Simulation of Non-Uniform Current Distribution in Stacked HTS Tapes*)

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Low-Temperature Superconductors (LTS) are sensitive to non-uniform current distribution, which produces quenching. So, transposition of strands is indispensable in LTS cables to help current redistribution. In contrast, High-Temperature Superconductors (HTS) have higher thermal stability, which is expected to help current redistribution among strands (tapes) without quenching. Generally, HTS cable designs consider transposition to reduce quench likelihood and better handling AC operation. However, transposition causes mechanical strain in the tapes, reducing their performance. Recently, a 20-kA-class Stacked Tapes Assembled in Rigid Structure (STARS) conductor is being developed at NIFS, for the next-generation helical devices. To weigh the simple stacking feasibility of HTS tapes, a previous experiment confirmed, that 5 non-transposed HTS tapes can stably conduct a worst-case non-uniform current distribution without quenching. This further suggests that when using HTS tapes for DC HTS cables, transposition may be optional, but not strictly required. A numerical simulation was developed, dealing with the current distribution among the HTS tapes in a worst-case scenario, reproducing the previous experimental observation, and a second experiment was performed to give insights into the contact resistance between HTS tapes. The self-magnetic field effect and temperature fluctuations are to be explored for quench scenarios.

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1. Introduction

On a superconducting cable, a uniform current distribution through its cross section helps stable operation [1]. Additionally, on a cable wound in a coil shape, a non-uniform current distribution naturally forms, due to the differences in the resistance and inductance values between the inner and outer conducting parts.

For a high-current Low-Temperature Superconducting (LTS) cable, the strands have to be twisted and transposed among themselves in order to make the current distribution more uniform, and also allow reduced AC losses, to then operate in a steady manner.

Twisting and transposing of tapes is common in high-current High-Temperature Superconducting (HTS) cables to help stable operation, as it can be seen in designs such as CORC, TSTC, Roebel, etc. [6, 7]. Also, as HTS have a higher cryogenic stability compared to LTS, the principles that work for LTS operation might not necessarily be fully applicable to HTS.

Manufacturing cables out of HTS tapes, such as Rare-Earth Barium Copper Oxide (ReBCO), becomes inconvenient, as they have a planar tape form and are brittle due to their materials composition. Twisting and transposing produces mechanical strain, reducing their current handling capacity [2], and makes the conductor more expensive due to the extra manufacturing step.

Observing the effect of twisting in AC losses, for LTS and HTS high-current cables, it can be seen that the behavior is different [5]. Twisting is a must for LTS, specially for AC operation, but for HTS it seems that it might not be necessary, due to the comparatively small reduction in AC losses. Additionally, the higher cryogenic stability of HTS helps for a more stable operation, and the heat produced to be extracted by the cooling system.

FFHR fusion reactor design uses HTS helical coils, based on the STARS conductor [3, 8]. As they operate in DC current, AC losses are less of a concern, and it is expected that twisting the HTS tapes is not necessary. Sectioning the magnets and using joints is considered, to ease the manufacturing process of these coils [9–11].

Alongside the investigation for the stable operation of a stacked tapes conductor, as confirmed by Meulenbroeks et al., this configuration is resilient to a worst-case non-uniform current distribution, and it can operate in a stable manner for slowly changing currents [4].

This paper further explores with a simulation of this (first) experiment, and gives some insights for the contact

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resistance among the HTS tapes from a second experiment. As such, it expands on the research to determine technical operation parameters, towards a stacked tapes conductor in DC operation, as in FFHR HTS helical coils.

2. Simulation Outline

Figure 1 shows the side view configuration, to produce a worst-case non-uniform current distribution in a stack of 5 HTS tapes, 4 mm width and 1.3 m length.

The current distribution along the tape stack depends on the total input current, and as it keeps increasing, there is a current share towards lower tapes. Since the tapes are superconducting, the current share only happens to a lower tape after reaching the critical current value of the tape above it.

2.1 Numerical model as resistor grid

The situation is modeled as a 2D resistor grid, accounting for the resistance value depending if the segment is a regular conductor (copper) or a superconductor (HTS).

