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Developing and testing of rotor with HTS coils for electric machine

***Abstract**. The integration of high temperature superconducting materials in power systems is still quite limited. The transition from the element to the system is not trivial, because the behaviour of an isolated element (tape, coil) can be quite different when it is integrated into a system (rotor or armature of machine). In this paper high temperature superconducting field coils and test results are described. Besides results of experimental research of assembled rotor of fully superconducting machine cooled with liquid nitrogen also provided in the paper. Results are compared to 3D FEM simulation of magnetic field for a separate coil and an assembled rotor*

Streszczenie.** W artykule opisano wykorzystanie nadprzewodnika wysokotemperaturowego do konstrukcji uzwojenia wirnika maszyny chłodzonej ciekłym azotem. **Projekt ibadanie wirnika z uzwojeniem HTS

Keywords: superconducting motor, HTS, high volumetric power electrical machines, electrical machines, high power density, testing of HTS coils, HTS rotor, high temperature superconducting coil
Słowa kluczowe: nadprzewodnik wysokotemperaturowy, uzwojenie wirnika.

Introduction

A global reduction of the emissions of pollutants into the atmosphere is needed and a large part of the emissions comes from transportation vehicles, including airplanes due to the nature of combustion based propulsion system. One of the solutions in aircraft sphere is Electric-drive Aero propulsion (EA) based on high efficient electric motors [1].

The overall cost of a passenger flight is assumed to reduce by 40% with EA. Moreover, EA meets the following requirements: 1. Reduction of operational cost, 2. Low emissions of pollutants. 3. Low noise. However, conventional machines exhibit output power densities typically lower than 1 kW/kg and have reached their optimum in terms of performance, leaving a little room for further improvement [1].

On the contrary, superconducting electrical machines could possess extremely high specific parameters such as power density (kW/kg) and volume power (kW/m3) [2,3]. That is why superconducting rotating machines are destined to play a key role as the enabling technology for the EA. So superconducting motor smaller and lighter than a gas turbine with equal power that can be potentially built, which makes EA possible [1].

The most promising superconductors for application in electrical machines are high temperature superconductors (HTS) as they can transport higher current with much less loss than normal metal conductors when they are operating in a superconducting state. Specific parameters of electrical machines have a strong dependency from critical parameters of applied superconductors. It is known that critical current of the coil is lower than critical current of the tape which it is made of [4]. Besides, the external magnetic field also decreases critical current of HTS.

The integration of high temperature superconducting materials in power systems is still quite limited. The reasons are not only related to the technical constraints of realization but also to the high sensitivity of such materials to the electromagnetic environment. Even if a lot of work has been done on the characterization of superconducting elements (pellets, tapes, etc.), the transition from the element to the system is not trivial, because the behaviour of an isolated element can be quite different when it is integrated into a system [5]. Characterization at the system scale is thus necessary which makes the determination of properties of HTS windings during development and producing machine crucial. In this paper manufacturing and testing of HTS field coils and assembled rotor of fully HTS machine cooled with liquid nitrogen are described.

HTS coils

The rotor consists of 6 HTS coils. They are made of American Superconductor (AMSC) 2G tape, wire dimensions (with insulation) are 5x0.5mm. This tape has high critical current and provides good mechanical properties due to large thickness of the substrate. The inner radius of HTS coil is 10 mm, the axial length is 220 mm.

Coils were compounded by «Loctite Stycast 2850»[6] during manufacturing. This compound has good properties in the liquid nitrogen (LN) temperatures and application of it does not cause delaminating of tape. We used a compounding technique to avoid vibration of layers of the coil during operation in an electrical machine and under AC current. Stycast resin was inflicted on each layer during manufacturing, providing secure bonding between layers.

Brass terminals are used as current leads. Potential taps are soldered on maximum allowable distance from current inputs to eliminate end effects. Parameters of each coil are summarized in the Table 1. HTS coils were made according to the technology of double pancake and have racetrack form. The carcass of coils is made of PLA plastic and produced with 3D-printing technology. Figure 1 shows the construction and appearance of coils. One of the advantages of details made using additive technology is low weight. Metal 3d-printed details could possesses an extreme decreasing of the weight of electrical machines but it is expensive technology today. To decrease cost and increase quality and reliability of metal 3D-printed details special techniques should be used [7]. It could be seen that coils represent a composite structure. The calculation of mechanical and thermal conditions of such structure during operation in an electrical machine is a very complex task and could be solved only using a multidisciplinary approach [8].

