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Simulation and Testing of Stacked HTS 2G Tapes for Superconducting Cable

Ankit Anand*, Srikumar Nayek, Abhay Singh Gour and V. V. Rao

Cryogenic Engineering Center, IIT Kharagpur – 721302, West Bengal, India; ankit5088@gmail.com

Abstract

High Temperature Superconductor (HTS) tapes experiences tension, bending and torsion along with stress due to thermal cycling and electromagnetic forces during operation. This combined effect of mechanical forces, moments and stresses can affect the performance of superconducting tape. In this paper investigation of I-V characteristic of Superpower makes 2G HTS stacked tapes under strain.

Keywords: Critical Current, Cryogenic UTM, HTS Tape, Stacked HTS Tape, Strain

1. Introduction

Recent developments in the manufacturing of long length HTS tapes have resulted in realization of various practical devices such as, superconducting cables for power transmission, superconducting fault current limiters to safeguard the power system under faults and Cable-In-Conduit (CICC) based superconducting magnets for particle accelerators. In general, superconducting tapes offer zero DC resistance thus leading to zero joule heat loss. However, for AC operation they show a small resistance causes heating due to AC losses. The current density in HTS tape is much higher than that of conventional copper wires which helps in high flux density with reduced number of turns thereby reducing the size and weight for superconductor based machines.

A 2G HTS tape is made up of composite layers as shown in Figure 1[6]. The total thickness of tape is around 0.1 mm and that of YBCO layer is only 1 µm.

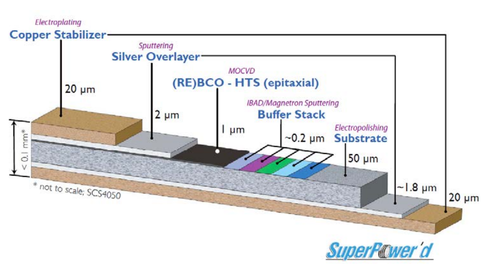

Figure 1. Layered structure of 2G HTS tape[6].

Celentano G et al. has proposed future fusion magnets for high magnetic flux density can be wound using cable in conduit formed by stacking 150 2G HTS tapes[2]. Figure 2 shows a CICC type cable for high current transportation. Total layers used will be around 150 as there are 5 strand and each strand consists of 30 tapes. This CICC cable has an ampacity of 10 kA.

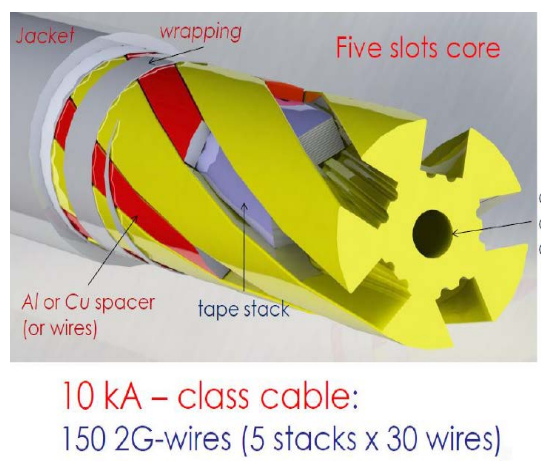

Figure 2. CICC made up of 2G HTS tape stack[2].

In this paper Superpower HTS tape (Model No. SCS4100) was used for study. The critical current specified by the manufacturer was 120A at 77K for self-field. Stacked HTS tapes (2 Numbers) arrangement is shown in Figure 3. The ends of stacked tapes were soldered using Sn (63%) Pb (37%).

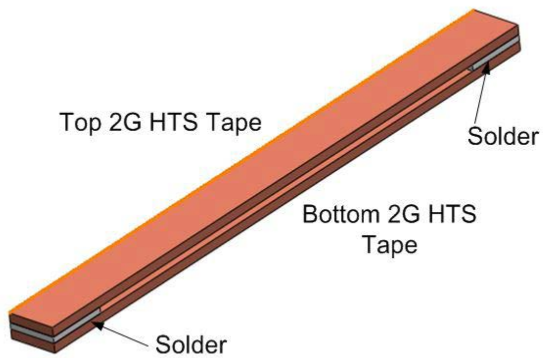

Figure 3. 2G HTS stacked tape.

