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Superconducting Electric Machine with Permanent Magnets and Bulk HTS Elements

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Abstract

Theoretical methods of calculating of two-dimensional magnetic fields, inductive parameters and output characteristics of the new type of high-temperature superconducting (HTS) synchronous motors with a composite rotor are presented. The composite rotor has the structure containing HTS flat elements, permanent magnets and ferromagnetic materials. The developed calculation model takes into account the concentrations and physical properties of these rotor elements. The simulation results of experimental HTS motor with a composite rotor are presented. The application of new type of HTS motor in different constructions of industrial high dynamic drivers is discussed.

Keywords: high-temperature superconductor, bulk element, composite rotor, permanent magnet, synchronous electrical motor, calculation methods, experimental model.

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1. Introduction

Last years the development of HTS current leading elements from yttrium ceramics of the bulk and foliate shape allows to improve power parameters of existing types HTS of motors, and also to consider a number of new perspective schemes HTS of electrical machines with higher specific power parameters.

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One of such schemes is a design of HTS electrical machine with a composite layered rotor that contains alternating plates: permanent magnets, ferromagnetic materials and HTS current leading elements. At cryogenic temperature $T < T_c$ the considered rotor has a low magnetic conductivity along axis d, coinciding with orientations of magnets and high magnetic conductivity along axis q that is a perpendicular axis to permanent magnets magnetization. Limiting parameters for such HTS electrical machine in the literature are considered not full enough. In this paper variants of constructive schemes of two poles HTS motors and the results of research of their limiting power parameters are presented.

Nomenclature

μ	magnetic permeability
$\overline{B}$, $\overline{H}$	induction and intensity of magnetic field
$\overline{M}$, M	magnetization, torque
I, $\overline{J}_0$	current and linear current density
L	length, inductance
D	diameter, constant
ρ, φ	radial and angular coordinates
γ, θ	angle
R	radius, resistance
T	temperature
Φ	magnetic flux
E_0, U	electromotive force, voltage
X	reactance
d, q	longitudinal and perpendicular axis of electric machine
W	energy, winding turns number
P	power
n	rotating velocity

2. The general statement of two-dimensional electrodynamics' problem

At the solving of electrodynamics' problem in an active zone of synchronous HTS machine the real structure of a layered composite rotor (fig. 1a) is replaced with the equivalent anisotropic environment having a tensor of average relative magnetic permeability $\hat{\mu} = \begin{pmatrix} \mu_x & 0 \\ 0 & \mu_y \end{pmatrix}$ and equivalent magnetization $\overline{M}\{M_x, 0\}$. Three phase stator winding is considered like a current layer producing rotating magnetic field.

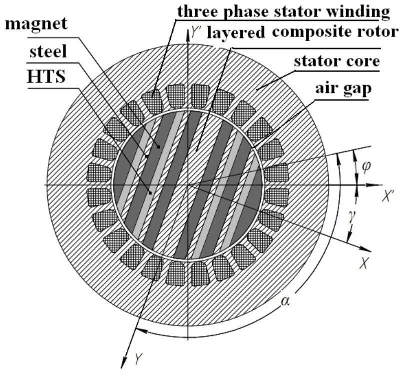


Fig. 1. Constructive scheme of electric motor

Taking into account the mentioned assumptions the distribution of magnetic field B in linear zone of HTS motor with a long rotor (L/D> ~3…4) can be found from the decision of the two-dimensional electrodynamics' problem described by the Maxwell's equations [1, 2]:

$$\begin{cases} rot\bar{H} = 0; \quad div\bar{B} = 0;, \\ \bar{B} = \mu_0\hat{\mu}(\bar{H} + \bar{M}) \end{cases} \tag{1}$$

where

- $\hat{\mu} = 1$ and $\bar{M} = 0$ — for air gap domain;
- $\hat{\mu} = \infty$ and $\bar{M} = 0$ — for stator yoke;
- $\hat{\mu} = \begin{pmatrix} \mu_x & 0 \\ 0 & \mu_y \end{pmatrix}$ и $\bar{M}\{M_x, 0\}$ — for composite rotor domain with equivalent anisotropic medium.

Here $M_x = M_x(\mu_S, \mu_M, \mu_{Fe}, M_H)$ is an equivalent magnetization of a rotor; μ_x, μ_y components of the relative magnetic permeability tensor which are defined functions of concentration of rotor elements and their local relative magnetic permeability μ_s, μ_M, μ_{Fe} in HTS plates, PM and ferromagnetic blocks accordingly.

On interfacing boundaries of environments with different magnetic permeability following conditions are used [2, 3]:

on boundary "stator - air gap" ($\rho = R_s$):

$$H_{\tau+} - H_{\tau-} = J_0; \quad B_{n+} = B_{n-}; \tag{2a}$$

on boundary "air gap – rotor" ($\rho = R_r$):

$$H_{\tau+} = H_{\tau-}; \quad B_{n+} = B_{n-}. \tag{2b}$$

Here indexes "+" and "-" concern the parameters on the different sides of boundary of sections with different magnetic permeability.

