HTS high-dynamic electrical motors

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Abstract. The application of bulk HTS elements in the electrical machines allows to improve their output parameters. In the presented article HTS high-dynamic electrical motors with excitation from permanent magnets (PM) and bulk HTS elements in the rotor are considered. The analysis of parameters of such HTS motors with radial, tangential and Halbach array arrangements of PM was carried out. The influence of bulk HTS elements on their output characteristics is investigated. It was shown theoretically and experimentally, that application of HTS bulks together with PM allows to improve the output characteristics of the motors with PM. The experimental synchronous HTS motors with bulk HTS elements and PM and high dynamics were designed and manufactured. The experimental investigations of these motors were carried out and are in good agreement with theoretically results. This HTS motor was developed for usage as the drive for cryogenic pumps of hydrogen power lines.

1. Introduction

Nowadays HTS materials are developed worldwide. The HTS material shapes mainly are: thin films, bulks and tapes. YBCO bulks are still the most available HTS material for the application at the temperature of liquid nitrogen. 2G CC tapes are expected in the future but up to now can not be produced in sufficient amount for the usage in the electric machines as soon as normally kilometers are needed. Nevertheless application of bulk HTS elements in the electric machines gives the advantages in their performance.

There are several types of electrical machines where HTS bulks can be used:

- hysteresis motors, where torque is in linear proportion to the total hysteresis loss in the rotor consisting of bulk HTS elements [1];

- reluctance motors, where rotors contains both ferromagnetic and HTS elements providing magnetic anisotropy along the perpendicular rotor axes [2];

- “trapped field” electric machines, where the ability of HTS elements to trap magnetic flux is used [3].

Another possibility to use HTS bulks in the electric machines’ rotors - is to utilize their diamagnetic properties for magnetic flux concentration and magnetic field in the gap increasing.

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In this article synchronous electric machines on the base of permanent magnets and HTS bulk elements in the rotors are discussed. Such motors are intended for usage as high-dynamic drives for various applications.

2. Main principles of high-dynamic electrical motors design

The main dimensions (diameter *D* and axial length *L*) of the usual cylindrical electrical motors operating in the more or less stable regimes with the given value of output power *N* and rpm *n* can be determined according to the well-known Arnold formula:

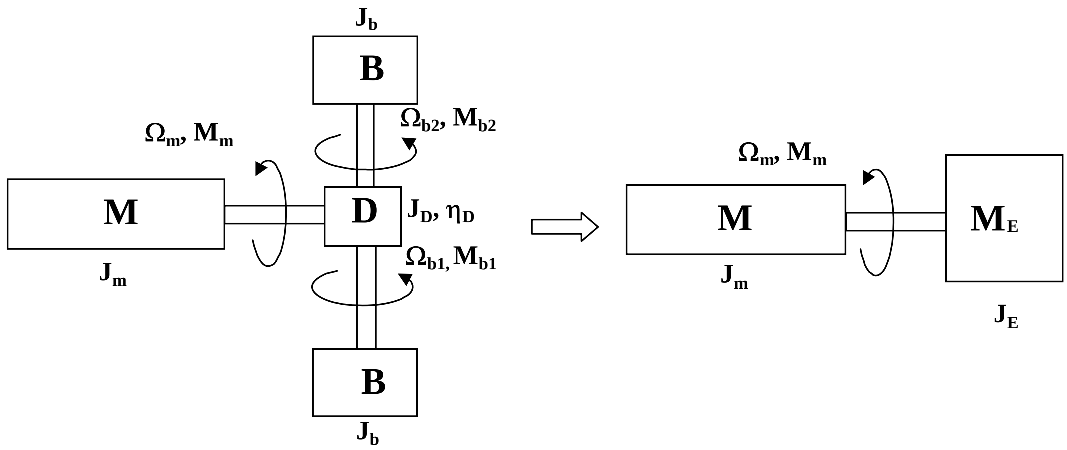
$$D = \sqrt[3]{\frac{N}{C \cdot A \cdot B_\delta \cdot n \cdot \Lambda}}; \quad L = \Lambda \cdot D. \tag{1}$$

Here *A* – current load of the stator coils; B_δ – magnetic induction in the air gap; *n* – rotating speed of the shaft (rpm); Λ – relative axial length (recommended value of Λ = 1–3); *C* – some constant value ($C \sim k\pi^2/60 \sim 0.1$).

