Numerical Study of the Influence of the Encapsulation Layer on the DC Over-current Performance of HTS Coated Conductors

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Introduction

- The application of resistive superconducting fault current limiters (R-SFCLs) in voltage source converter (VSC)-based systems has been studied, and adding additional encapsulation layers to high temperature superconducting coated conductors (HTS-CCs) used for the R-SFCLs is getting practical.
- Based on the fault current of a VSC system, a 2-D and a 1-D HTS-CC model are respectively developed in the COMSOL Multiphysics to analyse the effect of the encapsulation layers on their over-current performance. The maximum current-tolerance, the resistance characteristics and the quench recovery time are investigated under DC over-current impact.

2-D Electrothermal Model

A. Model Description

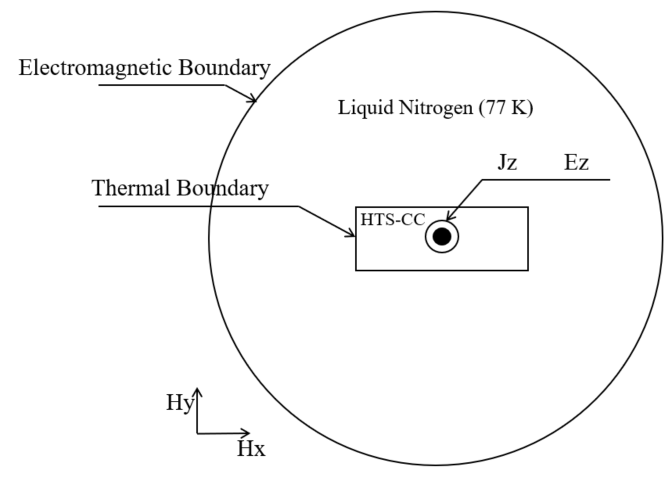


Fig. 1. Schematic of the transversal 2-D model (not to scale)

$$\begin{cases} \nabla \times E = -\mu_0\mu_r \dfrac{\partial H}{\partial t} \\ \nabla \times H = J \end{cases}$$

$$\begin{cases} \dfrac{\partial E_z}{\partial x} = \mu_0\mu_r \dfrac{\partial H_y}{\partial t} \\ \dfrac{\partial E_z}{\partial y} = -\mu_0\mu_r \dfrac{\partial H_x}{\partial t} \\ J_z = \dfrac{\partial H_y}{\partial x} - \dfrac{\partial H_x}{\partial y} \end{cases}$$