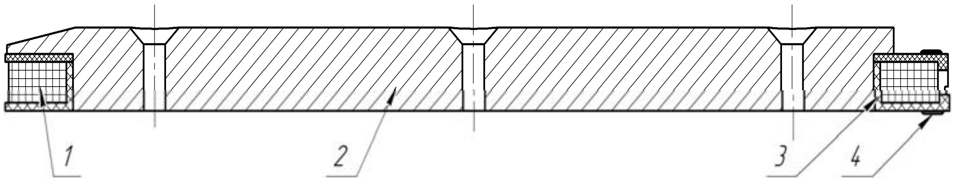
The special test bench was used for testing (Figure 2) [9]. It consists of a computer, extension module, programmable current source, sensors, oscilloscope and cryostat. DC and AC test of HTS coils and other devices can be performed. Keysight Technologies (Agilent) 6680A used as a current source. It has 875 A maximum current and has an external control of output waveform. The current sensor consists of non-inductive resistors connected in parallel, total resistance is 1mOhm, total inductance is less than 1μH. The extension module is used to manage form and amplitude of current source output.

Table 1. Parameters of rotor coils

Parameter	Value
Wire	AMSC
Width, mm	5 mm
Type	Double pancake
Insulation	Kapton
Length of wire, m	37.8
Number of turns	68
Coil height, mm	10

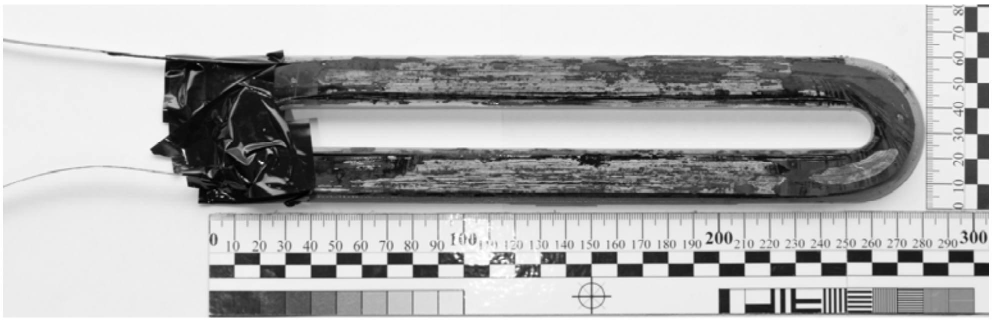
Volt-ampere characteristic of the short sample is shown in Figure 3. It can be seen that critical current of tape is 103 A at 77K under self-field using 1μV/cm criterion.

Each coil was tested in LN with normal conditions for 3 times and critical current was determined. Besides coils were heated up to 300K (room temperature) between each test. There were no cores installed into coils during tests. An example of volt-ampere characteristic of one coil is shown in the Figure 3. Criterion of 1μV/cm was used for the determination of critical current. Critical current for all coils is higher than 60A (see Table 2) and complies with design value, inductance is equal and close to 1 mH. Degradation of critical current in comparison to tape critical current is connected with small bending radius and magnetic field distribution in the area of the coil. It is important to note that there was no degradation of critical current after 3 times testing and thermal cycling.



1 – HTS coil, 2 – core, 3 – carcass, 4 – current lead

a)



b)

Fig. 1. HTS rotor coil: a) – construction scheme, b) – outer view (without core and brass terminals)

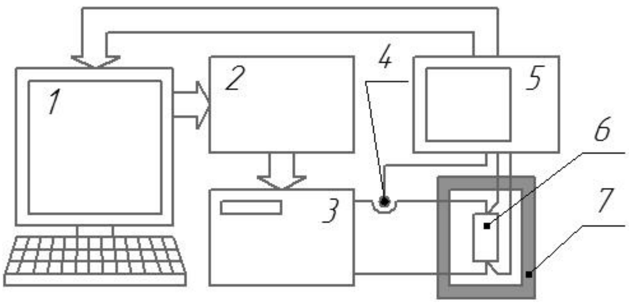


Figure 2. Test bench: 1 – computer, 2 – extension module, 3 – current source, 4 – sensor, 5 – oscilloscope, 6 – coil, 7 – cryostat.