In the given statement an obtaining of two-dimensional distributions of magnetic fields is reduced to the problem decision (1)–(2) for two areas: a composite layered rotor [$0 \le \rho \le R_r$ with (μ_x, μ_y, M_x)] and an air gap [$R_r \le \rho \le R_s$ with $\hat{\mu} = 1$].

The distribution of magnetic fields in the specified areas is obtained on the basis of the elliptic equation solving for vector potential $\bar{A}(0,0,A)$, ($\bar{B} = rot\bar{A}$):

$$rot\left|(\hat{\mu})^{-1}rot\overline{A}\right| = 0 \tag{3}$$

with boundary conditions (2) [4]. The amendment on parameters of the machine due to limit size teeth zone and stator yoke can be found s known methods from the theory of magnetic circuit [2, 3].

3. Analytical solutions of an electrodynamic problem

The Laplace equation for axial components of vector potential A_δ in air gap in polar system of coordinates $\{r,\ \varphi\}$ fixed with stator will be written as:

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial A_\delta}{\partial\rho}\right)+\frac{1}{\rho^2}\left(\frac{\partial^2 A_\delta}{\partial\varphi^2}\right)=0\cdot \tag{4}$$

Taking into account boundary conditions (2a) on an internal surface of the stator the common solution (4) for the first harmonic is the following [2]:

$$A_\delta = D\left\{\left[\left(a+\frac{1}{R_s}\right)\rho+\left(a-\frac{1}{R_s}\right)\frac{R_s^2}{\rho}\right]\sin\varphi + c\left[\rho+\frac{R_s^2}{\rho}\right]\cos\varphi\right\}\cdot \tag{5}$$

Here $D = \mu_0 m_\phi i_m W_a K_a / 2\pi$, where W_a and K_a – number of turns and winding factor of stator winding; m_ϕ – number of phases, i_m – amplitude value of the stator winding current. Constants of integration a, c, c_{R1}, c_{R2} are defined after substitution of partial solution for vector potential [5] and (5) in boundary conditions (2b) on the rotor surfaces $\rho = R_r$ which has been written down for axial components of vector potential A. The obtained expressions for constants of integration are:

$$a=\frac{M_X}{D\cdot\left(1+\overline{R}^2\right)\cdot\left(l\mu_x-1\right)}\cos\gamma+\frac{1}{R_s}\left(\frac{m+n}{2}+\frac{m-n}{2}\cos 2\gamma\right); \tag{6}$$

$$c=\frac{M_X}{D\cdot\left(1+\overline{R}^2\right)\cdot\left(l\mu_x-1\right)}\sin\gamma+\frac{1}{R_s}\frac{m-n}{2}\sin 2\gamma; \tag{7}$$

$$c_{R1}=(l-n)D\frac{\left(1+R_s^2\right)}{R_s}\sin\gamma-\frac{M_X}{\left(l\mu_x+1\right)}l\mu_{x'};\ c_{R2}=(l-m)D\frac{\left(1+R_s^2\right)}{R_s}\cos\gamma; \tag{8, 9}$$

where $\overline{R}=\frac{R_s}{R_r}$; $l=\frac{\overline{R}^2-1}{\overline{R}^2+1}$; $m=\frac{\mu_{y'}l}{l\mu_y+1}$; $n=\frac{\mu_x+l}{l\mu_x+1}$ – parameters of the problem.

4. EMF and inductive parameters of linear zone of HTS electrical motor

Operating value of EMF E_0 is obtained through the PM magnetic flux of an anisotropic rotor at zero stator currents by means of known expressions [1, 4] and can be transformed in a following kind [1]:

$$E_0\left(M_x\right)=2\sqrt{2}R_sL_sW_aK_a\frac{M_x}{\left(1-l\mu_x\right)\left(1+\overline{R}^2\right)}\omega\cdot \tag{10}$$

Using known expressions $W_I = L_i I^2/2$, $x_a = \omega L_S$ (where L_S – inductance of a stator winding), it is possible to get the main reactance x_{ad} and x_{aq} of linear zone of HTS electric machine:

$$x_{ad} = 2\frac{\mu_0}{\pi}\omega L_s m_\phi W_a^2 K_a^2 n\,;\; x_{aq} = 2\frac{\mu_0}{\pi}\omega L_s m_\phi W_a^2 K_a^2 m \qquad (11)$$

