An experimental investigation of a reluctance electrical drive with bulk superconducting elements in the rotor at temperature below 20 K

I K Kovalev¹, K V Ilushin¹, V T Penkin¹, K L Kovalev¹, V N Poltavets¹, S M A Koneyev¹, K A Modestov¹, W Gawalek², T A Prikhna³ and I I Akimov⁴

¹ Moscow Aviation Institute (MAI), Volokolamskoe sh. 4, Moscow, 125993, Russia
² Institut für Physikalische Hochtechnologie (IPHT), Albert Einstein Str. 9, D-07745, Jena, Germany
³ Institute of Superhard Materials (ISM), Avtozavodskaya st. 2, Kyiv, 04074, Ukraine
⁴ Research Institute of Inorganic Materials named after A A Bochvar (VNIINM), Rogova st. 5, Moscow, 123060, Russia

kovalev@mai.ru

Abstract. This work is devoted to experimental investigation of a reluctance motor for which the rotor contains bulk superconducting elements to provide different permeabilities along the pole axes and in perpendicular direction. Three materials are under consideration - YBCO monocrystal plates, BSCCO foliate material and the bulk MgB₂ plates. A comparative analysis of an output performance of the motor is done at the temperature below 20 K to define the best material with the ratio “cost-quality”.

1. Introduction
In the 21-st century a technical reequipment of power systems will take place due to the use of superconductivity in many aspects of power generation and transmission. One of the advanced trends is an incorporation of the liquid hydrogen (LH₂) fuel transportation by the pipeline and superconducting cable inside as a transmission line for electrical power. Cryogenic pumps for LH₂ transportation with electrical drive on the base of the bulk superconducting material may become essential part of such power system of two energy carriers.

In particular the temperature level of LH₂ in the power generation opens the door for the use of MgB₂ as an advanced superconducting material.

The results of theoretical and experimental investigation of high temperature superconducting (HTS) motors of hysteresis and reluctance type and machines with trapped magnetic flux at temperature 77K are presented in [1-2].
2. **Superconducting materials for the rotor of a reluctance motor**

An interest to LH$_2$ power line with working temperature 20.3 K that incorporates a power transmission by superconducting cable and LH$_2$ transmission as a cryogenic fuel gives the opportunity to use MgB$_2$ as an active superconducting material of the electric machine. The synchronous reluctance electric drive (figure 1) with the dimensions of rotor $\varnothing \times L=39 \times 72$ mm was chosen as a testing device to compare influence of the magnetic properties of the bulk YBCO, MgB$_2$ and foliate composite BSCCO elements (figure 2) on the output performance of electric machine. Small dimensions of the rotor limit the use of superconducting wires for stator winding and in the rotor that is caused by minimal radius of bending of the wire (>100mm). A star-connected copper winding of stator produces rotating magnetic field with value 0.95 T in the air gap. The motor has a vertical immersed design. The rotor is supplied with ball bearings. Liquid helium was chosen as a coolant to provide the necessary temperature. An evaporation of helium in bottom part of motor provides cooling of superconducting rotor down to 12 K. During the dynamic test the rotor temperature varies in the range 15…20 K.

![Figure 1. Design of the motor](image)

![Figure 2. Cross-sections of superconducting rotors of reluctance electric motor](image)

YBCO bulk elements of the rotor are 4 rectangular plates of dimensions 37.5x32x4 mm$^2$ and 4 rectangular plates of dimensions 37.5x39x4 mm$^2$. The mechanical and magnetic quality of the plates was verified by field mapping. Applied external field was 1.8 T that enabled to trap of 1.4 T induction of magnetic field by each YBCO plate at 77 K. The current density in the samples was accessed of 70 A/mm$^2$.

BSCCO foliate materials of the rotor (figures 3 - 4) were produced of Bi – 2223 in Ag matrix by PIT technology. As a result of multiple rolling in different directions a high isotropy of the material was obtained. Produced BSCCO/Ag-sheathed sheets have a thickness 0.2 – 1 mm and dimensions 1000x300 mm$^2$ and contain up to 40 layers of superconducting material. A comparison of carrying current properties of Bi-2223/Ag sheets and tape of 3 mm width with 61 HTS layers of the same material demonstrated close dependencies of critical current versa external magnetic field.

This testing was done to assess an influence of rolling to the superconducting properties of BSCCO/Ag material. It is necessary to mention that BSCCO/Ag material is more technological due to easy bending.
The rotor MgB$_2$ bulk elements being produced at present by technology of ceramic synthesis are 12 plates of dimensions 25x18x7 mm$^3$. Each plate was tested on the ability to trap the magnetic field.

![Figure 3. Billets for stacks that were cut away from the BSCCO sheet](image1)

![Figure 4. Assembled rotor with BSCCO stacks](image2)

Testing was done at the temperature 21 K in the magnetic field 1.8 T. The highest value of frozen magnetic field is 1.49 T and current density 110 A/mm$^2$.

3. Dynamic testing of reluctance electric motor with different types of the superconducting rotor

3.1. Testing at 77 K.
The output power of the motor without superconducting plates of the rotor in liquid nitrogen is 200 W. The insert of BSCCO sheets increases that parameter up to 350 W and the insert of YBCO plates results to 500 W. These values relate to the maximum of power factor cos $\phi$. The test was carried out at the nominal value 120 V of line–zero (L-0) voltage with frequency 50 Hz for stator winding that provides 3000 rpm rotating velocity.

3.2. Testing at 15…20 K.
Testing of the motor without superconducting elements in the rotor in this temperature range showed that output power is about 210 W. Small change of the value compared with obtained one at 77 K is explained by big part of reactance in impedance of stator winding and neglected little electric resistance. The reactance doesn’t depend on temperature and its value characterizes a current of stator winding. Test results at 15…20 K are presented in figures 5 – 7. It is seen that monocrystal YBCO bulk material provides the highest 1000 W output power at the high cost of superconducting material (2000 EUR/kg). More technological and suitable for electric machines of high rotating velocity the foliate Bi-2223/Ag sheathed material results to slightly less value of 820 W with approximate cost 1500 EUR/kg. The cost of MgB$_2$ bulk elements is accessed at the level 700 EUR/kg. This material in the rotor provides of 700 W output power rating.

It is important to mention that obtained output power of the motor is not a limit level and can be increased twice by double value of voltage. However this results to saturation effect of magnetic circuit of the machine and decreases the power factor down to 0.3. Low value of cos $\phi$ excludes the advantages of reluctance motor compared with the other types of electric machines. Moreover the saturation doesn’t allow comparing superconducting materials of rotor correctly.

4. Conclusion
A comparative analysis of obtained output performance allows concluding that a decrease of the temperature from 77 K to 20 K results to enhance of output power of the motor with YBCO from 500 W to 1 kW. For the motor with BSCCO an increase from 350 W at 77 K up to 820 W at 20 K has been observed. The bulk MgB$_2$ elements at LH$_2$ temperature work stable in reluctance electric drive and have magnetic permeability close to the monocrystal YBCO materials at substantially less cost. This material can be recommended for electric machines of LH$_2$ power systems.
Figure 5. Test results of the motor with YBCO blocks
hereinafter $\eta$ - efficiency, $N$ - output power, $\cos \phi$ - power factor, $I$ – current of stator winding

Figure 6. Test results of the motor with BSCCO blocks

Figure 7. Test results of the motor with MgB$_2$ blocks

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