Table 2. HTS coils critical current

Coil	Critical current, A	Inductance, mH
№ 1	64.6	1.16
№ 2	64.1	1.2
№ 3	63.3	1.14
№ 4	63.4	1.17
№ 5	65.7	1
№ 6	65.2	1.14

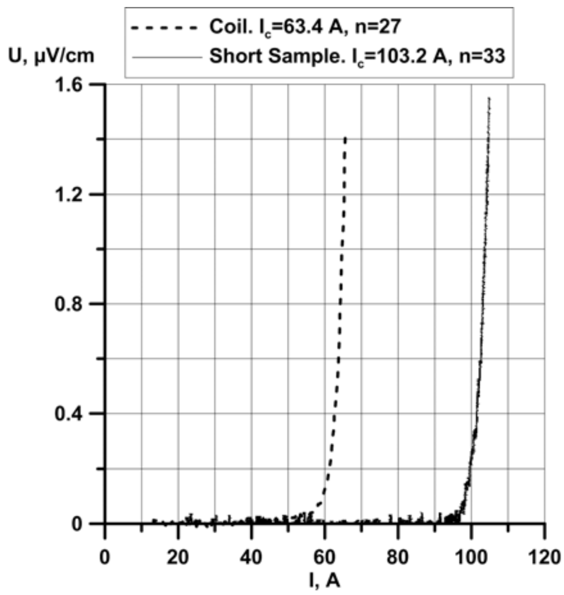


Fig. 3. Volt-ampere characteristic of HTS coil

Rotor winding

Rotor has salient pole construction and its winding is represented by 6 coils connected in serial (see Figure 4a). It was assembled after coil individual tests were carried out. The electrical connection between coils is made by copper bus instead of superconductor for several reasons. Firstly, the interconnection between coils in the rotor is short. Secondly, thin HTS tape could be damaged during mounting and soldering at a cramped space between coils. Thirdly, the critical current could be lower in this case due to vibration and mechanical stress of HTS joints during rotor operation, so, inappropriate complicated techniques should have been developed.

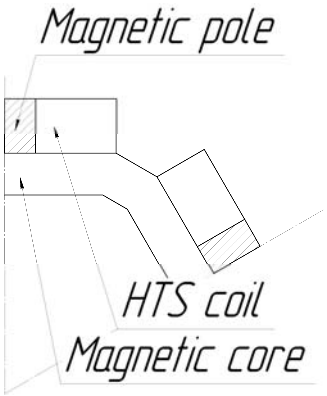


Fig. 4. Scheme of the rotor with HTS coils

The model and outer view of the rotor are shown in Figure 5. Main parameters of the rotor are summarized in the Table 3. In contrast to the usual magnetic systems, in superconducting ones the permissible deformations and stresses are determined not only by the corresponding strength and stiffness limits, but also depend on a number of factors related to the stability of the superconducting state. When working in the windings of electric machines, the HTS coils absorb centrifugal forces during rotation of the rotor, as well as electromagnetic forces arising due to the presence of strong magnetic fields. In addition, low operating temperatures invoke thermal stresses in the structural elements of the machine, especially when it is thermally cycled. In this case development and production of the cryogenic rotor is a more complex problem in comparison to a conventional one [8].