In this approach it is difficult to take into account directly the dynamic parameter $din \sim d\Omega/dt$ of the drive. This parameter can be determined by the following acceleration equation of the drive.

$$\left(J_E + J_m\right)\frac{d\Omega}{dt} = M_m - M_E \quad \text{or} \quad M_M k_d = J_m \frac{d\Omega}{dt}. \tag{2}$$

Here $M_M = \left(\pi^2/8\right)\sqrt{12} B_\delta A D^2 L k_p$ – the brake torque the motor; k_z, k_p – winding coefficients; $k_d = \left(1 - M_z/M_m\right)\left(1 + J_E/J_m\right)$ – factor taking into account the structure and parameter of the drive and the load on the shaft. The other values of the parameters of this equation can be usually seen from Fig. 1.



(a) - real schematics (b) - model schematics

where M – motor, D – differential gear, B – electromagnetic breaks, *J* – moment of inertia

Fig. 1 Model of high-dynamic motor

It is important only to mention that developed analytical approach shows that the inner diameter of the high dynamic motor is determined not only by the value of average output power *N* and rotating speed *n* of the motor (as in formula (1)) but also by the value of dynamic parameter and the torque for one unit of the motor length $\left(M_L \sim AB\right)$. The axial length of the motor in this approach can be determined by the total value of torque on the shaft *M*. This leads to the following formulas for the inner diameter and the axial length of the motor:

$$D = \sqrt{\frac{120\sqrt{2}ABk_p k_z}{\gamma\left(din/k_d\right)}}\ [m];\quad din\,[r.p.m./s]; \tag{3}$$

$$L = \frac{M\gamma\left(din/k_d\right)}{30\pi^2 A^2 B_{av}^2 k_p^2 k_z^2}\,[m]. \tag{4}$$

Here din – is the dynamic parameter $\left(din \sim d\Omega/dt\right)$.

From these two formulas (3)-(4) it can be seen that the active volume of the high dynamic motor can be determined as:

$$V = \pi D^2 L = \frac{4\sqrt{2}}{\pi}\frac{M}{AB} \sim \frac{1}{AB}. \tag{5}$$

From the dependence (5) it can be seen that in order to realize the smaller volume of high dynamic HTS motor the active zone of HTS motor must have the highest values of current load *A* and magnetic induction in the air-gap *B*. The probable solution of this problem is illustrated on Fig. 2.

Implicit-pole Motor with Permanent Magnets　　Salient-pole HTS Motor with Permanent Magnet

