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Transposed-Cable Coil & Saddle Coils of HTS for Rotating Machines: Test Results at 30K

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***Abstract*—We have manufactured and tested new HTS coil configurations in order to extend the range of rotating machines to which HTS tapes can be applied. The rotors of large utility generators require operating currents of several kA, which can be achieved by connecting several HTS tapes in parallel in a transposed cable. Design of a generator poses questions on winding technique for the coils, cooling technique at the required operating temperatures around 30K, and VI-relation and stability of such coils. These questions were addressed by winding a test coil using 31m of transposed cable comprising 500m of BSCCO tape and testing it at 30K.**

Smaller generators coupled to gas turbines have to work at many thousands of rpm. The high g-forces and need for compactness make it necessary to place the rotor coils as close as possible to the shaft, which requires coils with 3D-bent heads, like in accelerator dipoles. We have produced this type of coils with BSCCO tapes for the first time. After developing a winding technique using simple tooling, 700m of BSCCO tapes were used to manufacture two 3D demonstrator coils, which were tested at 30K as well. We describe winding methods, cooling technique and test results for both types of coils.

***Index Terms*—superconducting coil, transposed cable, saddle coil, heat pipe**

I. INTRODUCTION

SEVERAL groups worldwide are developing rotors with High-Temperature Superconducting (HTS) field windings, for various kinds of synchronous electrical motors and generators [1], [2], [3], ranging from compact high-rpm motors and generators to high-torque drive motors for ships and large utility generators. HTS technology enables higher efficiency, smaller volume and weight, and better dynamic behavior. Each type of machine has special requirements for the HTS windings. This paper deals with the high-current coils required for utility generators, as well as saddle coils which may be required for compact high-rpm machines. YBCO coated conductors are presently becoming available in long lengths and offer benefits for future machines. However, until now most experimental coils and all large-scale demonstrators have been made with BSCCO/Ag multi-filament conductors, whose performance has been continuously improved. The test coils described in this paper were manufactured using Bi-2223/Ag tapes, with 121 non-twisted filaments and an AgMg sheath, produced by European High-Temperature Superconductors (EHTS), Alzenau, Germany.

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II. HIGH-CURRENT COILS FOR LARGE GENERATORS

A. Requirements

The field coils in large utility generators need a large number of Ampere-turns. Furthermore for fast control of the output power, the current has to be adjusted quickly at reasonable voltage, which means low inductance. Therefore operating currents of several kA are required for these windings. These currents cannot be carried safely by a single HTS tape, so a multi-tape conductor is required. Such conductors have been developed by several groups, originally for application in HTS transformers [4], [5]. They usually have the form of so-called Roebel cables, where the tapes are fully transposed. For manufacturing these cables, we found that the optimum tapes are those with an AgMg tube as well as an Ag tube surrounding each filament, which reinforces the matrix: so-called duplex tapes [6].

New aspects in winding coils for large utility generators are:

- the multi-tape conductor
- unusually large coils (several m long)
- rectangular coil shape, which necessitates compressing the winding package from the outside at the straight sections.

The cooling system will comprise cold gas circulating in tubes. Its lay-out requires information on the thermal conductivities $\lambda_{//}$ and $\lambda_{\perp}$, parallel and perpendicular to the tapes, in such windings at operating temperature. The test coils were designed to provide this information as well.

B. Manufacturing

Roebel cables are manufactured as described in [6]. Properties of the final 50m length of cable manufactured in this project are listed in Table I. The 66% fill factor of tapes in the cable is due to the tape insulation and the cable bandaging. Due to the cable self-field, its actual critical current at 77K is lower than the “design” critical current, which is just the sum of the critical currents of the 13 tapes. This self-field effect can be calculated and in this case there is good agreement between calculated and measured critical current of the cable. We cannot test the cable itself at 30K in relevant background fields. However, the calculated critical currents in the table meet the project goals and are approaching the values required for generator windings.

