Modeling of AC losses in the CS and TF conductors for the ITER Project

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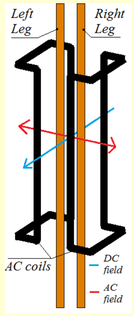
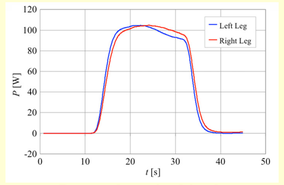
Abstract - The cable-in-conduit conductors (CICCs) that will be used for the ITER Central Solenoid (CS) and for the Toroidal Field (TF) magnets of the ITER magnet system have been extensively characterized in the SULTAN facility in Villigen, Switzerland by means of DC and AC tests. The AC tests were performed superimposing a sinusoidal magnetic field (amplitude of 0.2−0.3 T and frequency of 0.1 – 5 Hz) to a background constant magnetic flux density of 2 T and 9 T.
This paper describes the analysis of the AC loss tests of two CIC Conductors, identical to those used for the CS Insert and TF Insert recently tested in the CSMC facility in Naka, Japan. The numerical modeling of these experiments was performed by means of the THELMA code, by pushing the analysis to different levels of discretization (sub-cables of different cabling stages and strands). The comparison between measured and computed losses per cycle allows computing the interstrand contact conductances per unit length.

SULTAN AC loss tests

- In the SULTAN facility coupling currents are induced in the conductor through a time varying magnetic field applied orthogonal to the cable axis
- Losses measured by means of calorimetric method with temperature sensors located 800 mm apart in the High Field Zone (HFZ) [1]



SULTAN AC coils

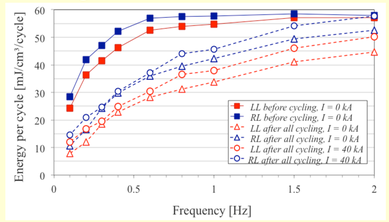


Power deposited in the supercritical helium

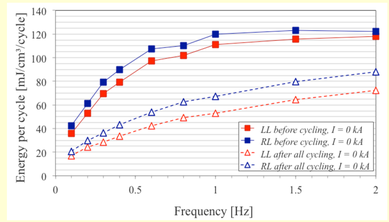
SULTAN Instrumentation

SULTAN tests of the CS conductor

- AC losses after cyclic loading are significantly less than before
- Increasing the magnetic flux density determines a significant drop of the losses
- The transport current in the conductor slightly modifies the AC losses after cyclic loading



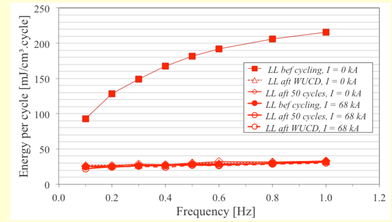
2 T DC, ± 0.2 T AC



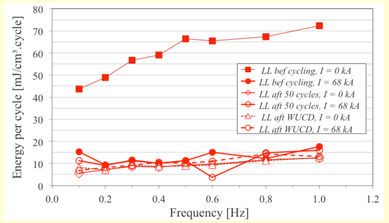
9 T DC, ± 0.2 T AC

SULTAN tests of the TF conductor

- The drop of the AC losses occurs during the initial phase of the test campaign
- Strong impact of the transport current: even before EM cyclic loading the losses with transport current drop to the values found at the end of the test campaign