In this paper I-V characteristic of Superconducting 2G tape and stacked tapes was investigated under strain in superconducting state using in-house developed Cryogenic Universal Testing Machine (C-UTM). This paper also details about the thermal analysis of developed C-UTM and FEM strain analysis of a 2G HTS Tape was carried out to determine the deformation at cryogenic temperature.

2. Design and Developement Of Cryogenic UTM

A C-UTM was developed by modifying an existing UTM as shown in Figure 4. It consists of a metallic cylinder with a flange mounted with the body of UTM. This provides a freedom to demount the cryostat as in when required for testing other samples. In order to make the bottom leak proof Teflon sheet was used for sealing the two faces. This sealing helps in holding the liquid nitrogen inside this open cryostat. In order to have reduce in heat inleak various layers of insulation on the surface and bottom of the open cryostat were applied. This cryostat has a liquid capacity of 20 L. Inside this open cryostat fixed and movable sample holders, supply current and voltage sense leads provisions are available with suitable cryo compatible teflon supported metallic spring loaded jaws. The teflon support provides electric insulation for current leads and sample from other metallic parts of C-UTM during testing.

The shaft connected to upper jaw was fixed with upper cross head of C-UTM with Linear Variable Differential Transformer (LVDT) and load cell for the displacement and force measurement respectively as shown in Figure 7.

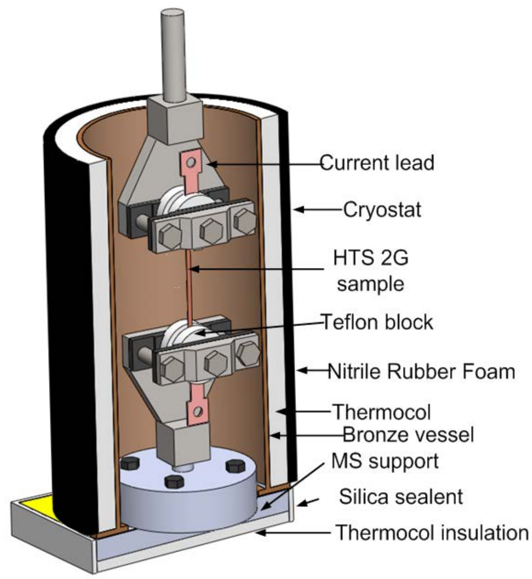

Figure 4. Schematic of C-UTM setup.

A 3D model of an open cryostat was developed in Solidworks as shown in Figure 5 for the thermal FEM analysis. The model consists of metallic cylinder surrounded by the multiple layers (20 mm of thermocol and 10 mm of Nitrile rubber foam) insulation.

3D model was simulated in ANSYS to determine the temperature variation along the radial direction of open cryostat. Inside temperature of cryostat is 77 K due to Liquid Nitrogen (LN_2) and outside as ambient temperature (303 K) was taken as a boundary condition. The temperature profile of open cryostat in steady state is shown in Figure 5.

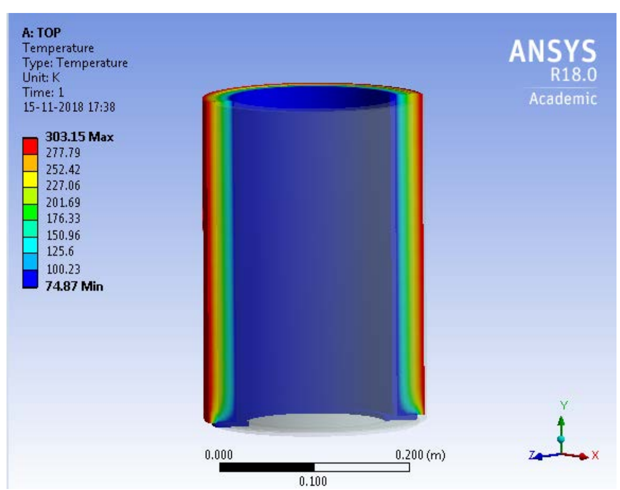

Figure 5. Temperature profile for open cryostat in radial direction.