TABLE I PROPERTIES OF MULTI-TAPE ROEBEL CABLE

Single tape	**EHTS Insulated**
Matrix / Sheath material	Ag + AgMg / AgMg
Width / Thickness isolated	4.02mm / 0.30mm
Critical current / N-value	78.5A / 23 (77K / 0T)
Cable comprising	**13 tapes**
Total length produced	50m
Width min. / max.	7.98mm / 8.35mm
Thickness min. / max.	2.06mm / 2.88mm
Transposition length	3.51m
Fill factor of tape in cable	66%
"Design" critical current I_c	13 x 78.5A = 1020A (77K / 0T)
Calculated I_c (cable field)	640 A (77K / 0T)
Measured I_c / N-value	643 A / 15 (77K / 0T)
Calculated I_c at operating conditions	1200 A (30K / 1.5T)
	990 A (25K / 4T)
Critical axial pulling force	1500 N

A race-track coil #1 was produced to test the winding of rectangular coils. During winding and before impregnation, the straight sections were compressed using straight pressure pieces. The coil properties are listed in Table II. The finished coil is displayed in Fig. 1. This coil was designed for test only in a liquid-Nitrogen (LN_2) bath at 77K. This coil was wound with an earlier-type cable having 401A critical current at 77K. The coil critical current of 335A is lower due to the coil self-field, as expected.

TABLE II PROPERTIES OF RACETRACK TEST COIL #1

Number of turns / layers	6 / 1
Outside length of winding	1250mm
Outside width of winding	430mm
Length of cable used	17.3m
Cable I_c at 77K in self-field	401A
Coil I_c at 77K in self-field	335A

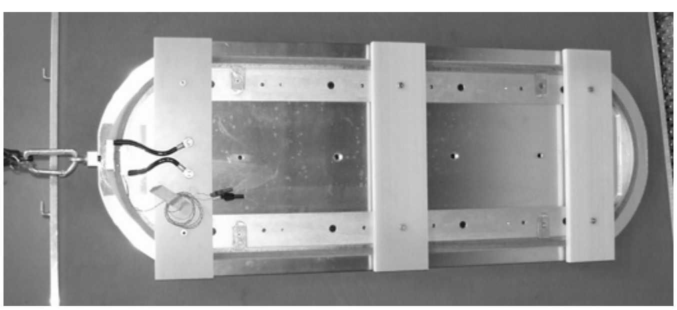

Fig. 1. Racetrack test coil #1, mounted on a supporting plate. The winding length is 1.25m. This coil is designed for a test at 77K only.

A double-pancake coil #2 was designed and manufactured for test at 30K as well as 77K. We used the cable described in Table I. The main coil properties are listed in Table III. The first half-coil (A) is wound and impregnated with epoxy resin between two Plexiglas disks, which are removed after hardening. The second half-coil (B) is then wound between the first half-coil and a Plexiglas disk. The current leads are on the outside; the two half-coils are connected by a copper bridge piece at the inner diameter. The finished coil is displayed in Fig. 2. The coil can be cooled to 30K by liquid Neon in a single turn of copper heat pipe, which is interrupted in order to prevent eddy currents in the loop during ramping. For better thermal contact to the winding, this tube is soldered together with a 0.2mm copper sheet, which is also interrupted. The assembly of heat pipe and sheet is then glued to the winding upper face using Stycast (= Epoxy resin filled with Al_2O_3 powder for better thermal conductivity). The critical current in an LN_2 bath at 77K is lower than expected by about 40A or 10%: see also Fig. 4.

TABLE III PROPERTIES OF DOUBLE-PANCAKE TEST COIL #2

Number of turns / layers	40 / 2
Inner / outer winding diameter	200mm / 297mm
Length of cable used	31.2m
Cable I_c at 77K in self-field	643A
Coil I_c at 77K in self-field	363A
Coil I_c at 30K in self-field	1816A

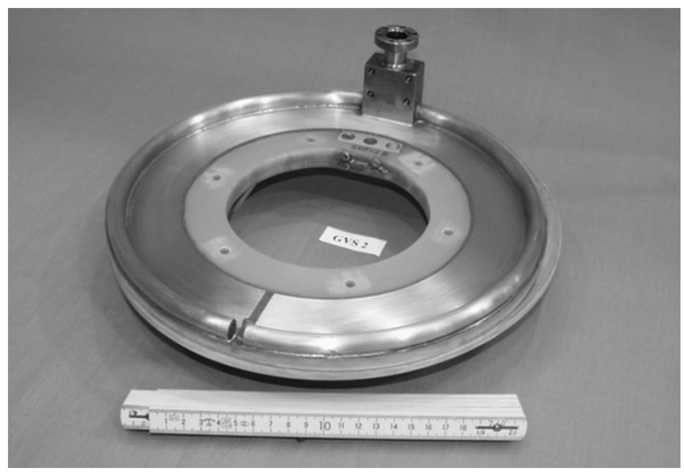

Fig. 2. Double-pancake test coil #2. The windings are below the copper sheet and copper tube, which is part of a heat pipe system for liquid Ne to cool the coil to 30K. The ruler below is marked in cm.

