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Superconductive cables current distribution analysis

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Abstract

A computational tool is being developed for the analysis of superconductive magnets, combining detailed descriptions of termination joints and cables to thermo-hydraulic (TH) models. In parallel, an experiment (Stability Experiment Upgrade—SexUp) has been designed with the target to study the current distribution in cable in conduit conductors (CICC). Finally, the establishment of a reliable method for the measurement of the current distribution profile on the cable cross section is being implemented on the ITER toroidal field model coil (TFMC).

Keywords: Superconductive cables; CICC; TFMC

1. Structure of the code THELMA

The code thermo-hydraulic electro-magnetic analysis (THELMA) is composed of three main parts:

a) a section devoted to the analysis of the resistive joints and of the associated short lengths of cable;
b) another section, solved simultaneously to the first one, dedicated to the modeling of the cable region, possibly over great lengths;
c) a thermo-hydraulic (TH) subroutine, coupled to the two electro-magnetic sections.

1.1. The model of joint region

The model of the joint termination is based on a lumped parameters electrical network and aims at the analysis of the current distribution in the resistive saddle material and in the contact regions

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between joint saddle and cable strands. The model of the superconductive cable is made up of a certain number of strands and macrostrands. The main input data are, besides the characteristic parameters of the strand material: the strand/macrostrand diameter, the void fraction, the distributed contact resistance and the features of the multi stage cable construction. The number of contact points between strands/macrostrands is then determined counting wherever the distance between the strands/macrostrands axis is below a certain threshold. Each contact point corresponds to a concentrated resistance in the electrical network. On the basis of the number of contact points and of the per unit transverse resistance, the “per contact” resistance is then calculated and assigned as lumped parameter at the electrical network model. The cross section of the joint is discretized by means of a 2-D polygonal mesh and is represented with a set of resistors.

1.2. The cable model

The description of the current distribution in the s-c cable is based on a distributed parameter circuit model [1]. The cable is characterized by a set of cable-elements: each cable-element can be a single strand or a bundle of strands. The unknowns are the differences between the actual current in each cable element and the current which would flow in case of uniform distribution. The geometry of each cable-element is calculated from the input data.

The cable model is well suited for the analysis of long cable sectors, as in real size coils. In fact, the distributed parameters circuit approach allows to describe long range coupling currents with a relatively coarse mesh, obtaining a significant reduction of the number of unknowns with respect to lumped parameters circuit models [2]. Moreover, the model structure, based on a set of partial differential equations, is essentially the same as that used for the TH description, simplifying the coupling of the two models. The model is also able to calculate AC losses due to inter-strand coupling currents and electric field in the strands.

1.3. The thermo-hydraulic model

A TH model is included in THELMA in the form of a subroutine of the main electro-magnetic program. The TH model solve a full set of 1-D Euler-like equations for helium in the variables velocity (v), pressure (p) and temperature (T_{He}) plus the transient heat conduction equations for strands and jacket separately ($T_s \neq T_{jk}$). The system is then discretized with a finite element, for the geometry, and finite difference, for the time, method. At each time step, first the electromagnetic model is solved with the temperature constant in time and a new value for the power loss is obtained. Then, the TH model is solved, taking into account the calculated power loss distribution, and the new value of the temperature is obtained.

2. Validations

The section of THELMA dealing with the cable model was successfully tested by comparing it against the code CUDI-cable in conduit conductors (CICC) [3]. In one of the test cases for example, the second half of a 10 m piece of cable is exposed to a time varying external magnetic field with a time rate of 1 T/s. Only the six last stage cable elements were considered. The main results are shown in Fig. 1.

3. Experimental activities

3.1. Check of the geometrical accuracy of the cable model

To verify the geometrical model of the cable, the self and mutual induction coefficients of the strands of two test samples of the have been measured and the results have been compared with the calculated ones. The test samples were manufactured with 36 enamel coated copper strands ($3 \times 3 \times 4$), having a diameter of 0.81 mm, and twist pitches of 42, 83 and 126 mm for the three cable stages. The void fraction was 36.1% and the conductor outer diameter was 8.55 mm.

