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Optimized and practical electrical joints for CORC type HTS cables

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Abstract. Within CERN the development of REBCO-CORC (Conductor On Round Core) type cables is pursued in view of possible application in future detector and accelerator magnets. An important issue is the design and qualification of terminations for connecting CORC cables mutually or to bus-bars. A termination design is envisaged that combines a simple manufacturing process with a lowest possible joint terminal resistance in the few nΩ range at 4.2 K, first for a single CORC cable and subsequently for CORC based Cable-in-Conduit Conductors. The investigation concerns the effect of tapering the CORC cable within the joint to form a staircase like geometry, which allows current to pass more directly from the copper joint casing to the inner REBCO layers of the CORC cable. Simulations have shown a substantial decrease in joint resistance at operating current in the case both CORC cable and joint casing are tapered. The CORC cable and new joint were tested at CERN. In this paper, some details of the new joint design, fabrication process, and model are presented and the results are summarized.

1. Introduction

The CORC (Conductor On Round Core) cable is a new REBCO tape based cable technology. The CORC cable is a flexible round cable that comprises many REBCO tapes wound in multiple layers around a cylindrical wire [1]. CERN is pursuing the development of CORC type REBCO cables in view of possible application in future detector and accelerator magnets. CORC is especially interesting for detector magnets because its design is simple and robust, the cable has a high T_c and cable geometry allows manufacturing of a Cable-in-Conduit type of Conductor of several CORC strands. Furthermore, the cable does not require heat treatment and has good mechanical properties [2]. An important issue in the development is the design and qualification of low-resistive and practical joint terminals. These joint terminals can be used to connect a CORC cable to a busbar or to connect two CORC cables mutually.

In the past, several CORC joint terminals were designed that were either bulky [3] or injected current only via the outer layer into the cable. The electrical contact to the inner layers is poor, due to the Hastelloy substrate within the tape, leading to a relatively high joint resistance and bad current sharing. At CERN a new joint terminal is designed by which current is injected in each layer of the cable as opposed to just the outer layer. This results in a significant decrease in resistance at high currents near to the critical current of the cable. Complimentary, a custom-built Finite Element Model (FEM) is developed to help understanding the behavior of the joints. The model is clearly able to demonstrate the



improvements when comparing the old and new designs, and is used to evaluate and optimize different terminal configurations.

2. Cable and new joint terminal

A 12 meter long CORC cable was manufactured for CERN by ACT for characterization, joint development and the production of the first 6-around-1 REBCO-CORC cable Cable-in-Conduit Conductor. This cable actually is (in 2015) the longest CORC cable ever produced. The cable comprises 38 SCS4050 (4 mm wide and 96 μm thick) Superpower tapes wound in 12 layers around an aluminum core. The aluminum core has a diameter of 4 mm and is increased to 5 mm with five layers of copper tape. The total diameter of the cable is 7.6 mm. This cable is used to test the fabrication method and the characterization of joint terminals.

2.1. Joint terminal design

In the past, the joint terminal comprised a copper casing in which the CORC cable was inserted, after which it is filled with solder material. The solder material is able to flow between the layers since the tapes spring out after the sleeve around the cable is removed. The new joint terminal design features a change to the CORC geometry that leads to a low-resistive path to the inner REBCO layers. The path, created by trimming several layers of tapes into shorter sections, exposes the layers underneath. The assembly is then filled with a solder material, thereby creating a low-resistive path from casing to cable. In this configuration current can flow directly into the lower layers without passing the Hastelloy substrate of the upper layers. Automatically, it follows that the current is distributed more evenly over all layers. The resistance can be optimized for the specific operating conditions of the joint by varying the number of trimmed layers, the length of the trimmed sections and the overall length of the joint terminal. In addition, the copper casing can be machined to create a similar staircase-like geometry that matches the shape of the trimmed cable. This geometry causes an increase of the copper to solder ratio in the joint terminal and thus, a lower joint resistance can be achieved. A schematic view of the original and new design are presented in figure 1.