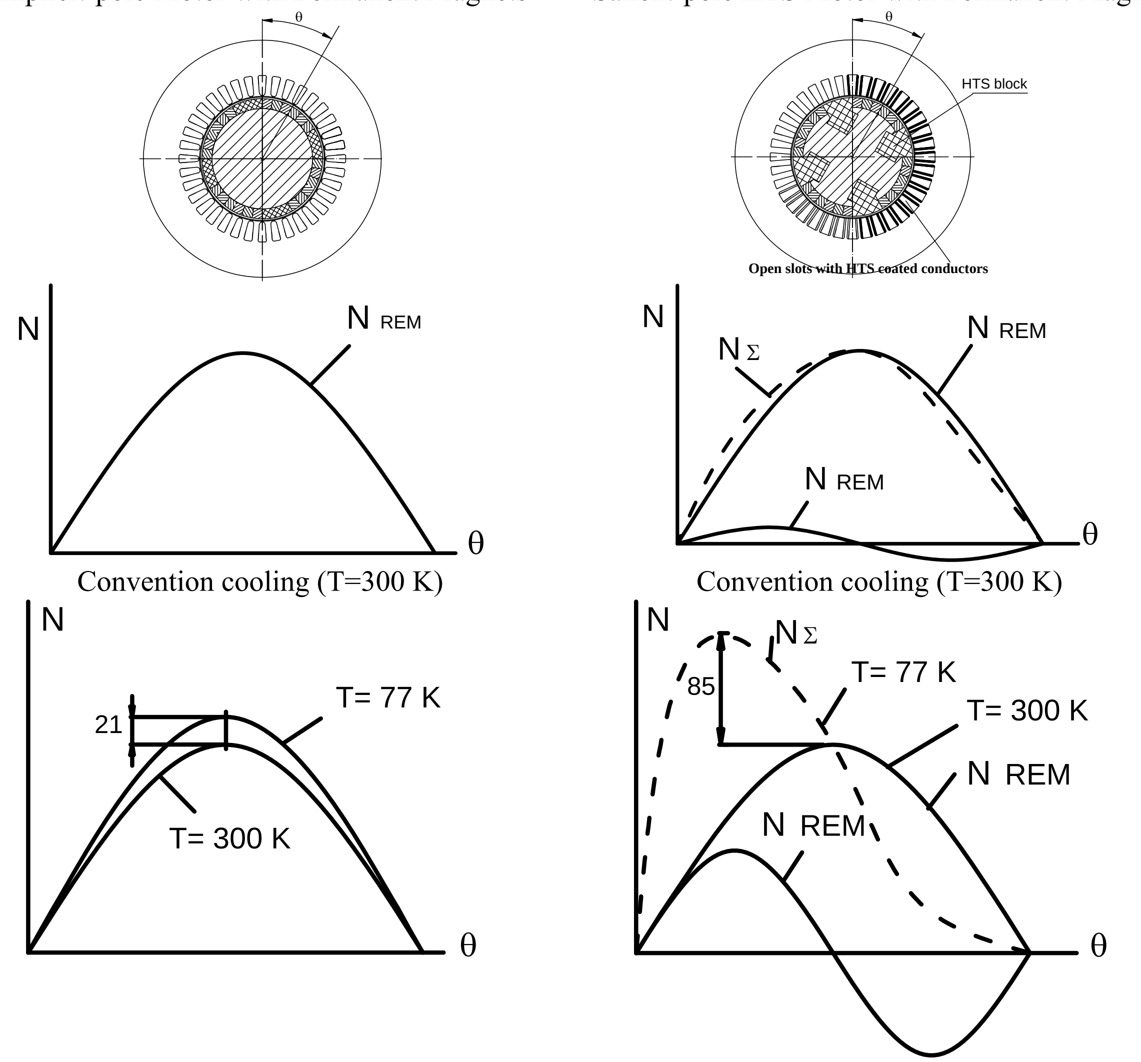
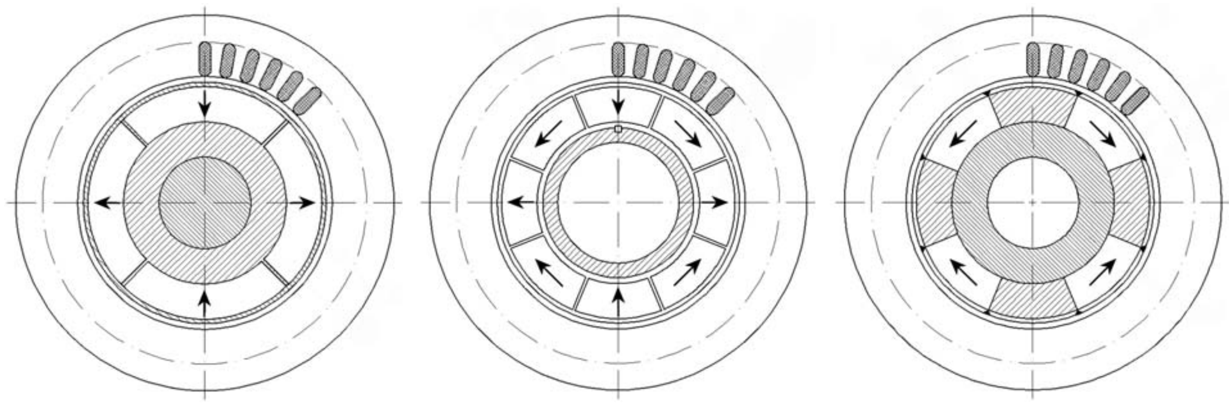


Fig. 2 Expected profit of the use of Composed HTS motor with Permanent magnets

Most impressive result we can obtain if we shall develop the special construction of the rotor with the use of HTS bulk materials (with good magnetic properties $\mu_s \leq 0.25$) together with strong permanent magnets (see left side on Fig. 2). The analysis of the optimal schematics of HTS motor with permanents magnets and HTS is given below.