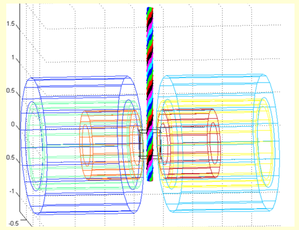
2 T DC, ± 0.3 T AC



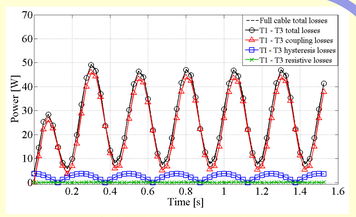
9 T DC, ± 0.3 T AC

THELMA modeling of the CS conductor in SULTAN

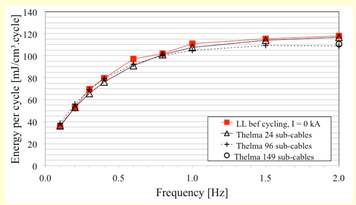
- Numerical model for interstrand coupling currents induced between sub-cables and corresponding losses [2]. The model fitting parameter is the contact conductance between sub-cables per unit-surface.
- Analytical model to compute hysteresis losses, with effective diameter derived from the strand magnetization cycle [3].
- Three models of the CS cable developed, increasing the number of sub-cables described:
  24 (last but one cabling stage)
  96 (third cabling stage)
  149 (144 strands of one petal and 5 non-discretized petals)
- Contact conductances per unit surface:
  9.2 10^8 S/m^2 for sub-cables in the same petal (p.u.l. 8.2 10^6 S/m)
  7.4 10^8 S/m^2 for sub-cables in different petals (constant ratio from [4])



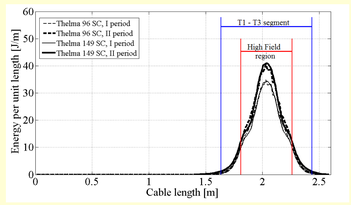
THELMA CS Conductor model



149 sub-cables model
2 T DC, ± 0.2 T AC, f = 2 Hz



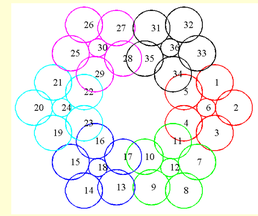
Thelma models vs experimental results
2 T DC, ± 0.2 T AC



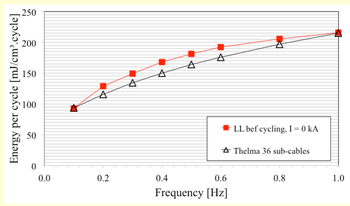
149 vs 96 sub-cable models
2 T DC, ± 0.2 T AC, f = 2 Hz

THELMA modeling of the TF conductor in SULTAN

- Cable discretized with 36 sub-cables of the last but one cabling stage
- Copper cores at the center of the petals described with a temperature and magnetic field dependent resistivity.



36-sub cable model



Thelma model vs experimental results
2 T DC, ± 0.3 T AC

- Contact conductance per unit surface between sub-cables of the same petal: 6.3 10^8 S/m^2
- This parameter is of the same order of magnitude as the value found for the CS conductor.

Summary

- Analysis of AC losses of TF and CS conductors in the SULTAN facility shows dependencies on DC magnetic flux density, EM cyclic loading and transport current
- The THELMA model results provide insight on the space distribution and time evolution of the AC losses
- The numerical results suggest that refining the model to reach the strand level does not significantly modify the computed AC losses with respect to models including sub-cables of the third and fourth cabling stage

References

[1] P. Bruzzone, et al. "Test results of two European ITER TF conductor samples in SULTAN." *IEEE Trans. Appl. Supercond.*, vol. 18, n. 2, pp. 1088-1091, 2008.
[2] M. Breschi, P. L. Ribani, "Electromagnetic Modeling of the Jacket in Cable-in-Conduit Conductors", *IEEE Trans. Appl. Supercond.*, vol. 18, n. 1, pp. 18 – 28, 2008
[3] M. Breschi, et al., "Analysis of AC Losses in the ITER Central Solenoid Insert Coil", *IEEE Trans. Appl. Supercond.*, vol. 27, n. 4, Article Number 7762085, 2017
[4] E. P. A. van Lanen, et al, "Full-scale calculation of the coupling losses in ITER size cable-in-conduit conductors", *Supercond. Sci. Technol.*, 25, Art. ID 025012, 2012