B. Fault current & Sample Architecture

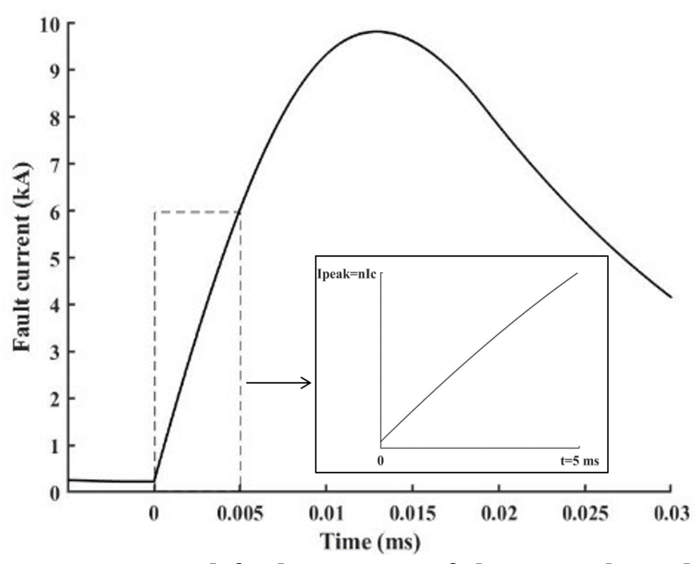


Fig. 2.Typical fault current of the VSC-based DC system and the applied current

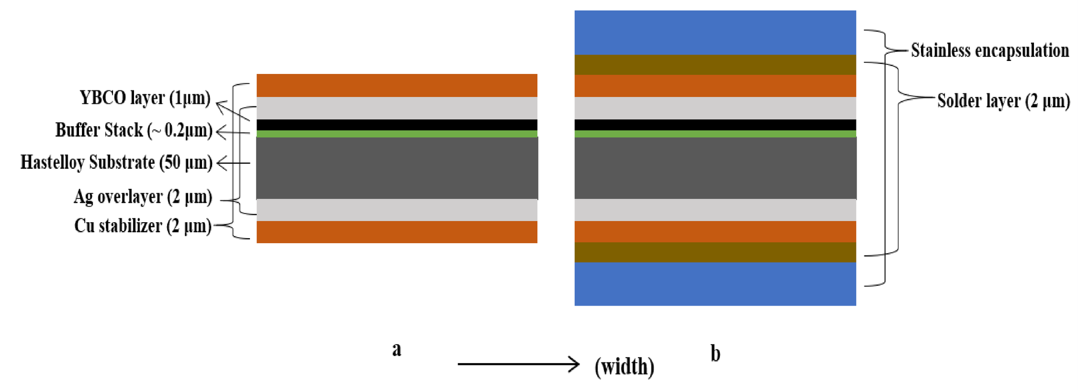


Fig. 3. Sample architecture of the studied HTS-CCs (not to scale). a. HTS-CC without the encapsulation. b. HTS-CC with the encapsulation

C. Simulation of the Maximum Current-tolerance

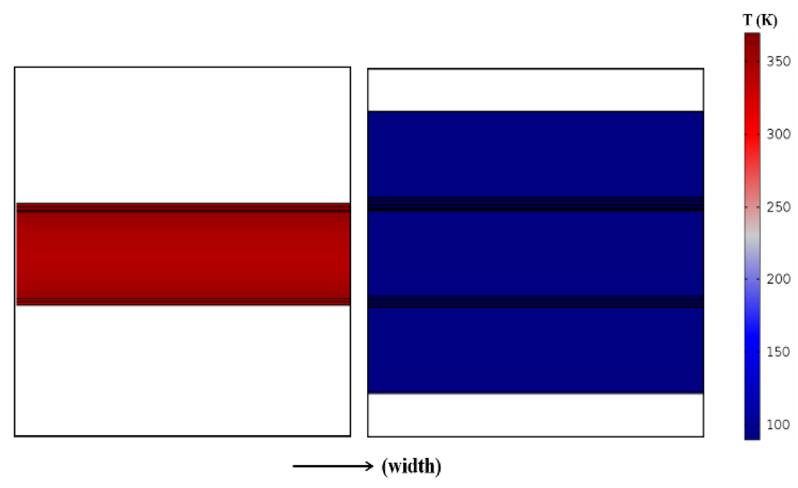


Fig. 4. Temperature distribution comparison of the tape without encapsulation and with encapsulation

- When subjected to an over-current peak at 1200 A (4Ic), the HTS-CC without the encapsulation withstands a temperature more than 350 K. Meanwhile, the one with the encapsulation layer only reaches a temperature less than 100 K.

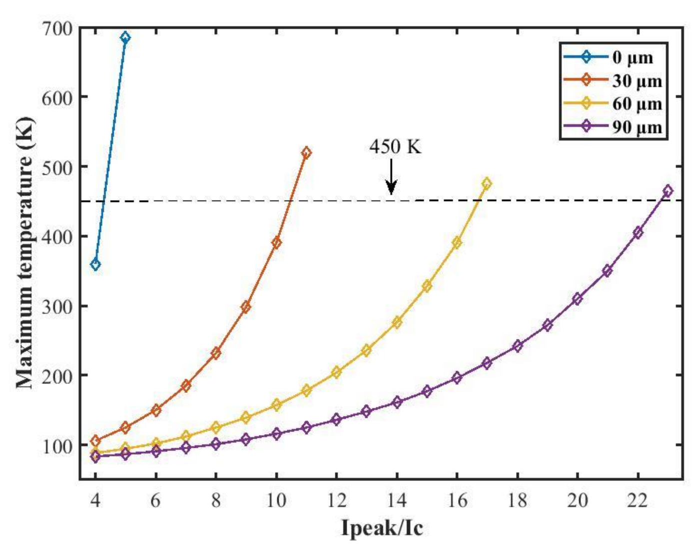
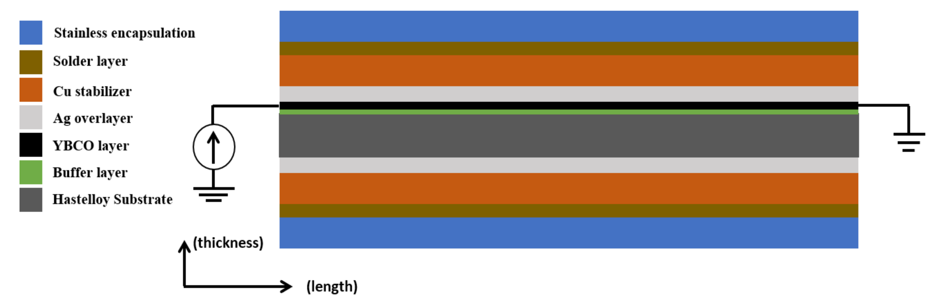