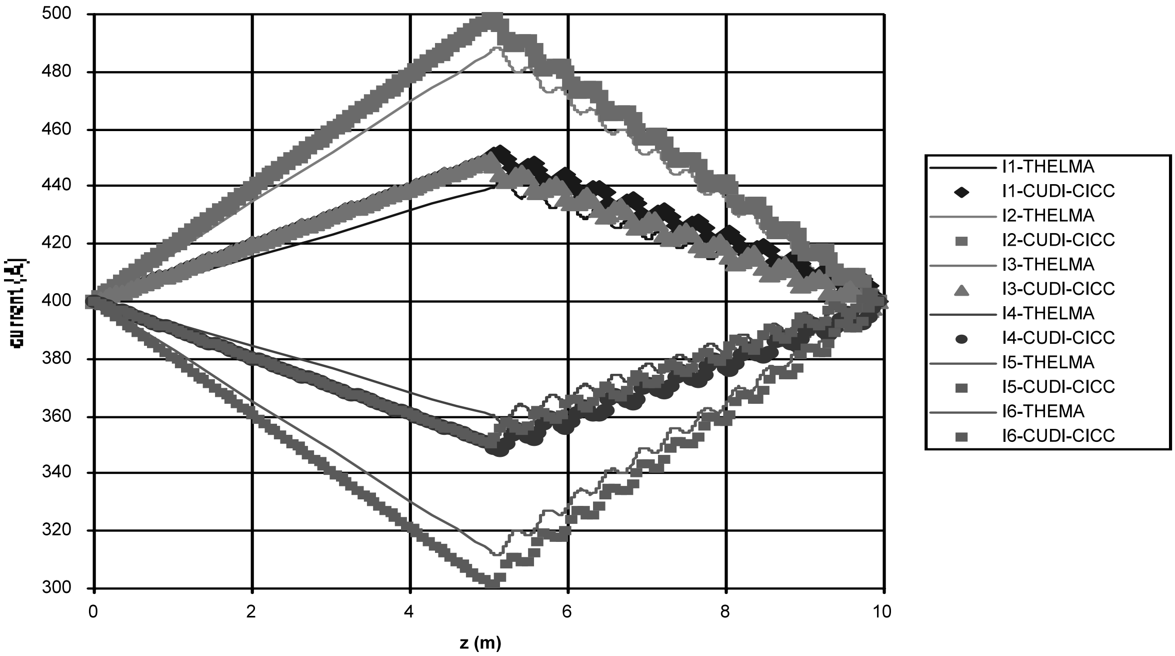

Fig. 1. Current distribution calculated by means of CUDI-CICC (lines) and THELMA (symbols), 1/4 pp.

One of the samples was rectilinear and 3 m long; the other was wounded, 13 m long. The results of about 150 measurements performed at 1 kHz on the rectilinear sample are shown in Fig. 2, where they are compared with the same number of values from calculations of inductances between randomly chosen strands. The values are grouped at intervals of 0.2 μH on the horizontal axis. The similarity between the two distributions gives confidence on the accuracy of the geometrical representation of the cable.

3.2. The stability experiment upgrade

The behavior of two sub-size superconducting cables, forced flow liquid helium cooled, CICC, will be compared in the new Stability Experiment Upgrade (SexUp). The only difference between the

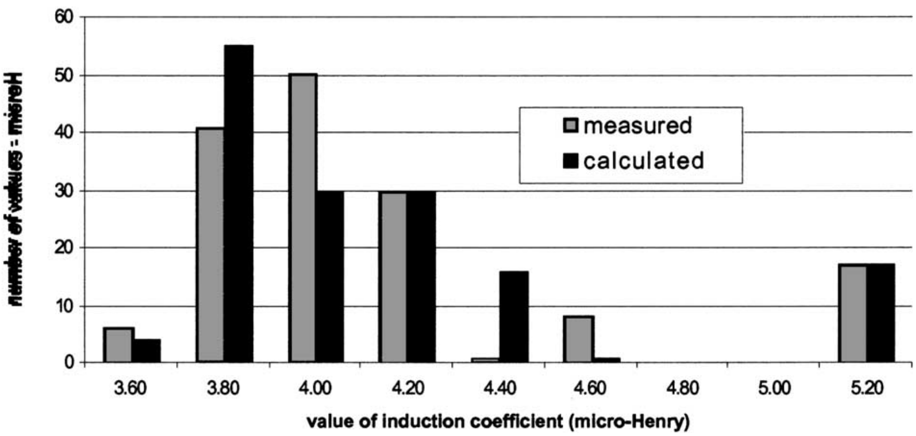

Fig. 2. Comparison between inductances measured (light grey) and calculated (dark grey) value, 1/4 pp.

