frac{2\dot{R}_1^3}{\dot{R}^3} - \frac{2\dot{R}_0^4}{\dot{R}^3} \right) \ln \frac{\dot{R}_0^3 + \dot{R}\dot{R}_1}{\dot{R}_0^3 - \dot{R}\dot{R}_1} + 4 \frac{\dot{R}_0^3}{\dot{R}^3} (1 - \dot{R}_1) \quad (10)$$

when $p = 2$

$$K_p' = \frac{2}{R} \ln \frac{\dot{R} + \dot{R}_0^4}{\dot{R} - \dot{R}_0^4} - \frac{2\dot{R}_1^3}{R} \ln \frac{\dot{R}\dot{R}_1^3 + \dot{R}_0^4}{\dot{R}\dot{R}_1^3 - \dot{R}_0^4} + \frac{2\dot{R}_0^4}{R} \ln \frac{\dot{R} - \dot{R}_0^4}{\dot{R}\dot{R}_1^3 - \dot{R}_0^4} \quad (11)$$

when $p = 3$

$$K_p' = \left(\frac{2}{R} + \frac{\dot{R}_0^4}{\dot{R}^3} \right) \ln \frac{\dot{R} + \dot{R}_0^4}{\dot{R} - \dot{R}_0^4} - \left(\frac{2\dot{R}_1^3}{R} + \frac{\dot{R}_0^4}{\dot{R}^3} \right) \ln \frac{\dot{R}\dot{R}_1^3 + \dot{R}_0^4}{\dot{R}\dot{R}_1^3 - \dot{R}_0^4} + \frac{3\dot{R}_0^4}{\dot{R}^3} \ln \frac{\dot{R} - \dot{R}_0^4}{\dot{R} + \dot{R}_0^4} - \frac{3\dot{R}_0^4}{\dot{R}^3} \ln \frac{\dot{R}\dot{R}_1 - \dot{R}_0^4}{\dot{R}\dot{R}_1 + \dot{R}_0^4} + \frac{2\sqrt{3}\dot{R}_0^4}{\dot{R}^3} \left(\arctg \frac{2\dot{R} + \dot{R}_0^4}{\sqrt{3}\dot{R}_0^3} - \arctg \frac{2\dot{R}\dot{R}_1 + \dot{R}_0^4}{\sqrt{3}\dot{R}_0^3} + \arctg \frac{2\dot{R} - \dot{R}_0^4}{\sqrt{3}\dot{R}_0^3} - \arctg \frac{2\dot{R}\dot{R}_1 - \dot{R}_0^4}{\sqrt{3}\dot{R}_0^3} \right) \quad (12)$$

when $p = 4$

$$K_p' = \frac{2}{R} \ln \frac{\dot{R} + \dot{R}_0^4}{\dot{R} - \dot{R}_0^4} + \frac{2\dot{R}_1^3}{R} \ln \frac{\dot{R}\dot{R}_1^3 + \dot{R}_0^4}{\dot{R}\dot{R}_1^3 - \dot{R}_0^4} + \frac{2\dot{R}_0^4}{\dot{R}^3} \ln \frac{(\dot{R} - \dot{R}_0^4)(\dot{R}\dot{R}_1^3 + \dot{R}_0^4)}{(\dot{R} + \dot{R}_0^4)(\dot{R}\dot{R}_1^3 - \dot{R}_0^4)} + \frac{4\dot{R}_0^4}{\dot{R}^3} \left(\arctg \frac{\sqrt{2}\dot{R} - \dot{R}_0^4}{\dot{R}_0^3} - \arctg \frac{\sqrt{2}\dot{R}\dot{R}_1 - \dot{R}_0^4}{\dot{R}_0^3} - \arctg \frac{\sqrt{2}\dot{R} + \dot{R}_0^4}{\dot{R}_0^3} + \arctg \frac{\sqrt{2}\dot{R}\dot{R}_1 + \dot{R}_0^4}{\dot{R}_0^3} \right) \quad (13)$$

The field shape factor when $\mu_g = \infty$ and $k_\mu = 1$ equals

$$k_{f0} = \frac{K_{g1} + K_{g1}'}{K_g + K_g'}.$$

In the case when $\mu_g = 0$ and $k_\mu = -1$,

$$k_{f0} = \frac{K_{g1} - K_{g1}'}{K_g - K_g'}.$$

The dependence $k_{f0} = f(\bar{R})$ when $p = 2$ is depicted in Fig. 8.