3. Design of high-dynamic motors with the rotors containing permanent magnets and HTS elements

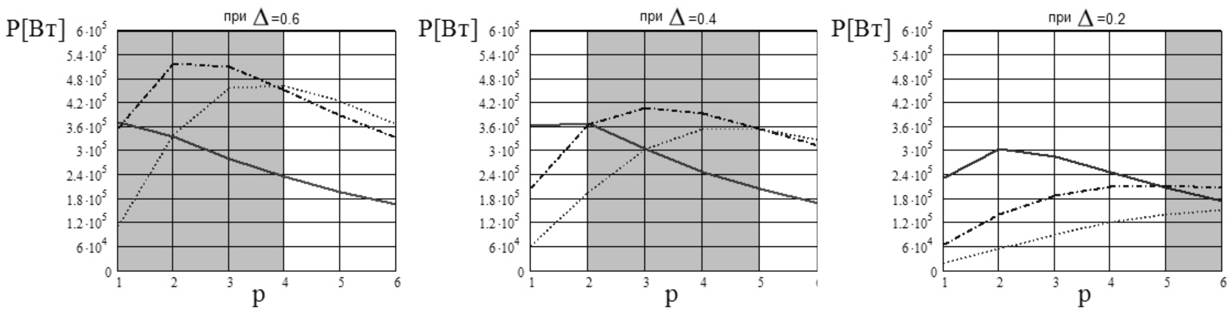
There are three the most commonly used schematics of the motors with permanent magnets: with radial magnetization of the rotor (Fig. 3a), with tangential magnetization of the rotor (Fig. 3c) and combined (Halbach array) magnetization of the rotor (Fig. 3b).



(a) (b) (c)

Fig. 3 Schematics of the motors with permanent magnets: with radial magnetization of the rotor (a), with combined magnetization of the rotor (b) and with tangential magnetization of the rotor (c)

As the investigations showed [5] each schematics provides greater output power depending on the number of pole pairs and magnet thickness (Fig. 4).As it is seen from Fig. 4 at small number of pole pairs (p<3) the greater output power is given by the rotors with radial magnetization, at intermediate number of pole pairs (2<p<5) the greater output power is given by the rotors with Halbach array magnetization, and at the higher number of pole pairs (p>4) the greater output power is given by the rotors with tangential magnetization. These results were taken into account during the optimization of the rotor's structure for high-dynamic motors.



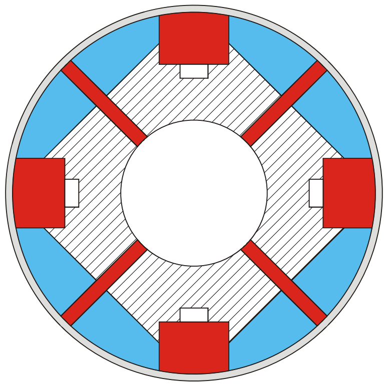
(a) (b) (c)

Fig. 4 Output power depending on the number of pole pairs of the motor at different thickness of the permanent magnets (a – at Δ=0,2; b – at Δ=0,4; c – at Δ=0,6)

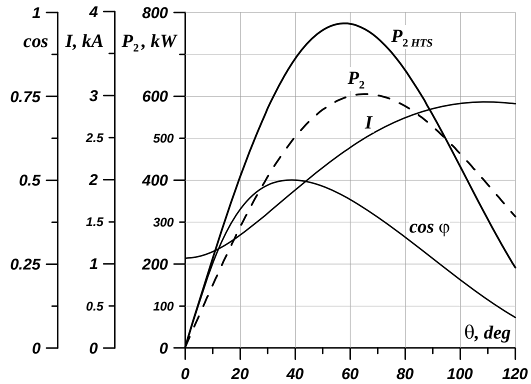
Two high-dynamic motors with the rotors containing permanent magnets and YBCO bulk elements were designed and constructed. The first one is 4-pole 500 kW motor and the second one – 6-pole 150 kW motor. Both motors have immersed construction and are cooled with liquid nitrogen.

General view of 500 kW HTS motor is shown in Fig. 5a. The dimensions of the stator bore and stator length of this motor are DxL=110x400 mm. The cross-section of the rotor is presented on Fig. 5b. It is seen that this 4-pole rotor has rather complicated structure and contains ferromagnetic core, permanent magnets with radial magnetization and HTS elements. Such rotor construction provides higher output power of the motor in comparison with the motor without HTS blocks (see Fig. 5c).


(a)


(b)

- permanent magnets; - HTS; - magnetic core



(c)

- output power with HTS; - output power without HTS

Fig. 5 500 kW HTS motor: (a) – general view, (b) – cross-section of the rotor, (c) –characteristics of the motor.