Fig. 5. Maximum temperature dependent on current amplitudes at different thicknesses

- The used solder has the lowest melting point of approximately 456 K, so 450 K is selected as the criterion of estimating the maximum current-tolerance;
- When the thickness of the encapsulation goes up from 30 μm to 90 μm, the maximum current the HTS can tolerate increases from 10Ic to 22Ic

1-D Electrothermal Model

A. Model Description



$$\begin{cases} -n \cdot \left(-\dfrac{\nabla V}{\rho(T)}\right) = J \\ V = 0 \end{cases}$$

Fig. 6. Schematic of the 1-D longitudinal model (not to scale)

B. Simulation of the resistance characteristics

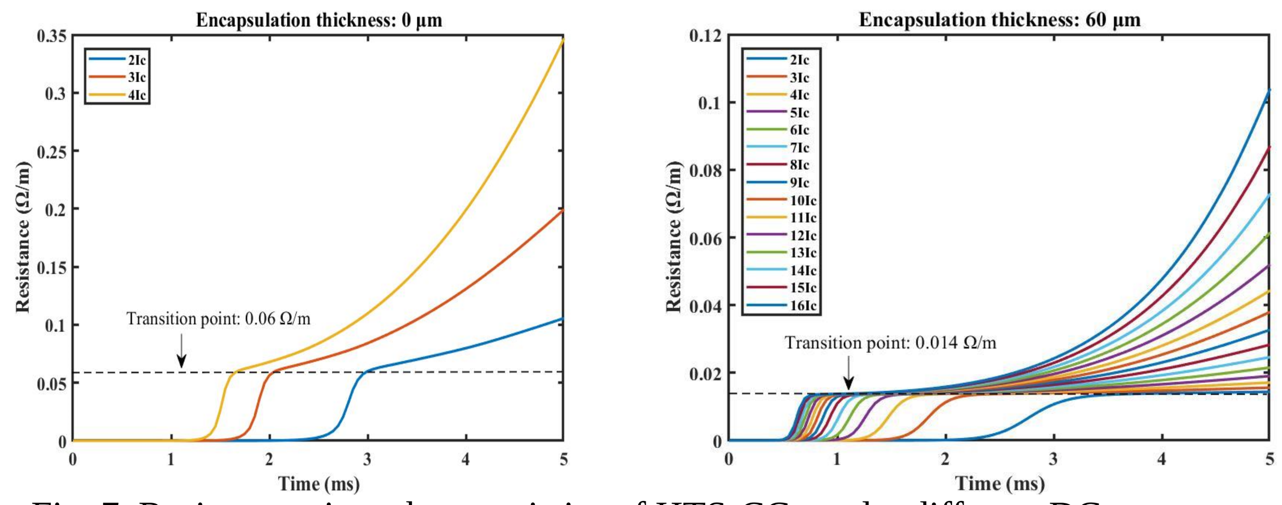


Fig. 7. Resistance-time characteristics of HTS-CCs under different DC over-currents

- The resistance of the HTS-CC increases as the rise of the magnitude of the over-current, and the encapsulation decreases the resistance of the tape subjected to the same over-current;
- There is a set of transition points between the flux flow state and the normal state, which indicates that the current is completely transferred from the superconducting layer to other layers;
- When the magnitude of the over-current is larger, the lag time is shorter.