C. Coil test rig

For the testing of HTS coils at temperatures around 30K, a special test rig was designed and built [7]. The coil is placed inside an outer vacuum vessel and surrounded by a copper heat shield with super-insulation. The coil space inside the shield can be up to 1.40m tall, with diameter 0.50m. Fig. 3 shows the lid of the vacuum vessel and the top of the shield. A single-stage GM-type refrigerator (CryoMech AL330) provides cooling power ≈100W at 30K and ≈75W at 25K. This power is used to condense Neon gas in a double condenser. The liquid Neon flows downward in heat pipes to evaporators, the Neon gas returns in the same pipe. Heat-pipe #1 has its evaporator at the top of the shield, which cools also the current leads. Heat pipe #2 can be connected to an evaporator coupled to a test coil. The condenser is kept at a fixed temperature with heaters connected to a temperature controller. Of course all other cold parts have temperatures slightly above this fixed value, dependent on local power dissipation and thermal conductances.

At the target current of 2kA, metal current leads from room temperature would give too much heat load at 30K for a single refrigerator. HTS leads would take much space and need extra cooling at their warm ends. The problem is solved by surrounding the current-lead tops with small LN_2 vessels: see Fig. 3. These need to be filled only for currents larger than 500A; the evaporating LN_2 then reduces the heat load at the 30K level. For the current-lead sections from the bottom of these vessels to the top of the shield, there are two versions:

- copper strips optimized to carry 2kA from 77K to 30K, for multi-tape conductor coils
- brass strips optimized to carry 300A from 300K to 30K, for single-tape coils (no LN_2 needed).

The resistance of the cold parts is about 35μΩ. The test rig can carry 1700A DC indefinitely and 2000A for a few minutes: long enough to measure coil voltages.

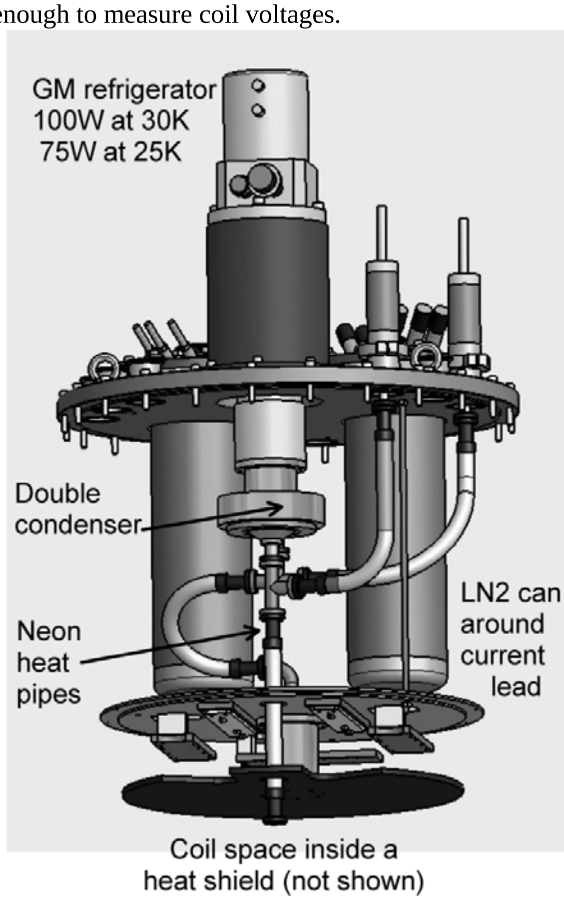

Fig. 3. Top part of the test rig for HTS coils at 30K, shown without the outer vacuum vessel and heat shield. The diameter is 0.70m. Cooling power is provided by a CryoMech AL330 refrigerator and transferred to the coil and the heat shield by two independent Neon heat-pipe systems. The current leads are anchored at ≈30K at the shield top; their tops can be additionally cooled by LN2 for a current capacity of 2kA at 30K.