3. Experimental Setup

Figure 7 shows a schematic of experimental setup with instrumentation and data logging system. The sample was mounted between the jaws which was configured for 4 probe system for supplying constant DC current from Intermegnetic power supply and measure the voltage across the sample using KEITHLEY 2700 digital multi meter. The four probe connection with sample holder is shown in Figure 6 which was used to excite it and sense voltage across it. The temperature of the sample was measured using RTD (Pt-100) via LAKSHORE 325 temperature controller. The current supplied to the sample was measured by sensing the voltage across by series connected 0.1 mΩ resistor in 4 probe configuration using KEITHLEY 2700 digital multi meter. An LVDT connected to the KEITHLEY 2400 source meter for measuring the displacement of upper crosshead. All the meters were connected to computer system for data logging via RS-232. The photograph of experimental setup is shown in Figure 8.

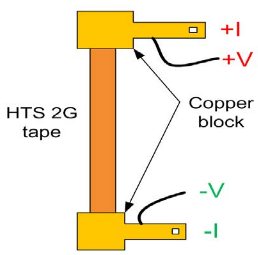

Figure 6. Schematic of sample holder with 4 probe provision.

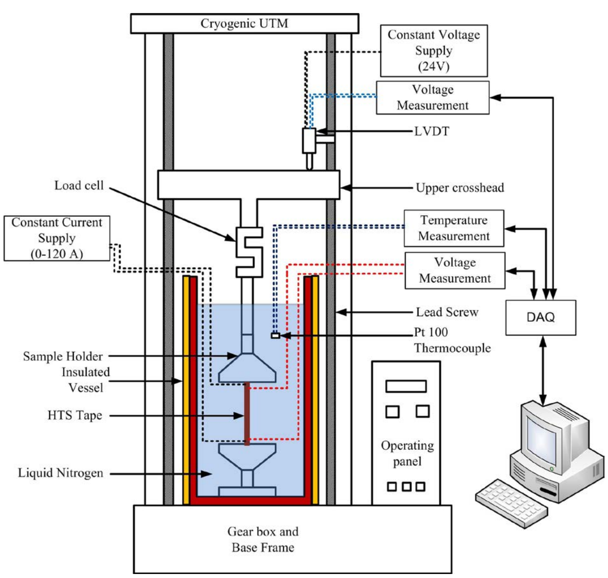

Figure 7. Schematic of Experimental setup.

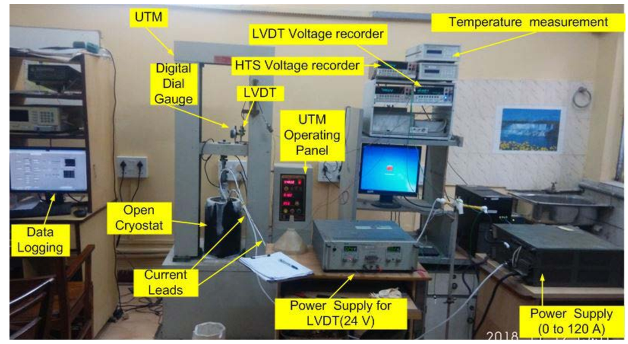

Figure 8. Photograph of experimental setup.

The current to the sample was supplied through current lead which has an ampacity of 120 A at room temperature. The cross sectional area of current lead is determined by the following relation using current lead datasheets[7].

$$R = \frac{\rho L}{A} = \frac{V}{I}$$

$$A = \frac{\rho L I}{V}$$

Where R is the resistance of current lead in Ω, L is length of current lead in meters, I is maximum current supplied through current lead in Amperes and V is the applied voltage in volts and A is the cross sectional are of current leads in m^2.

4. Experimental Procedure

Procedure for testing HTS tape samples are as follows:

1. The sample 2G HTS tape was mounted between upper and lower jaws of sample holder soldered with current lead connections inside the open cryostat.
2. Check for short between the sample and UTM via multimeter in continuity mode.
3. Start the cool down process of UTM by pouring the liquid nitrogen. Wait till the liquid nitrogen boil off rate stabilizes.
4. LN_2 level should be maintained in the open cryostat of C-UTM during the complete experiment.
5. After thermal stabilization of setup and sample move upper cross head to create tension in the sample.
6. Excite the sample with constant current supplied from Intermagnetic power supply gradually from 0 A to the maximum current which can be supplied by the source. Hold the current value for few seconds and reduce it back to 0 A.