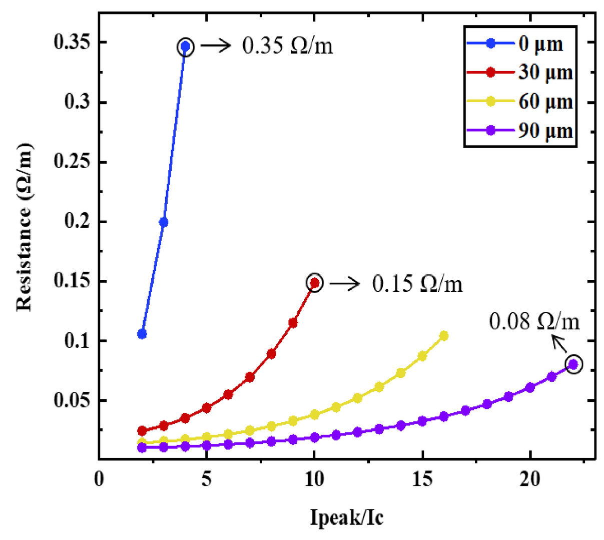


Fig. 8. Resistance characteristics of HTS-CCs under different DC over-currents

- Maximum current tolerated by the tape with 90 μm encapsulation (22Ic) is more than twice the corresponding value of the 30 μm encapsulation (10Ic); the final resistance of the former (0.08 Ω/m) is more than half of the latter thickness (0.15⁄2=0.075 Ω/m);
- The HTS-CC with suitable thickness is likely to reduce branches of R-SFCLs and improve the total resistance of the device.

C. Simulation of the recovery time

- Recovery time increases linearly with the rise of the over-current;
- Because of the increased thermal mass, the thicker the encapsulation, the shorter the recovery time when subjected to the same amplitude of the fault current;
- If the thicker encapsulated HTS-CC tolerates a higher over-current, its recovery time goes up.

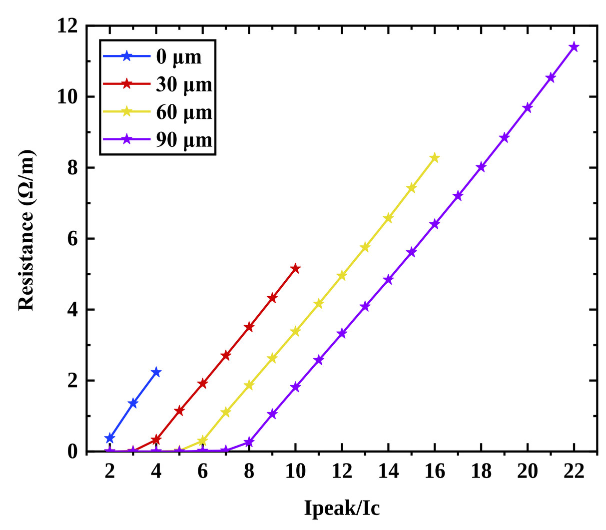


Fig. 9. Recovery time dependent on current amplitudes at different thicknesses

Conclusion

- The 2-D model proves that the encapsulation can significantly improve the maximum tolerated current of the HTS-CCs used for R-SFCL in VSC-based DC system.
- While the increase in capsulation thickness reduces the resistance per unit length, the simulation in the 1-D model demonstrates that the increase in maximum current-tolerance can reduce the number of parallel branches. This is still likely to improve the total resistance of the applied R-FCL. Also, the HTS-CC tolerating larger current is also more active to the fault.
- The HTS-CC operating at a larger fault current means a longer recovery time, but at the same fault current, the thicker the HTS-CC is, the faster it will recover.
- The benefits of the encapsulation in HTS-CCs used for the R-SFCLs of VSC-based systems should be recognized, and the thickness should be taken into account based on the peak value of the fault current, the resistance and the recovery time.

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