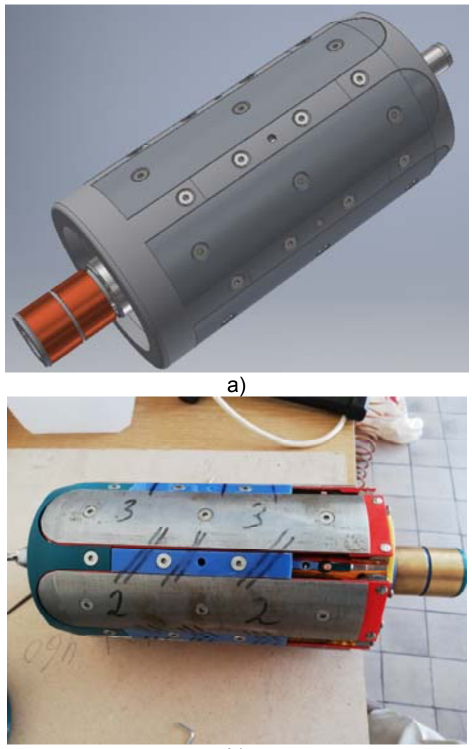
Table 3. Parameters of HTS rotor

Parameter	Value
Outer diameter, mm	150
Length, mm	250
Weight, kg	16
Number of poles	6
Nominal operating current, A	40

The developed rotor consists of ferromagnetic core and poles made of ferromagnetic (30HGSA type) steel, HTS coils, wedges and covers. Rotor shaft consists of three parts – core, left half-shaft, right half-shaft. This construction allows changing parts of the shaft to provide different magnetic circuit schemes. Hollow shaft is filled with LN which goes out from it under the influence of centrifugal forces. Also, the rotor has slip rings for connection with an outer circuit. Technically, the important role of the pole shoes (coil covers) is to maximize the flux linkage between the rotor and stator, namely, at the air gap, as well as to guide and fix the HTS coils from the centrifugal force during rotation. To provide cylindrical construction of rotor and, thus, decrease hydraulic resistance during rotation in liquid nitrogen, special wedges and covers are used. They are made of 3D-printed PLA plastic.

Assembled rotor was tested in LN using the same test bench (see Figure 2). Figure 6 represents results of testing: voltage, current and power consumption time-dependency.

Supply current was increased from 0 to 45 A during 90 s. So input speed was 0.5 A/s. It could be seen that during the first 30 s transition process takes place due to the inductance of the winding. Linear increasing of losses power can be explained by the active resistance of soldered contacts and copper connections between coils. But the value of losses is rather low and could be eliminated by a negligible rise of liquid nitrogen flow through the machine. Figure 7 shows that the critical current of winding is 44.5A for 1 μV/cm and 46.5 A for 10 μV/cm criteria.



a)

b)

Fig. 5. Rotor with HTS winding: a) – model, b) – outer view

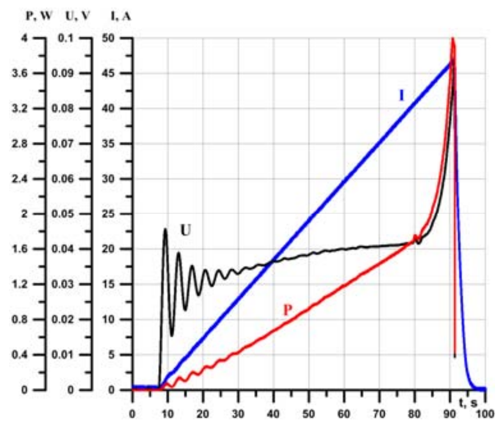


Fig. 6. Results of testing of rotor winding

Degradation of critical current is connected with two aspects. The first is implementation of ferromagnetic cores. The second is influence of coils on each other. These factors increase magnetic field density in the area of HTS coils. It is known that superconductors have three critical parameters: temperature, current, magnetic field density. Particularly, if temperature is constant, critical current decreases in presence of an external magnetic field. The influence of the magnetic field and temperature on the critical current of HTS-2G tape is shown in Figure 8 [10].