Cool-down of the test rig takes about 9 hours when empty, longer with a large coil. There are 174 voltage feed-throughs which can be used for voltage taps, heaters and thermometers.

D. *Test of coil #2 at 30K*

The DC V(I) curves measured in test coil #2 in its self-field at various temperatures are displayed in Fig. 4. The voltage taps were not placed on one of the 13 HTS tapes in the cable, but on the copper current-lead pieces. The measured voltage also includes the voltage over the copper bridge between the half-coils. This causes a resistive foot of about 0.1μΩ at 30K. The figure gives the set-point temperatures at the condenser, as well at the highest temperatures in the coil, which are always measured at the current leads. The figure indicates measured critical currents, obtained by a fit around the 1μV/cm level, which is indicated by a horizontal line. The slope of the V(I)-curves is indicated by the so-called N-value, which is about 13 for coil #2.

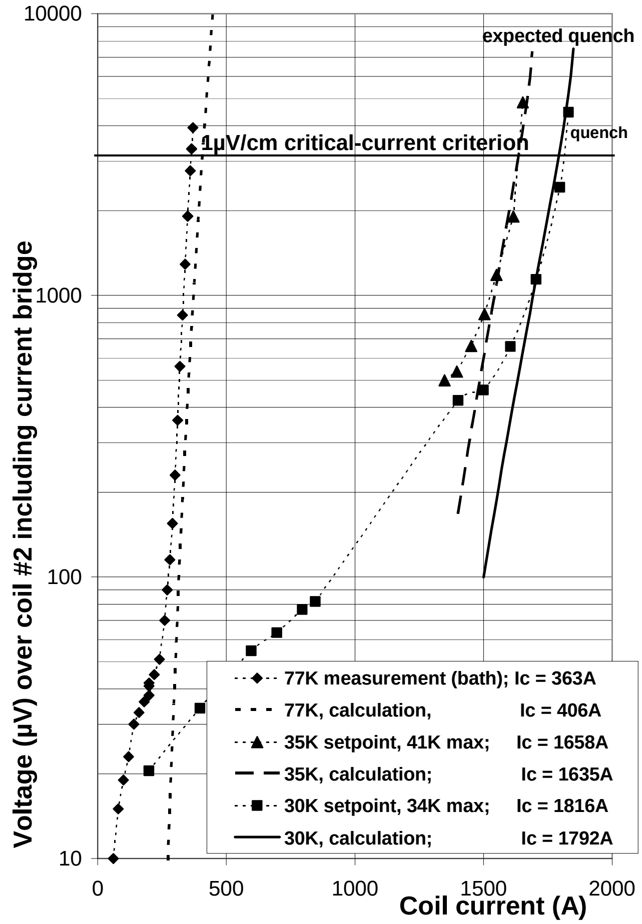

Fig. 4. DC V(I) curves of coil #2 measured at various temperatures, and compared to model calculations. The critical current is slightly lower than expected at 77K, but at 30K and 35K there is good agreement.

The expected critical currents and V(I)-curves (displayed as lines in Fig. 4) are calculated using a software tool described earlier [9], [10]. The tool describes the $I_c(B,T)$ dependence of HTS tapes, based on a small number of fit parameters obtained by measurements on a tape sample. The magnet-field distribution in the coil is calculated and used to obtain the local I_c-values, overall voltage and power dissipation for DC as well as AC currents. The V(I)-curves of coil #2 at 30K and 35K above the resistive foot are well described, the deviation in I_c is only a few %. This is a further indication that the cabling, coil manufacturing and cool-down has not damaged the Bi-2223 tapes.