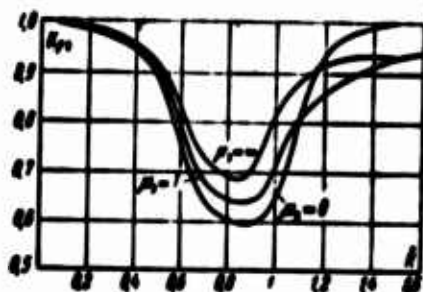


Fig. 8. Dependence $K_{f0} = f(\bar{R})$
for $p = 2$, $R_1 = 0.6$, $\bar{R}_g = 1.5$.

The field shape factor inside the area limited by the shield has, when $\mu_g = \infty$, smaller values in comparison with machines without a shield. On the surface of the shield the field shape factor when $\mu_g = 0$ becomes equal to one, while when $\mu_g = \infty$ it remains without change, just as when $\mu_g = 1$.

Conclusions

Analysis of the obtained expressions for the components of the magnetic field strength for superconducting synchronous machines with a ferromagnetic shield shows that the magnetic strength inside the shield increases.

The presence of a superconducting shield adversely affects the distribution of the resultant radial magnetic field strength component; such a shield is used expediently with external magnetic fields of dispersion which exceed the saturation limits of the ferromagnetic material.

References

1. Woodson, H. H., Z. J. J. Stekly, and E. Halas. A study of alternators with superconducting field winding. Power Appar. and Systems, 1966, Vol. 85, No. 3.
2. Štafl, Miloš. Elektrodinamicheskiye zadachi v elektricheskikh mashinakh i transformatorakh (Electrodynamic problems in electric machines and transformers)., Translated from the Czech, Energiya, 1966.

Received

12 July 1968

DATA HANDLING PAGE				
01-ACCESSION NO. 90-DOCUMENT LOC TP9001873		30-TOPIC TAGS internal magnetic field, ferromagnetic structure, electric machine, super-conductivity, electric power engineering		
09-TITLE THE MAGNETIC FIELD IN SUPERCONDUCTING SHIELDED SYNCHRONOUS MACHINES -U-				
47-SUBJECT AREA 09, 20, 10				
42-AUTHOR CO-AUTHORS BERTINOV, A. I. ; 16-GOLOVKIN, A. V.; 16-ZHEMCHUGOV, G. A. ; 16-MIRONOV, O. M.				10-DATE OF INFO -----69
43-SOURCE AN SSSR. IZVESTIYA. ENERGETIKA I TRANSPORT (RUSSIAN) FTD-				88-DOCUMENT NO. HT-23-430-69
				89-PROJECT NO. 6040102
63-SECURITY AND DOWNGRADING INFORMATION UNCL. 0			84-CONTROL MARKINGS NONE	97-HEADER CLASH UNCL
76-REEL/FRAME NO. 1890 1551	77-SUPERSEDES	78-CHANGES	40-GEOGRAPHICAL AREA UR	NO. OF PAGES 10
CONTRACT NO.	X REF ACC. NO. 65-	PUBLISHING DATE 94-	TYPE PRODUCT. TRANSLATION	REVISION FREQ NONE
STEP NO. 02-UR/0281/69/000/002/0096/0101				
ABSTRACT (U) The magnetic field of the superconducting winding of a shielded synchronous machine is investigated, expressions for components of magnetic field strength are obtained, and the shape factor of the field of a synchronous machine with ferromagnetic and superconducting shields is determined. Graphic dependences are given for the distribution of the components of magnetic field strength along the radius for various numbers of pairs of poles, and the relationship of geometrical dimensions of a superconducting winding and shield is shown.				