To model the simplest scenario at currents below the total critical current of the tape stack, the superconducting layer of each HTS tape is considered separately. The equivalent copper resistance of all the tapes is considered as a single row. This is shown in Fig. 2.

The material properties at 77 K are taken for the copper resistances (R_{st} and R_v), whereas, the resistance of the superconducting material R_{sc} is computed based on the Power Law Equation (1). The parameters correspond to $GdBa_2Cu_3O_x$ tapes, 4 mm width.

$$R_{sc} = \frac{E_c}{I_x}\Delta x\left(\frac{I_x}{I_c}\right)^n, \quad (1)$$

where Δx is the length of the horizontal mesh segment, E_c is the electric field criterion, I_c is the critical current, I_x is the current flowing through $R_s c$, and n is the n-value exponent index.

A system of equations is constructed via Kirchhoff's Voltage Law, and solved by Newton-Rhapson to obtain the loop currents $I(i, j)$ in the grid. From the loop currents, the current flowing at each resistance on the grid is determined, and voltages obtained via Ohm's Law.

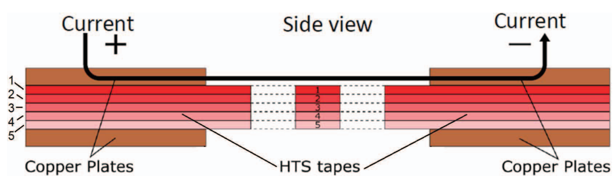

Fig. 1 Schematic of the experimental setup, to produce a non-uniform current distribution in a stack of HTS tapes. Injecting the current from one edge of the stack produces the worst-case scenario. From [4].

2.2 Contact resistance between HTS tapes

The real contact resistance was expected to be higher than the computed theoretical value, as the HTS tapes are in physical contact without soldering. Each HTS tape has a copper coating as a stabilizer layer, and have a contact surface area between them. To determine the experimental contact resistance value, it was measured in a second experiment, as shown in Fig. 3:

The experimental contact resistance was measured to be between one and two orders of magnitude higher than the computed value, and dependent on the mechanical pressure between the HTS tapes.

The mechanical pressure applied on the tape stack was not measured. Two scenarios for 'low pressure' and 'high pressure' were tested, by tightening clamps in the stacked conductor. The 'low pressure' values were about half of the 'high pressure' values, and as in the first experiment a high pressure was not applied to the tape stack, the 'low pressure' values were used.

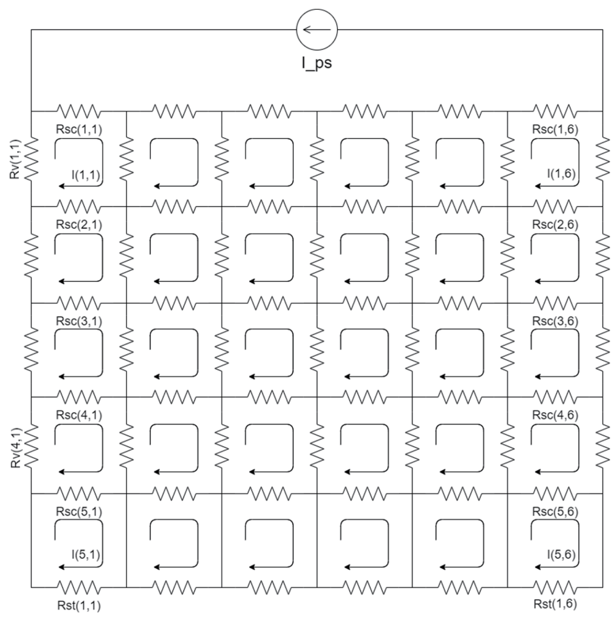

Fig. 2 2D resistor grid for 5 HTS tapes. The top 5 rows correspond to superconducting resistance segments of each HTS tape (R_{sc}); last row is the stabilizer equivalent resistance (R_{st}); and vertical resistances account for the contact resistance between each tape superconducting layer (R_v).