Alternating currents up to 25Hz and 250A amplitude were also applied to coil #2. These were combined with direct currents up to 1500A, in order to approximate the situation in the field winding in a generator whose output power is continuously adjusted. (In a generator field winding, the frequencies would be 0.1-0.5Hz, but the magnetic fields will be much higher than in this small coil.) The alternating currents and fields cause AC losses in the HTS tapes, as well as eddy-current losses in the cold copper parts: current-lead blocks, cooling sheet, heat pipe and heat shield. In this set-up it is not possible to measure these loss components separately. Only their sum is measured, either electrically (using a Wattmeter attached to voltage taps over the coil) or calorimetrically (recording the changes in heater power by which the temperature controller keeps the condenser at a fixed temperature). There is good agreement between both measurement methods. A typical result is displayed in Fig. 5. The power loss increases nearly linearly with frequency, indicating that most of it is caused by hysteresis in the superconductor. The increase caused by the DC component originates completely in the superconductor; the resistive loss in the current leads has already been subtracted. This loss increase caused by DC is clearly smaller than predicted by the software tool as described in [10]. In these tests the coil was always thermally stable.

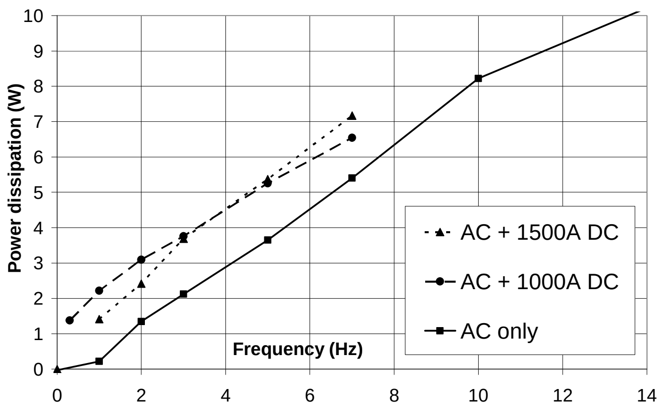

Fig. 5. Power dissipation measured calorimetrically in test coil #2, at 30K set-point temperature, with alternating current of 250A amplitude, triangle shape, at various frequencies, added to a DC component.

Finally, during DC and AC tests, the temperature differences between various positions in the coil were related to the dissipated power, in an attempt to obtain the heat conductivities $\lambda_{//}$ and $\lambda_{\perp}$ in the winding at operating temperature. These are different from conductivities in a random stack of HTS tapes, due to the regular stacking of the tape cross-sections in the multi-tape cable and the bandaging around the cable turns. We find $\lambda_{//} = 1.7\pm0.2$ W/m·K, but no consistent value for $\lambda_{\perp}$ could be obtained.

III. 3D Saddle Coils for High-RPM Machines

A. *Manufacturing*

Generators directly coupled to gas turbines, or motors coupled to compressors, have to work at high rotating speeds of >5000rpm. Because of the high g-forces, compactness is required. For this reason, as well as for efficient use of the HTS material, the coils should be placed as close as possible to the drive shaft. A possible geometry based on elliptical coils was published earlier [8]. However, ideally only the coil heads should be bent over the shaft, which results in a three-dimensional (3D) saddle-shape coil: see Fig. 6. The coil shape is similar to the low-T_c superconductor coils used for accelerator dipoles, whose heads also have to bend over the beam pipe. The HTS coils comprise a single tape, which requires many turns.

We have produced these 3D coils without complex and expensive 3D winding machinery, for the first time with HTS. First the tape is dry-wound in-plane with a usual winding machine. Then the coil is bent onto a tube of the required shaft diameter, by pressing. The result is shown in Fig. 6. The winding is impregnated with Epoxy resin. After hardening, the coil can be removed from the former and is then self-supporting: see Fig. 7. For a real machine, a series of coils of increasing diameter might be produced and stacked together.

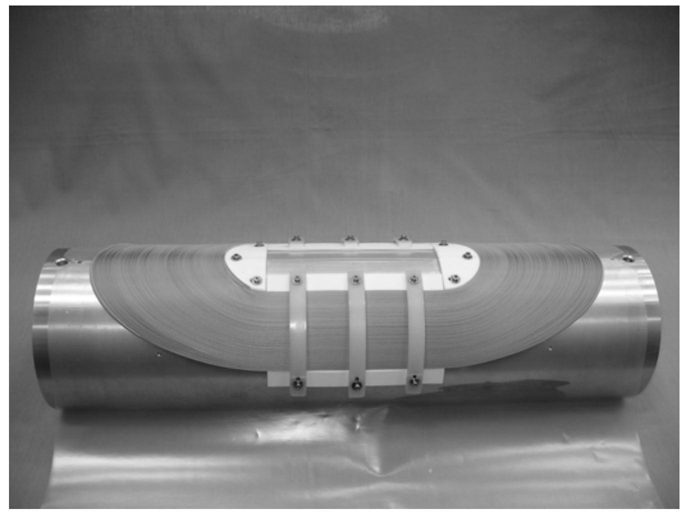

Fig. 6. Saddle coil just after 3D bending, before impregnation, on the bending former.