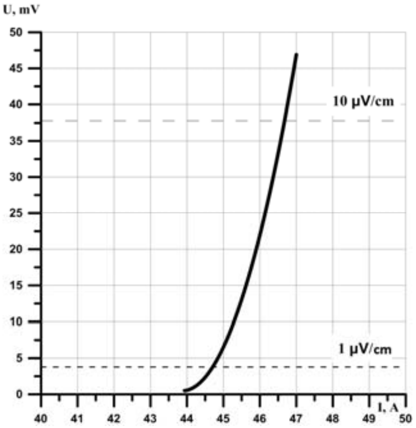


Fig. 7. Volt-ampere characteristic of HTS rotor winding

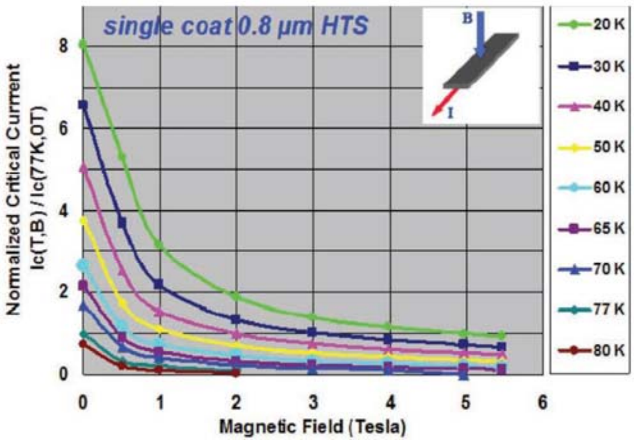


Fig. 8. Effect of magnetic field and temperature for the critical current

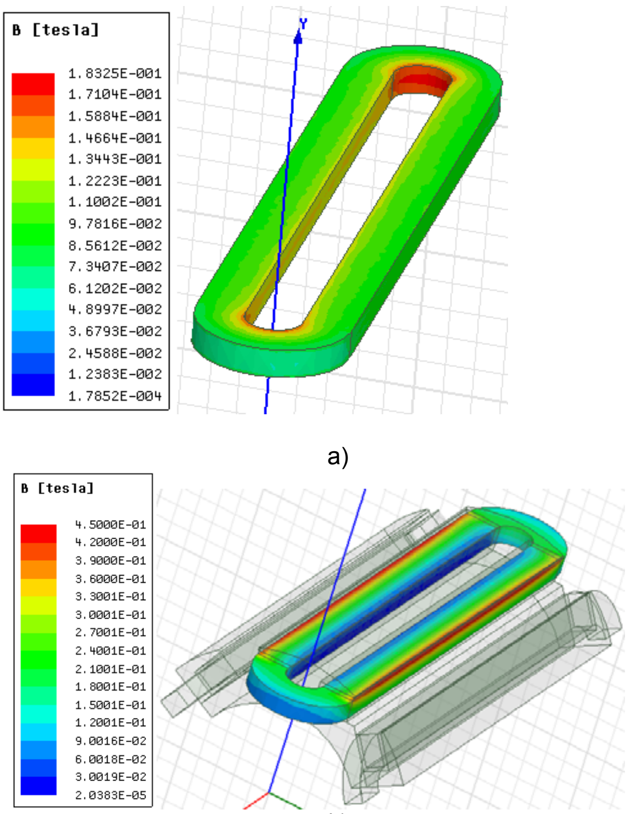


Fig. 9. Magnetic field distribution: a) separated coil; b) assembled rotor

Distributions of magnetic fields produced by separated coil and in the assembled rotor are shown in Figure 9. One can see that for separated coil maximum value of magnetic flux density is 0.18 T in the inner radius of the coil. But for assembled rotor the maximum is 0.45 T in the linear part of coil due to the presence of ferromagnetic cores. According to Figure 8 for 0.45 T critical current is 45A. That is equal to the measured value. It means that for produced coils and rotor this value of critical current matches theoretical maximum.

Conclusions.

Determination of critical parameters of HTS tapes and devices (coils, windings) has critical influence on output parameters of electrical machines. The paper considers testing results of HTS tape, double pancake racetrack HTS coils and assembled rotor. Special test bench is developed allowing to provide DC and AC testing. It is shown that critical current is 103 A for short sample, 60 A for separated coils and 44.5 A for assembled rotor using 1μV/cm criterion. So the paper reflects the change of critical current for different levels of the HTS system (tape, coil, winding). It is important to note that there was no degradation of critical current after 3 times testing and thermal cycling of coils. Using this experience, we could choose the operating current of HTS windings during preliminary calculations of electrical machines and devices.

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