2.2. Joint production

The tapes in the cable are trimmed by precisely cutting the individual tapes with a sharp precision knife. After cutting the tape, it tends to spring out and thus has to be held in place. This can be achieved by wrapping a thin copper wire tightly around the trimmed layer. The wire can be removed while inserting the trimmed cable section into the casing of the joint terminal. However, for casings with a staged bore closely following the trimmed section this is impossible, since the tapes spring out in the casing and get stuck at the edge of the first machined section. Our solution is to keep the tapes together with a bandage of solder as can be seen in figure 2. The solder adds a few μm to the diameter of the trimmed cable. On

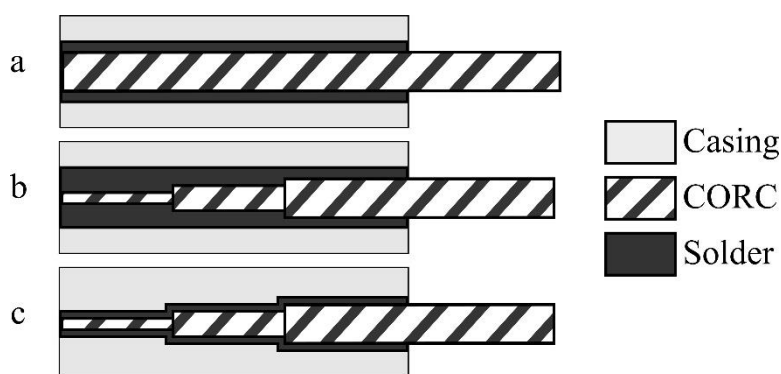


Figure 1. Schematic view of (a) the original joint terminal design, (b) the new joint design with a trimmed CORC cable and (c) the new joint design with a trimmed CORC cable and a staged casing.



Figure 2. Five tapered sections of the CORC cable, each 17 mm in length, held together by a bandage of solder.

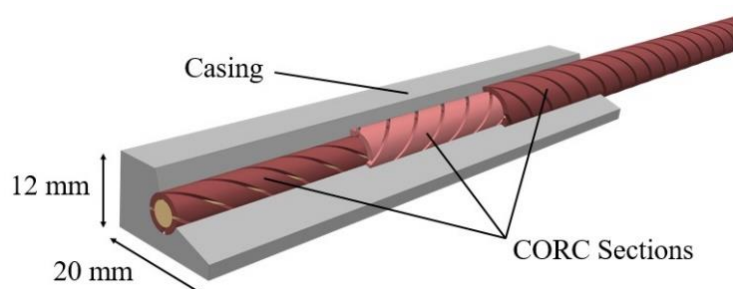


Figure 3. 3D representation of the trimmed CORC cable inside a rectangular copper casing shaped to fit the cable. All voids between the tapes inside the casing are filled with a soldering alloy.

filling the joint casing with solder, the bandage of solder melts and the tapes can spring out as required for achieving minimum resistance.

Two manufacturing methods were tested. In the first method the joint terminal comprises several individual sections each with a different bore diameter. The sections are moved over the cable; each section fitting the different trimmed steps of the cable. The sections are soldered together at the time the casing is filled. The second method uses a single casing covering the entire joint length by which the stepping is achieved with multi-stage drilling. Prototypes of both variations were manufactured. The multiple sections of the first method is more practical to machine, however the second method facilitates easy solder filling and handling after the cable is inserted. Overall the second method is preferred for future joint terminals. A picture of a block shaped prototype joint terminal is presented in figure 3.

Eutectic Sn63Pb37 is used in all joint terminal samples. This solder material has very good wetting properties, maintains good mechanical properties at cryogenic temperature, and with a melting temperature of 183 °C it does not exceed the 200 °C degrees at which REBCO starts to degrade [5, 6]. The casing is attached to an aluminum block, which is fitted with two controllable cartridge heaters and a thermometer to monitor the temperature. Through small holes present in the top surface, non-acid flux and solder can be injected and they allow gas to escape. Both, joint and aluminum block are inclined to facilitate flow and escape of evaporated flux. When solder starts to come out of the first hole, the hole is closed and the filling continues step by step.