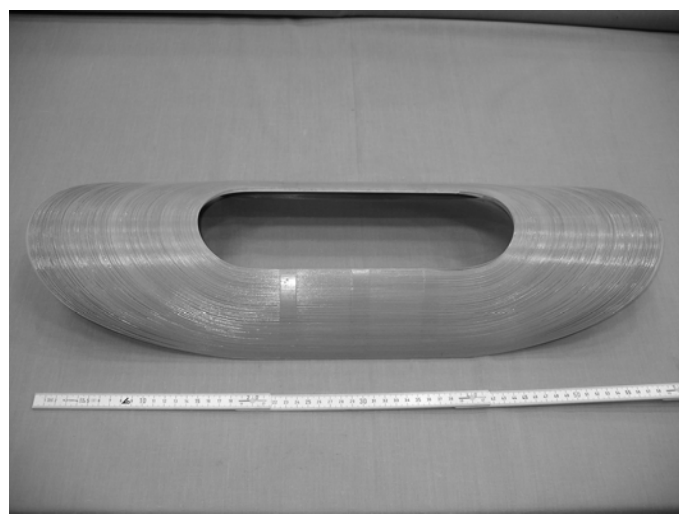

Fig. 7. Saddle coil after impregnation, removed from the former, still without current leads. The ruler is marked in cm.

During this process the HTS tape is subject to torsion and to bending in the "good" direction (out-of-plane) of the tape. These deformations should be only elastic, so the coil heads should not be too short. At the coil heads, the tapes are tilted inward. From the inner to the outer turns, this tilt increases. In order to allow the movement of the tapes during the 3D-bending process, distance pieces have to be placed between the tapes during winding. The distance pieces are removed before bending the coil. The required number, lengths and thicknesses of the distance pieces are calculated using a special software tool.

A series of “learning” coils was manufactured, one of which was tested at 30K [7]. Finally we produced two demonstration coils of a size and geometry realistic for high-rpm machines. The coil dimensions and other properties are listed in Table IV. Both coils (A and B) are identical in dimensions and number of turns. Their critical currents at 77K are similar and are as expected, again based on the coil calculation tool described in earlier [9], [10]. The critical current of each coil is decreased by less than 0.5% when the other coil is added in a dipole configuration. This is because the magnet field of coil A is then mostly oriented parallel to the tapes at the position of coil B.

TABLE IV PROPERTIES OF SADDLE-COIL PAIR #3

Inner diameter (“shaft diameter”)	199mm
Length of straight sections	200mm
Coil length without current leads	610mm
Angle on shaft covered by coil	156°°
Coil aperture angle (“pole angle”)	58°
Number of turns per coil	310
HTS tape length per coil	330m
Tape I_c at 77K in self-field	98.3A
Calculated coil I_c, 77K, self-field	50.8A
Measured coil I_c, 77K, self-field	50.8A / 50.0A
Inductance of coil pair	81mH
Dipole field at 30K, 180A	342mT

For the test at 30K, the coils A and B are combined into a dipole, called in this paper #3. For cooling the coils, copper sheets are soldered together with copper heat pipes, and are attached to the straight sections of each coil using filled Epoxy. The coil heads are cooled only by heat conduction along the BSCCO/Ag tapes. The coils are assembled on GRP supporting pieces and clamped with stainless-steel strips against the Lorentz forces: see Fig. 8. The current leads of the coil are connected by flexible Litz wires to copper strips, which are thermally anchored to the heat-pipe system. Both coils are connected in series. During normal operation, all four heat pipes are filled with liquid Neon up to the distribution block; the gas bubbles through. The complete assembly as shown in Fig. 8 is suspended in the 30K test rig: see Fig. 3.