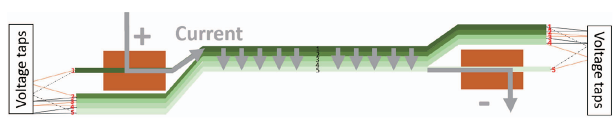

Fig. 3 Schematic of the experiment to measure contact resistance between HTS tapes. Current is forced to flow from up to down along the tape stack, and via voltage taps, the resistance across each HTS tape is measured.

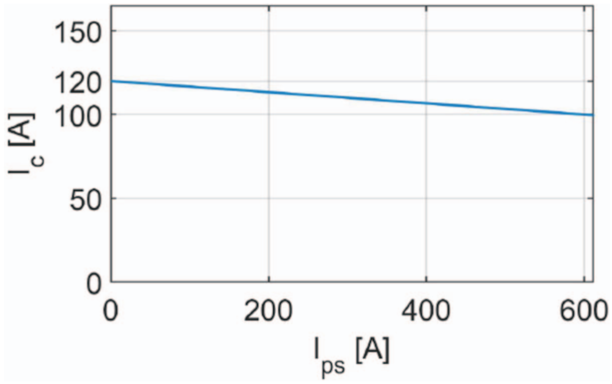

Fig. 4 Linear decreasing trend for critical current (I_c) as function of the total input current (I_{ps}), for one HTS tape.

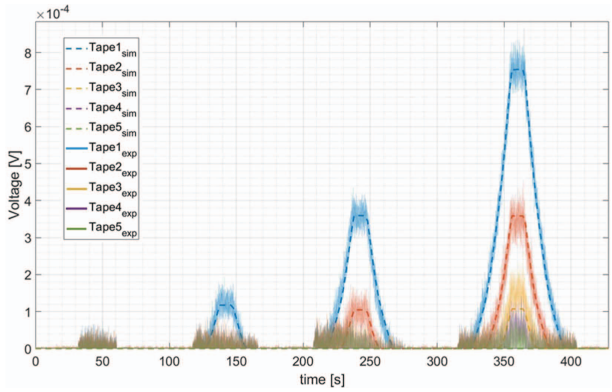

Fig. 5 Voltage comparison between experimental data (continuous lines) and simulation (dashed lines). Critical current adjustment and experimental contact resistance leads to a reasonably good match.

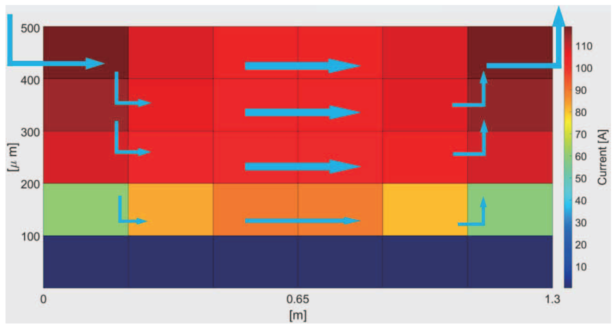

Fig. 6 Current distribution in each superconducting segment for 400 [A]. The color of each square is the horizontal current flowing through it, and the blue arrows are indications of how there is a current share at bottom tapes.

2.3 Simulation assumptions

In Meulenbroeks' experiment there were three observations:

- No signs of temperature increase at total input current below ~500 [A]
- Current injected from one edge gradually distributes to lower tapes, when increasing its value
- Current redistributes without quenching, even at values slightly above the total critical current of the stack (~600 [A])

A 1D temperature calculation was done to verify its negligible rise for this geometry, at input current values below the critical current of the tape stack (<500 [A]). Based on this and previous observations, the 2D Resistor Grid model has two main assumptions:

- Constant temperature at 77 K
- Approximation as a linear decrease in critical current (I_c), at increasing total input current (I_{ps})

The detrimental effect of the magnetic field in the critical current remains to be added. As a first step to account for the effect of temperature and magnetic field, a decreasing linear dependence of the critical current to the total input current was assumed, shown in Fig. 4.

The critical current value corresponds to the one with no self field and no current, of 120 [A]. At 600 [A] input current, the critical current value is taken as 100 [A], estimated by computing the magnetic field produced by that current, and accounting its reduction effect to the critical current of a HTS tape exposed to that magnetic field.