2.3. Fabrication issues

Two issues were encountered during joint manufacturing: delamination of the tapes and small gas pockets inside the joint. Delamination is observed in the terminal after cross-sections of the produced terminals were made. About 5% of the trimmed tapes showed slight delamination of REBCO tape. This is an issue because the copper delaminates from the REBCO layer and thus no longer facilitates an optimal electrical connection between solder and REBCO. Delamination is caused by the soldering temperature working on the Hastelloy layer that wants to spring out while the copper still is firmly attached to the layer below. The Hastelloy layer in the next generation of REBCO tapes will have less thickness and thus less delamination is expected. The second issue concerns small gas pockets observed

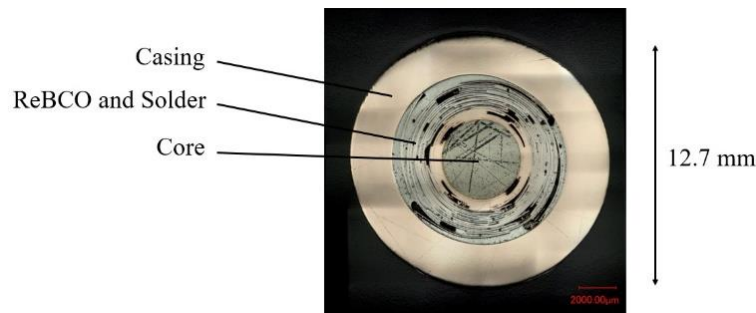


Figure 4. Cross-section of a cylindrical joint terminal with gas pockets (black areas) visible.

between the tapes as shown in figure 4. The number of gas pockets can be reduced by increasing the inclination angle during filling and increasing the number of holes for gas to escape.

2.4. Experimental joint terminals

The two joint terminals are manufactured and mounted on a 1.8 m long CORC cable. This cable and its joints are characterized in the FRESCA cable test facility [6]. The terminals are 200 mm long and follow the new design. The cable ends are trimmed into twelve 17 mm long sections. The joint casing comprises three OFHC copper cylinders with each a different bore diameter that matches the shape of the trimmed CORC cable. Each cylinder has two small holes for solder filling and degassing.

3. Joint model

A custom-built joint model is developed for simulating and evaluating joint terminal configurations. The model is based on a network of resistances that includes both linear resistances (solder and casing) and non-linear resistances (REBCO tapes) and assumes a steady state current. A schematic representation of the resistances network is shown in figure 5.

The current is injected in one terminal and extracted at the other terminal. The current is allowed to redistribute optimally over both terminals. Between the tapes in the present CORC cables there are only pressure contacts. For this reason it is assumed that for short cable sections the current is distributed only in the terminals. The model uses both Kirchhoff's voltage and current laws to solve the system of equations. Following Kirchhoff's voltage law the sum of the electrical potential differences between nodes in a closed network is always zero:

$$\sum_{k=1}^n V_k = 0. \quad (1)$$

In addition following Kirchhoff's current law, the sum of the currents that flow into a node is equal to the sum of the currents that flows out of that node:

$$\sum_{k=1}^n I_k = 0. \quad (2)$$

The system is solved for both the current between- and voltage over the nodes giving the following equation for all normal conducting sections:

$$(V_2 - V_1) - I_{12}R_{12} = 0, \quad (3)$$

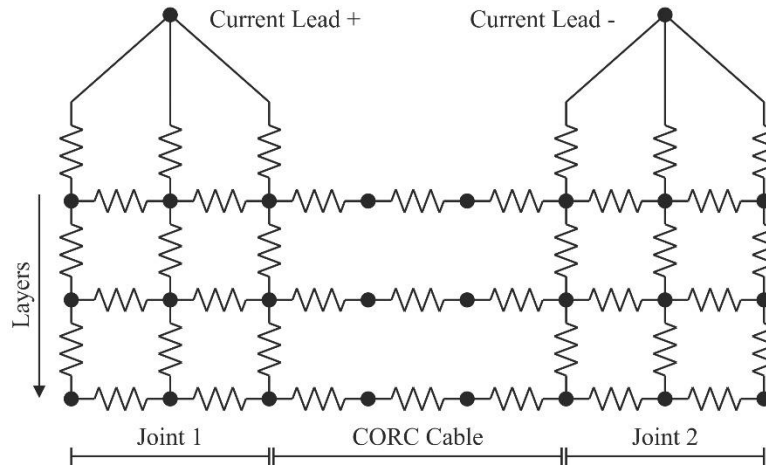


Figure 5. Schematic view of the resistances network used in the novel joint model.