B. *Test at 30K*

After the first cool-down, coil B was found to be no longer superconducting. Examination at room temperature showed a crack between one of the cooling tubes and the coil straight section. Probably the fast cool-down and contraction of the cooling tube could not be followed by the winding, which was still almost at room temperature. Most likely the outer turns of HTS tape have been damaged by the cracking. The cool-down was repeated at a slower rate, with only coil A connected to the current leads. This coil was still superconducting.

The DC V(I) curves of coil A for various temperatures are displayed in Fig. 9. The figure indicates the set-point temperature at the condenser, as well as the highest temperatures in the coil, which are always measured at the current leads, despite their thermal anchoring. The upper points of each V(I) curve were measured in pulsed mode, because the coil is thermally unstable when these currents are applied continuously.

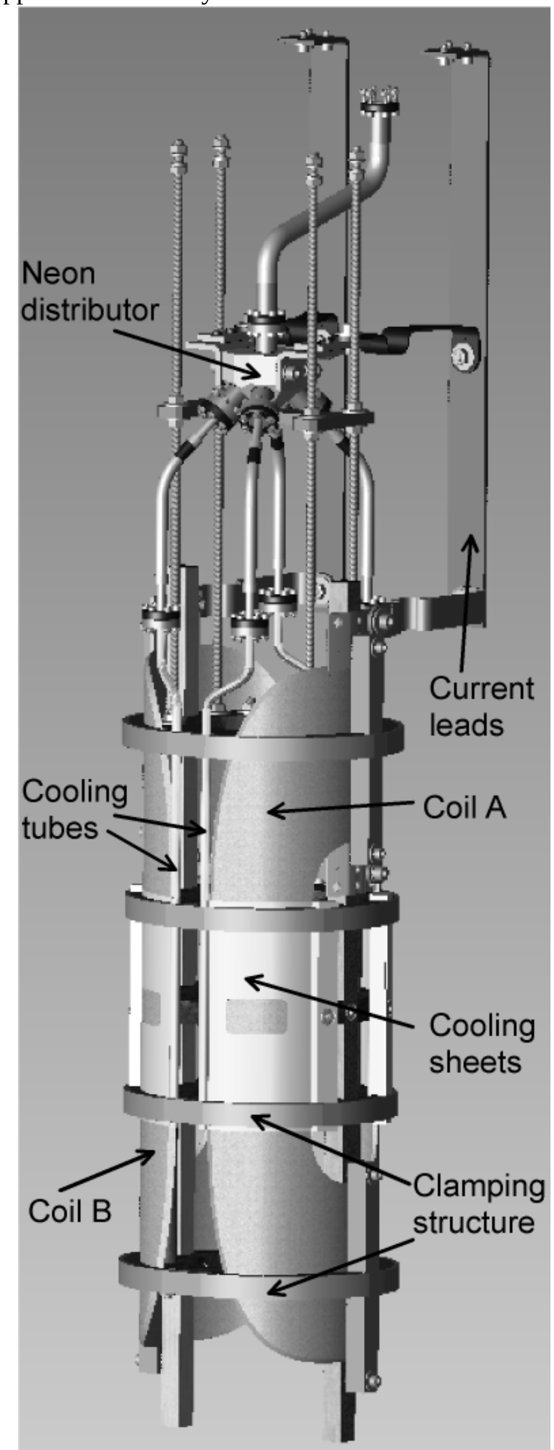

Fig. 8. The pair of saddle coils mounted in the 30K test rig, outfitted with current leads, cooling sheets, cooling tubes, clamps and supporting pieces.

The measured critical currents are listed in the figure. They are obtained by fitting the data around the 1µV/cm level. The N-values are between 20 and 25. The target operating current of 180A can be applied continuously at all these temperatures, at a voltage level below 0.1µV/cm.