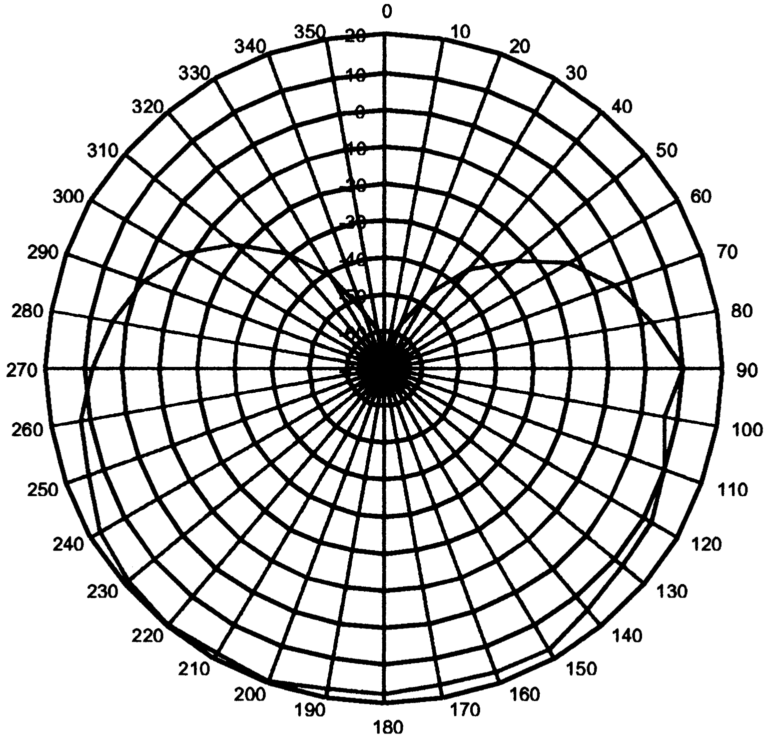

Fig. 3. Polar plot of compensated tangential field signals, 1/4 pp.

two cables is the presence on one of them of an external 1/3 wrapping. Thirty-six $(3 \times 3 \times 4)$ Nickel coated NbTi strands are used. The cable external diameter is 8.12 mm (bare) and 9.12 mm (insulated). The stainless steel jacket is 1 mm thick. The winding is about 100 m long and is composed of eight layers of 23 turns each. The coil has an inner diameter of 100 mm, an outer diameter of 250 mm and a height of 214 mm. The module electrical terminations have been designed to allow a controlled current non-uniformity. Three of the four last cable stages (nine strands each) are in fact connected to three separated current leads. The strands of the fourth last cable stage is subdivided in two bundles of six and three strands each and connected to other two current leads. The arrangement allows, therefore, the controlled injection of five independent currents in the cable. The experiment is an ideal test bank for the verification of the accuracy of methods based on Hall probes arrays for the reconstruction of the current distribution in s-c cables. Finally, the possibility to impose a known current imbalance offers of course the possibility to produce a series of results targeted to the validation of the THELMA code.

3.3. Measurement of the current distribution

The attempts to obtain the re-construction of the profile of the current density are normally based on sets of magnetic field probes, for instance based on the Hall effect, suitably located as near as possible to the conductors. For the 2002 test campaign on the toroidal field model coils (TFMC), two measuring heads, each provided with twelve Hall effect probes, will be installed on one of the busbars at a distance of a quarter of a pitch. While the aim is to obtain the current distribution at the location of the measuring heads, the local magnetic fields is also affected by the current flowing in other sections (e.g. the return conductor). To eliminate this influence, one can subtract the magnetic field readings from the ones obtained in case of uniform distribution of current, e.g. in resistive conditions, opportunely scaled to the same total transport current [4]. Alternatively, the effects can be calculated on the basis of the known geometry [5]. A full size measuring head was tested with a resistive mock-up of the TFMC busbar. The mock-up had six rectilinear petals, insulated one from the another, of which one could be fed with a current independently from the other five. In one of the test cases, the five petals were fed with 600 A (120 A each) while the sixth was unloaded. The polar plot of the tangential components of the magnetic field, obtained as described above to compensate for the effects of the return conductors, is shown in Fig. 3. The comparison between re-constructed currents, obtained using only six tangential signals at 60° intervals, and the actual ones in the petal shows good agreement.

	I1	I2	I3	I4	I5	I6
Actual	0	120	120	120	120	120
Reconstructed	15.6	112.8	115	112	120	116.9

4. Conclusions

A code, THELMA, aimed at the accurate representation of complete superconductive magnets in transient conditions is at an advanced stage of development. The tool combines the detailed description of joint terminations and cable with a TH model, so that a consistent and simultaneous solution of the system can be obtained.

Several complementary experimental activities are also in progress aimed at providing suitable and specific data for the validation of THELMA and at defining reliable measurement systems for the study of the current distribution in CICC.

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