and for all superconducting sections:

$$(V_2 - V_1) - U_0 \left(\frac{x(I)I}{I_c} \right)^n - (1 - x(I))IR = 0, \quad (4)$$

where V is the voltage, I is the current, R is the calculated normal-resistance between two nodes and x is a function stating the ratio between current in the REBCO layer and in the stabilizer material, respectively. The resistance between tapes is calculated as the serial resistance of the materials within the tape, with a small strip of solder in parallel, following:

$$\frac{1}{R_{mn}} = \left(x * \frac{\rho_{solder} \ln \left(\frac{r_n}{r_m} \right)}{2\pi L} \right)^{-1} + \left(\sum_{m=1}^n (1 - x) * \frac{\rho_m \ln \left(\frac{r_{m+1}}{r_m} \right)}{2\pi L} \right)^{-1} \quad (5)$$

Here x is the fraction of solder in parallel with the tapes and r is the radial position of the layer. Since the tape comprises different materials, the serial resistance is calculated across all materials [7, 8]. A uniform current distribution is assumed and therefore the resistance in the angular direction is ignored.

3.1. Simulation results

The model is used to simulate various joint terminal configurations and evaluate their performance. The primary subject of investigation is the difference in joint resistance between a cable that is trimmed and one that is not. The geometry of the CERN CORC cable with 12 layers and 38 tapes is used in the simulation with a joint length of 200 mm and at 4.5 K. The simulated joints are in zero magnetic field and self-field is ignored. In this section the following cases are discussed: the non-trimmed cable, trimmed in 3 sections of each four layers, trimmed in 6 sections of each two layers, trimmed in 12 sections of one layer and trimmed in 12 sections with a matching casing. In figure 6 simulation results for these configurations are presented.

The non-trimmed configuration has the longest length of the outer most layer, this layer has the lowest resistance to the casing and thus this configuration has the lowest resistance at $I \ll I_c$. The simulation clearly shows that different layers in the non-trimmed configuration saturate before current passes to subsequent inner layers. When a layer is nearly saturated, the resistance rises in a step-like

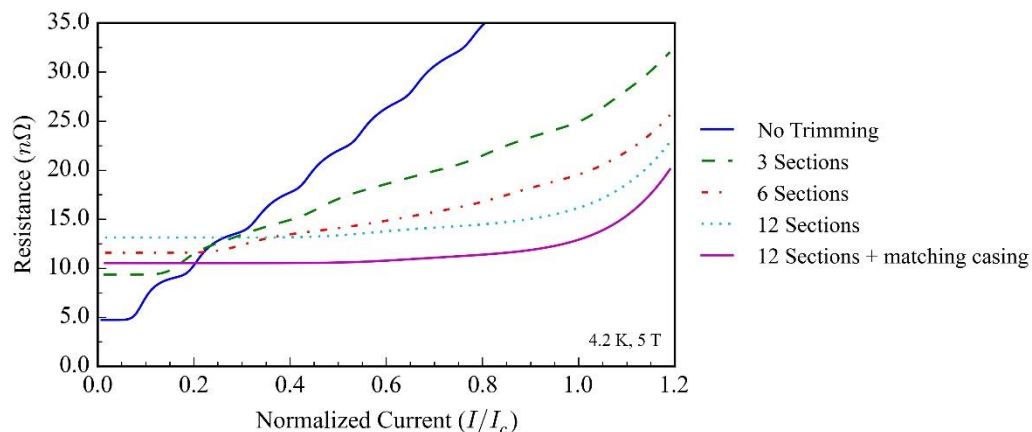


Figure 6. Simulated joint terminal resistance for five trimming configurations.

manner. The simulation shows that trimming the CORC cable increases the initial joint terminal resistance at low currents, but can cause a significant reduction in resistance at currents near I_c compared to the non-trimmed cable. The trimmed cable starts to excel when the current becomes high enough to cause saturation of the outer few layers of the cable. The lowest resistance at nominal current, about 75% of I_c , is obtained by trimming the cable into 12 sections. The joint terminal resistance can be reduced by about 50% by only trimming the cable.

Machining the casing to follow closely the shape of the trimmed cable reduces the joint terminal resistance further by another 15% relative to the non-trimmed cable. In total, the resistance of this type of joint terminal can be decreased by about 65% when following the new joint terminal design. The model also shows that cables with more layers will benefit more strongly from the new design. Furthermore, the terminal resistance scales with length. Increasing the length of the joint terminal to some meters reduces the terminal resistance significantly and long joint lengths are usually no issue in large magnet systems.