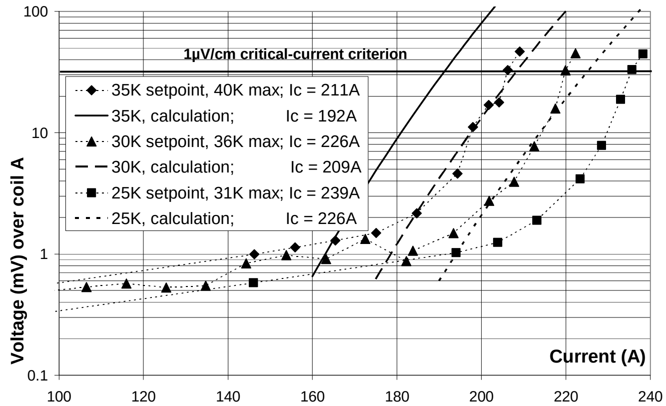

Fig. 9. DC V(I) curves of coil A, measured at various temperatures and compared to model calculations. The critical current is always higher than calculated.

The coil calculation tool as described in [9], [10] was used again to calculate expected V(I) curves. The tool is essentially 2D: it is able to evaluate circular coils and the straight sections in racetrack or saddle coils. In coil #3 the straight sections are less than half of the winding volume. The distributions of magnet field and temperature in the coil heads are unknown a priori. The magnet fields will be lower than in the straight sections, the temperatures will be higher because the coils are cooled only at the straight sections. Therefore the calculations results may be inaccurate. The calculated V(I) curves are displayed as lines in Fig. 9. The measured critical currents are always about 10% higher than the values predicted for the same temperature. This, together with the good N-values, indicates that the HTS tapes in coil A have not been much degraded by the coil manufacturing and cool-down.

At a set-point temperature of 30K, a direct current of 217A can be carried indefinitely by coil A. This is the maximum stable current, permitted by the properties of the HTS and the lay-out of the cooling system. At slightly higher currents, the voltage first increases slowly, then the increase accelerates until the current is turned off or the coil quenches. The voltage increase over time is displayed as lines in Fig. 10. In these measurements the current was automatically switched off at a voltage level of 80mV. This was low enough to prevent quench damage to the coil.

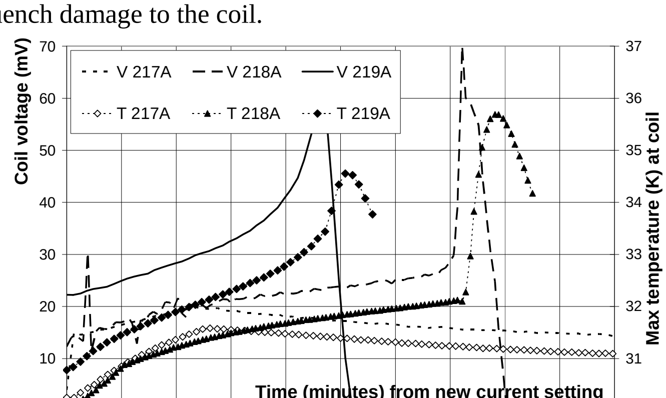

Fig. 10. Time-dependence of the maximum temperature at the inside of the coil head, and of the voltage over coil A, at currents just below and just above the maximum stable current, for a set-point temperature of 30K.

Fig. 10 also shows as symbols the temperature measured at the inside of the coil head, which is the warmest spot except for the current leads. At 219A (and at higher currents) the quench is additionally announced by an accelerated increase of this temperature. At 218A the temperature increase does not accelerate, the quench is announced only by the voltage. The quench probably begins somewhere else in the coil, where there are no temperature sensors.

Finally the coil was subjected to alternating currents up to 0.25Hz and 180A amplitude. At this current the total dissipation is about 16W and the coil is still thermally stable. The dissipation occurs in the HTS of coil A due to current and magnet field, in the HTS of coil B due to magnet field only, and in the cold copper parts of the cooling system and the current leads due to eddy currents. The dissipation is clearly higher than the calculated HTS loss for coil A only. The increase in loss brought about by an additional DC component is lower than expected, like in coil #2.

IV. Conclusion

Application of HTS to a larger variety of rotating machines requires new coil winding techniques. Large generators have rotor operating currents of several kA, which are possible with multi-tape conductors. These can be used to wind the required large rectangular coils. Saddle coils for high-rpm machines can be wound in 2D, then bent to a 3D shape and impregnated. Both types of coils were manufactured without large degradation to the BSCCO/Ag tapes. The coils can be ramped at frequencies relevant for rotating machines and still remain thermally stable.

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