Another high-dynamic 150 kW HTS motor is shown in Fig. 6. This motor has 6 poles and was designed for special cryogenic pump. The dimensions of the stator bore and stator length of this motor are DxL=130x130 mm. The cross-section of the rotor is presented on Fig. 5c. Fig. 5d illustrates the motor characteristics. From Fig. 5d it is seen that maximal output power is 300 kW – two times greater than nominal output power 150 kW. This is because the motor was designed also for overload mechanical regimes.

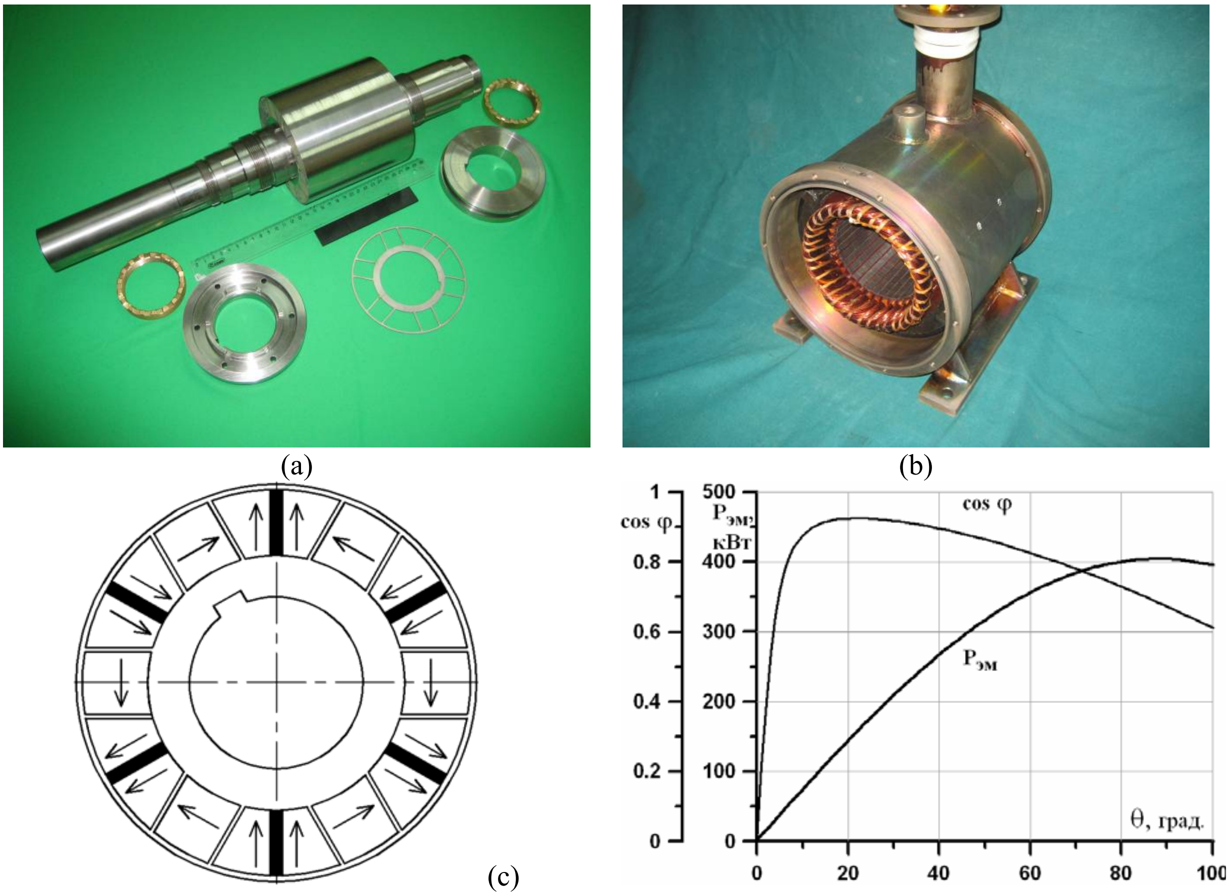


Fig. 6 150 kW HTS motor: (a), (b) – general view of the rotor and stator, (c) – cross-section of the rotor, (d) –characteristics of the motor.

4. Conclusion

Synchronous electric machines with permanent magnets and liquid nitrogen cooling possess greater output power in comparison with water-cooled machines. Application of bulk YBCO elements in the rotors increases the output power of these machines and therefore increases their dynamics. Application of CC HTS wires in cryogenic electric machines is expected in the future.

5. References

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