7. Record the observation for force using load cell, displacement using LVDT, voltage across sample and resistor using the program developed in LabVIEW software via RS-232.
8. Move the upper crosshead in upward direction 200 µm.
9. Repeat steps 6 to 8 till the sample breaks off.
10. Record all the observations and perform the data analysis

Safety aspects must be taken into consideration during experimentation. There are mainly two safety aspects (i) High current (ii) Low temperature of liquid nitrogen. During experiment one should make sure that that no physical contact exists between the current carrying conductor and the body of UTM as this can lead to short of power source with the setup. All cryogen handling safety precautions should be carried while transfer of cryogen to the open cryostat.

5. FEM Structural Simulation of Single HTS Tape

Using the experimental data of force, stress was computed and was plotted against strain as shown in Figure 9. The obtained curve was found to have a bilinear stress strain profile. Sample was subjected to strain and the cross ponding tensile force was measured.

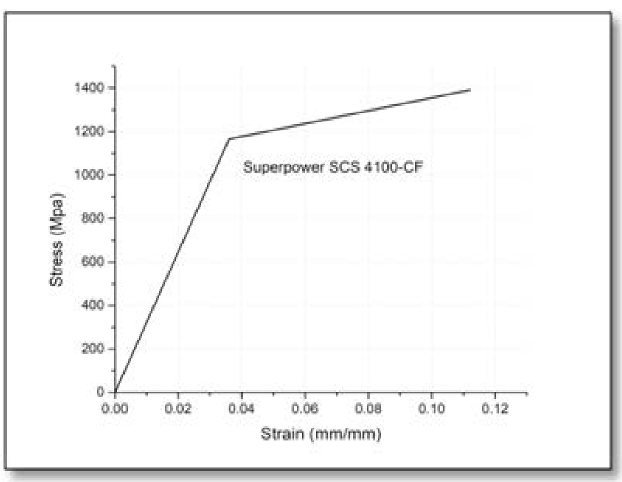

Figure 9. Stress Strain curve of Superpower SCS 4100-CF HTS tape at 77K.

The approximated bilinear inelastic property is shown in Table 1.

Table 1. Physical property of 2G HTS Tape at 77K

Young Modulus (GPa)	Poison's Ratio	Yield Stress (GPa)	Tangent Modulus (GPa)
32.158	0.25	1.182	2.976

A 2D model was created in ANSYS® as shown in Figure 10. A shell 181 element mesh with total 490 nodes was used. Shell 181 element has been use because 2G HTS tape is very less thickness (0.143 mm). The lower end of the tape was constraint to 0 DOF in all directions whereas upper end was subjected to tensile stress 1.3 GPa in Y-direction. The total vector some of deformation at 77K is shown in Figure 10. Due to simulation complexity deformation analysis for the stacked tapes was not carried out.

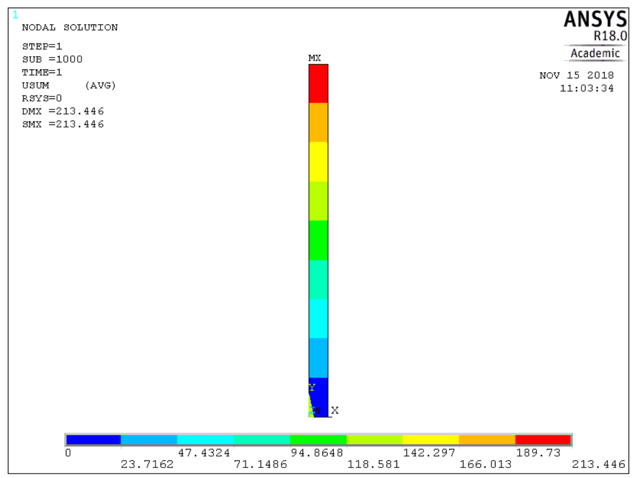

Figure 10. Total displacement vector sum of HTS tape deformation at 77 K under 1.3 GPa tensile stress.

6. Result and Discussion

Figures 11 and 13 shows current versus voltage response for a single and stacked tapes. This shows the resistance of the sample increases when subjected to higher tensile stress at 77 K for different current levels.

Figure 12 and 14 shows resistance versus current for the samples when subjected to various strain levels at 77 K. The variation of the resistance at higher strain levels increases for both types of samples with current.

The brake point of single HTS tape under tensile force was found to be 784 N with the strain of 7.82E-2. The brake point of stacked HTS tape sample was not achieved due to sample mounting issues in our experiment for which further investigation is in progress.