5. Vector diagram of HTS machine.

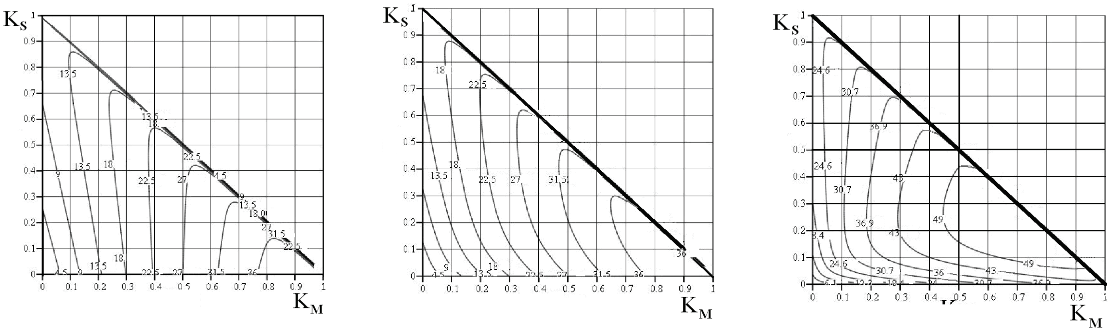
Using the vector diagram, it is possible to find following angular dependences for a stator current, power factor, electromagnetic power P and the torque M for given voltage $\dot{U}$ [2]:

$$\begin{cases} I = \sqrt{\dfrac{(U\cos\theta - E)^2}{x_d^2} + \dfrac{(U\sin\theta)^2}{x_q^2}}; \\ \cos\varphi = \dfrac{E_0 x_q \sin\theta + U\sin 2\theta\left(x_d - x_q\right)/2}{\sqrt{x_q^2(U\cos\theta - E)^2 + x_d^2(U\sin\theta)^2}}; \\ P_{эм} = M_{эм}\Omega = m\left[\dfrac{E_0 U}{x_d}\sin\theta + \dfrac{U^2}{2}\sin 2\theta\left(\dfrac{1}{x_q} - \dfrac{1}{x_d}\right)\right]. \end{cases} \qquad (12)$$

6. Calculations results of magnetic fields and characteristics of HTS machine

Calculation of magnetic fields and characteristics of a experimental model of two poles HTS synchronous machine is done at following values of parameters: internal stator diameter R_s = 42 mm, active length of the machine L_s =76 mm, an equivalent air gap $\delta = 3$ mm, number of phases m = 3, number of turns in a phase $w_a = 176$, rated voltage $U = 220$ V, voltage frequency of a of $f = 50$ Hz (rotating velocity $n = 3000$ rpm). Typical values of relative magnetic permeability of the composite rotor materials and the magnetic moment varied within $\mu_s = 0.1 – 1$, $\mu_M = 1$, $\mu_{Fe} \approx 500$, $M_M = 0.7 –$ 1.2 T.

In fig. 2 the results of calculations of lines of level of electromagnetic power $P_{эм}$ of HTS machine are



μS = 1 μS = 0,5 μS = 0,1

Fig. 2. Output electromagnetic power P [kW] for different concentrations

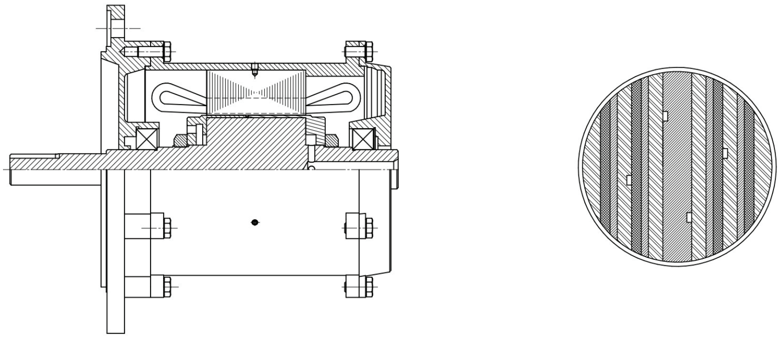


Fig. 3. Assembly of the motor (a) and cross-section of rotor (b)

presented at the maximum value $\cos\varphi$. From the analysis of these curves it follows that there is a zone of concentration $0{,}1 \le k_{s} \le 0{,}4$ and $0{,}5 \le k_{м} \le 0{,}8$ where the maximum values $P_{эм}$ are realized.

Calculations show that the increase of magnetic moment M_{M} from 0.7 T up to 1 T shifts this zone in area of great values $k_{м}$.

7. Characteristics of two-pole HTS machine for a drive of cryogenic pump

On the basis of the carried out calculations the experimental model of HTS machine of immersed design has been developed. It is intended for work in the environment of liquid nitrogen with temperature T=77 K. The design of the machine and a layered composite rotor is presented in fig. 3(a, b).

8. Conclusion

The new constructive scheme is suggested of HTS electrical motor with composite layered rotor consisting of alternating layers of massive HTS elements, permanent magnets and electrotechnical steel.

Analytical and numerical methods of calculation of HTS motors are developed and partial optimization of output parameters of two-pole HTS motors taking into account concentration and physical properties HTS of elements, permanent magnets and electrotechnical steel is done.

It is shown that suggested design of HTS machine with a composite layered rotor has higher power parameters and dynamic characteristics in comparison with known designs of synchronous HTS motors with permanent magnets at equal modes of cooling in the environment of liquid nitrogen.

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