3. Calculation Results

3.1 Voltages across each HTS tape

Taking into account the experimental contact resistance, a comparison between the total voltage across the HTS tapes is shown in Fig. 5.

The contact resistances in Meulenbroeks' experiment were not measured, but still, the agreement with experimental data is deemed reasonably good. However, there was some slight discrepancy at 400 [A], due to the uncertainty in the contact resistance values between Meulenbroeks' experiment and the contact resistance measurement experiment.

3.2 Current distribution in SC segments

In the simulation model of the resistance grid, the first 5 rows from top to bottom consider only the superconducting material in the tapes. In the experiment it was observed that for slowly changing currents, the current share happens only on the superconducting layer of the HTS tapes, for currents below the total current of the tape stack (roughly 5 I_c).

Figure 6 shows the current distribution across the tape stack for 400 [A]. Each square corresponds to a superconducting resistance, the color of the square is the magnitude of the current passing through it, and the blue arrows illustrate how the current distributes along the resistor grid. As the total input current increases, the lower HTS tapes start conducting a share of the current.

4. Discussion

The simulation developed reproduces the experimental data for a stack of 5 HTS tapes, operating in a worst-case non-uniform current distribution. Further steps are to be taken in order to expand the calculation for more scenarios, such as adding the magnetic field calculation, to replace the critical current adjustment.

Magnetic measurements were done in Meulenbroeks' experiment, via Hall sensors located on the center and edges, at a short distance from the stacked tapes conductor. It was observed that they were symmetrical and slightly higher on the upper side than on the lower side, giving an indication of a similar current distribution to the one shown on the simulation [4].

4.1 Contact resistance between HTS tapes

The contact resistance between HTS tapes is dependent on the mechanical pressure applied to keep them in place. In the two previous experiments, there were not dedicated measurements to determine their value.

The contact resistance sets the current share from one HTS tape to adjacent tapes, being relevant as it can set a limit on how fast the current share can happen from one tape to another. Even if operating at DC current, a HTS stacked tapes conductor can be affected by surrounding AC current transients. For FFHR, AC currents in poloidal field coils or other coils, and plasma ramp-up, can all be sources of disturbance for the helical DC magnets.

A more detailed analysis of the contact resistance can then further support the STARS conductor research, giving parameters to outline its technical specifications.

By testing a stacked tapes conductor at varying mechanical pressures, the required contact resistance across the HTS tapes can be determined, as a function of the expected surrounding AC transients. If the contact resistance is low enough, current can redistribute for stable operation of the conductor, while being resilient to external AC transients.

4.2 Calculation for quench analysis

When reaching or surpassing the critical current of the tape stack (>5 I_c), the superconducting material starts becoming resistive, so the copper parts get a share of the current as well. Hence, Joule heating starts being produced in all the current paths, temperature rises, and a quench can occur.

A temperature calculation was done for currents below 500 [A], verifying as in the experiment, that temperature rise is negligible in those conditions.

Given the current injection from one edge of the tape stack, when there is a current share in the copper coating of the HTS tapes, the vertical position is relevant, since closer copper segments will have a higher share of the total current. The model currently being considered is a single row of the equivalent resistance of all copper, and it can be updated for calculating more current paths, to be expanded in a future work for high-current quench scenarios.

5. Summary

A numerical simulation model was developed for non-uniform current distribution in stacked HTS tapes, based on a resistor grid, considering superconducting materials and copper.

An experiment was done in order to make measurements of the contact resistance between the HTS tapes. It highlights the need to pay attention to the mechanical pressure applied perpendicular to the tapes, in order to control the current redistribution rate when a non-uniform current distribution is present.

Remains to be done in a future work expanding the code to add the magnetic field calculation in the HTS tapes, and temperature rise at high-current for exploring quench scenarios.

Author Contributions

D. Garfias: Writing - Original Draft, Visualization, Software, Formal Analysis. M. Morbey: Investigation, Software, Formal Analysis. Y. Narushima: Investigation, Supervision. N. Yanagi: Supervision, Funding Acquisition.

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