Modelling Innovative High Temperature Superconductors for Fusion Applications

Summary

Most of the nuclear fusion reactors currently under design include conductors made of High Temperature Superconducting (HTS) materials in their magnet systems, at least as an option to be investigated, and the advantages of this technology are pushing the R&D of conductors suitable for tokamak operation. However, there are still several challenges in the conductor development and, a fortiori, in the magnet design. As for the ”classical” Low Temperature Superconducting (LTS) magnets, also for those to be built with HTS numerical tools are used to predict the magnet performance. Nevertheless, the numerical tools for the estimation of the, e.g., thermal-hydraulic (TH) and electric performance currently available are those developed for LTS magnets, such as the 4C code.

In this work, a qualitative assessment of the modelling assumptions of these numerical codes is carried out first, showing the inadequacy of LTS modelling approaches if applied to fast transients, such as the quench, in conductors based on HTS materials. After this qualitative analysis, a quantitative assessment based on detailed models developed on purpose is described, focusing on the HTS Cable-In-Conduit Conductor (CICC) designs proposed by ENEA and by the Karlsruhe Institute of Technology.

The quantitative assessment hints at a new modelling strategy, i.e., the conductor cross-section needs be lumped in several thermal, electric and fluid regions, rather than just two as in the LTS CICC. Therefore, since the 1D discretization *along* the conductor axis is still needed, a tool capable of handling an arbitrary number of 1D thermal, electric and fluid regions along the conductor axis is required. This calls for the development of a new numerical model which is described here and implemented in the new computer code H4C. Furthermore, an electric model able to handle transverse resistance between current carrying elements is required, while the (simpler) electric model adopted for LTS, e.g., that implemented in 4C, assumes no transverse electric resistance.

H4C is then subjected to the standard verification procedure, as well as to a preliminary validation based on recent quench experiments performed in SULTAN, showing that the new code can properly describe the quench propagation in HTS CICC.

An extensive set of applications of H4C is finally presented. The first one is the analysis of quench propagation in CICC, showing that indeed the LTS modelling approach fails in some situations where localized heating is present. The new model can also give a deep insight on how the current redistributes during a quench among the

different tapes of each stack. The code, however, relies on free parameters, such as the heat transfer coefficients between the different cable sub-elements related to the thermal contact resistance, as well as the electric contact resistance between the current-carrying elements. In order to feed the model with the needed parameters for the TH and electric model, dedicated experiments in liquid nitrogen were carried out to directly measure such parameters, such as the electric contact resistance between the tapes and the stacks. Whenever measurements are not available, values from the literature are assumed. The quench analysis of the ENEA CICC also has a feedback on the Divertor Tokamak Test (DTT) Central Solenoid HTS insert design, allowing to suitably tune the quench protection strategy.

H4C was then upgraded to simulate an entire magnet, equipped with HTS layers, such as one of the options of the EU DEMO CS. The simulation of the normal operation (plasma burn) of the EU DEMO CS is carried out, assessing the impact on the magnet performance of different level of localized defects, i.e., local decrease of the critical current density, in the HTS tapes. This analysis shows that damaged stacks lead to a strong decrease of the temperature margin in the neighboring strands. Finally, the simulation of quench propagation in the magnet is presented. The quench is initiated as a consequence of the defects in the stacks, which, beyond a certain threshold, can lead to quench of the conductor even during the normal operation of the magnet. The maximum temperature reached during the quench in the HTS CICCs stays below 160 K, however large temperature differences are observed in the cross-section during the quench initiation, requiring attention to limit secondary stresses.