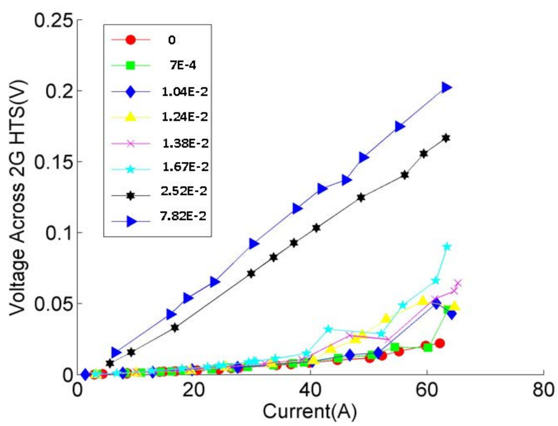

Figure 11. I-V characteristic for single HTS tape at 77 K for various strains.

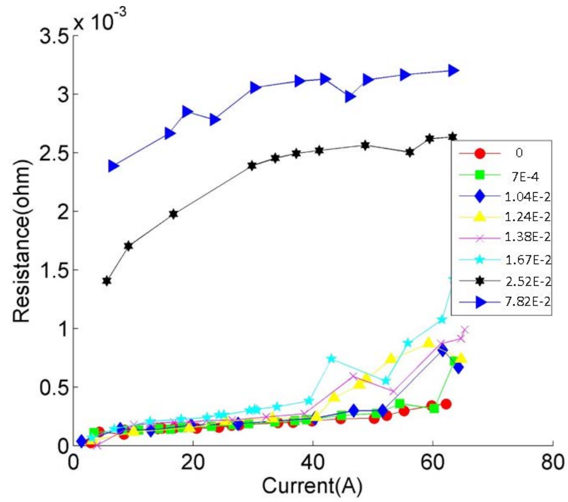

Figure 12. Variation of resistance at different current levels under strain for a single HTS tape at 77 K.

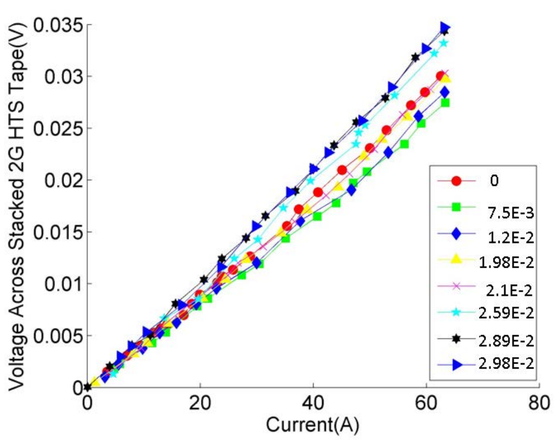

Figure 13. I-V characteristic for stacked HTS tape at 77 K for various strains.

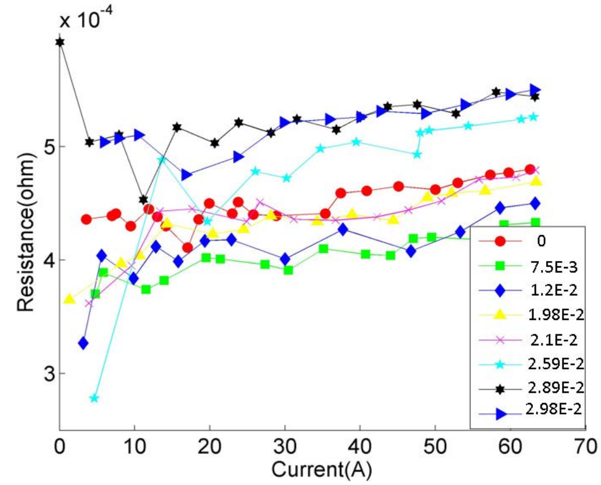

Figure 14. Variation of resistance at different current levels under strain for stacked HTS tape at 77 K.

7. Conclusion

An indigenous cryogenic UTM was developed for testing of superconducting tapes with the provision of high current supply (upto 200 A). The I-V characterization single and stacked HTS tape (2 Numbers.) were carried out at 77 K. It was found that the resistance across the samples during the test increases with the current for various strains. During the experiment brake point only for single HTS tape was achieved at the strain level of 7.82E-2. This information helps in determining the setting of pre-tension required for the fabrication of HTS cable and other superconducting devices.

8. References

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