Understanding AC losses in state-of-the-art superconducting cables: Physics insights from 2D to 3D computational modelling

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Abstract: This study develops computational models to forecast AC losses in cold-dielectric conductors, aiding in the design of lightweight superconducting cables with high current densities. Utilising the H-formulation of Maxwell's equations and various critical current density models, we analyse triaxial [1], CORC [2], and TSTC [3] cables. Our models, validated against experimental AC loss data, reveal the complex interplay of magnetisation and transport currents. Key findings include optimal current phase distribution in triaxial cables to minimise magnetic leakage and distinctive current density patterns in CORC and TSTC cables. This research benchmarks electromagnetic performance across different HTS cabling techniques, offering valuable insights for future developments.

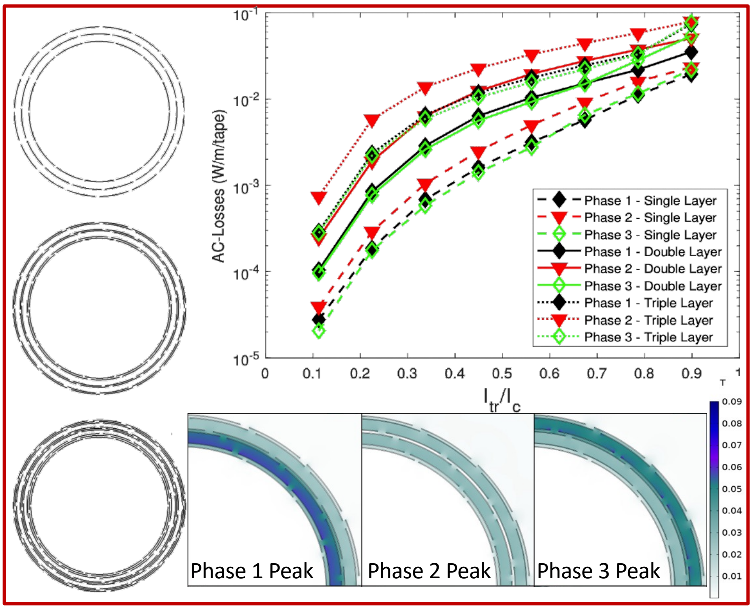

Figure 1. Schematic of three triaxial designs with increased layers per phase (left) based on a prototype cable by VNKIIP [1] and AC losses. The magnetic field produced by the double layered design for each phases peak.

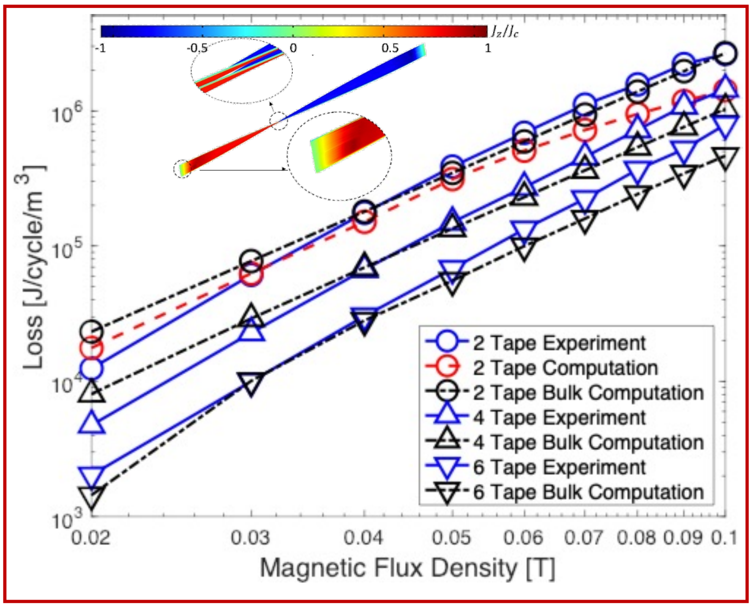

Figure 3. The AC-Losses per tape that are produced by the experimental prototype [3] compared to the computational simulation with the normalized current density profile (insert).

Method

- **H-Formulation** – When in a 3-dimensional configuration, both the magnetic field and the current density needs to be considered in all directions. Therefore, Faraday and Ampere's law are:

$$\begin{vmatrix} \partial_y E_z - \partial_z E_y \\ \partial_z E_x - \partial_x E_z \\ \partial_x E_y - \partial_y E_x \end{vmatrix} = -\mu \begin{vmatrix} \partial_t H_x \\ \partial_t H_y \\ \partial_t H_z \end{vmatrix} \qquad \text{Eq.1}$$

$$\begin{vmatrix} J_x \\ J_y \\ J_z \end{vmatrix} = \begin{vmatrix} \partial_y H_z - \partial_z H_y \\ \partial_z H_x - \partial_x H_z \\ \partial_x H_y - \partial_y H_x \end{vmatrix} \qquad \text{Eq.2}$$

SC Material Law – As is standard, the electrical behaviour of the superconducting material is defined as the E – J power law model with an electric field criterion of 1 $\mu V/cm$ and a n-value of 43 and I_c is 185 A

$$\boldsymbol{E} = E_0 \frac{J}{|J|} \left(\frac{|J|}{J_c} \right)^n \qquad \text{Eq.3}$$

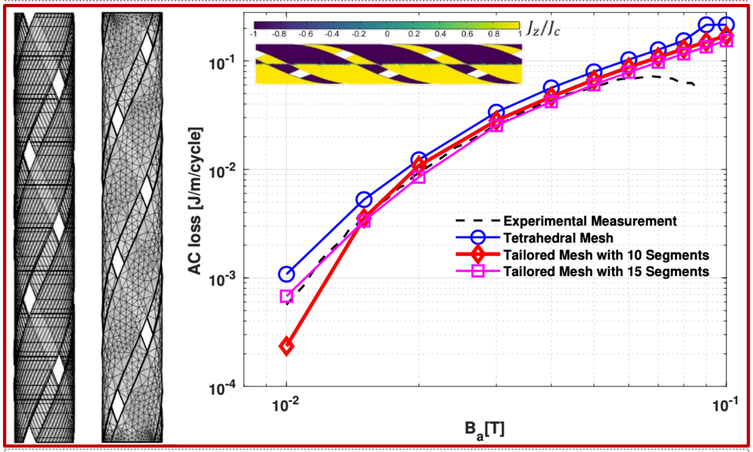

Figure 2. Comparison of AC losses between the experimental measurements [2], the tailored mesh (left) approach that significantly reducing the computational time and the automatic physics-controlled mesh (right) with the normalized current density profile (insert).

Conclusions

This study provides a comprehensive analysis of electromagnetic behaviour and AC losses in various superconducting cables, using advanced computational models validated by experimental data. Key findings include:

- Non-linear AC loss increases with tape layers,
- No magnetic leakage within the triaxial design.
- Accurate loss predictions for triaxial, CORC® and TSTC cables. With the significance of tailored meshing techniques especially in the CORC design.
- These insights offer valuable guidance for future cable design and optimisation to enhance superconducting cable technologies.

References

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[2] M. Majoros et al., Superconductor science and technology, vol. 27, no. 12, pp. 125 008–12, 2014.
[3] K. Choi et al., IEEE transactions on applied superconductivity, vol. 33, no. 5, pp. 1–5, 2023

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