4. Experimental

A characterization test of the CORC cable is performed in the FRESKA cable test facility at CERN. The joint performance is examined during the measurement. FRESKA's dipole magnet can provide a background field up to 10 T over homogeneous magnetic field region of 600 mm. The cable is centered in the peak field, both joints are outside the peak-field region and only see self-field. Current is injected in one joint and is carried by the CORC cable over the peak-field region. A stack of three NbTi Rutherford cables is connected to the second joint and return the current to the power supply. The sample is inserted vertically into the bore of the dipole magnet, therefore the joint terminals will be addressed as 'top' and 'bottom' terminal.

The test is performed in an applied magnetic field ranging from 3 to 9 T at 4.5 K. In figure 7 the measured and simulated resistance of the joint at 4.5 K is presented by which the mid-section of the cable is in the dipole field. The critical current of the cable at 6 T is about 11 kA, enabling a large current range in which the resistance can be determined and still with limited effect of the self-field on the joints. A constant, magnetic field independent, joint terminal resistance of 30 nΩ is measured for the bottom joint terminal and a non-linear magnetic field dependent resistance of 20-35 nΩ is measured for the top terminal. Although the top joint terminal does not see the applied field, it does show a large magnetic field dependency and a significant current dependency. The resistance increases up to 85% of I_c and decreases when the current is increased further. This joint terminal behavior is unexplained at this moment.

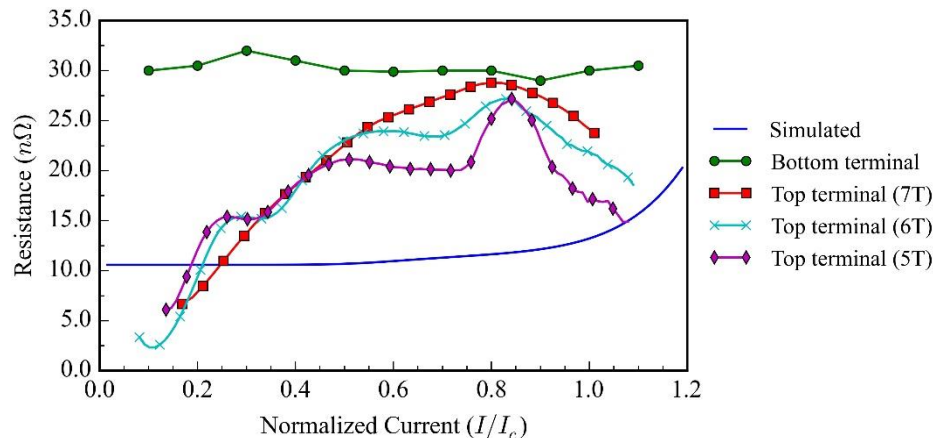


Figure 7. Measured joint terminal resistances of the bottom and top joint terminal at 4.5 K as function of the normalized current where the mid-section of the cable was placed in applied magnetic field. The resistance of the top terminal varies with the applied field, the resistance of the bottom terminal did not. The simulated joint terminal resistance is plotted as function of the normalized current at 4.5 K, 1 T, as the terminals are outside the peak magnetic field region.

During the measurement a large resistance between the bus bar and the CORC joint was observed, implying an imperfect electrical contact. Probably this led to an inhomogeneous current distribution over the joints, possibly causing the unexpected difference in resistance. More measurements are required to fully understand and benchmark the joints. Also an increase in the accuracy of the model is anticipated.

5. Conclusion

A novel joint technique for CORC type cables with many layers has been developed aiming at a drastic reduction of the joint resistance. Simulations have shown a possible reduction in joint resistance up to some 65% for a CORC cable with 12 layers following the new design. A test of the joint was performed at 4.5 K, at full current and in a background magnetic field of up to 9 T. The measured joint resistance is higher, roughly by a factor of 2 or 3, than the simulated values, possibly due to a non-optimal solder splice. More variations of such joints will be tested in the near future and, as the next step the design, will be scaled up for making joints to a 45 kA at 4.5 K and 10 T class CORC based Cable-in-Conduit Conductor.

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