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Fusion Engineering and Design 75–79 (2005) 11–15
Fusion Engineering and Design
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DC and transient current distribution analysis from self-field measurements on ITER PFIS conductor

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Available online 26 July 2005

Abstract

Current reconstruction in cable-in-conduit conductors (CICC) cables is a crucial issue to determine cables performance in working conditions, and must be performed using inverse problem approaches as direct measurement is not feasible. The current distribution has been studied for the ITER Poloidal Field Insert Sample (PFIS) conductor using annular arrays of Hall probes placed in three different locations along the sample during the test campaign at the SULTAN facility. The measurement apparatus is also described in the paper, together with the approach to current reconstruction.

Keywords: Current distribution analysis; ITER PFIS conductor; CICC cables

1. Introduction

A number of studies are presently being performed to investigate the behaviour of "cable-in-conduit conductors" (CICC) superconducting cables under conditions of practical interest for the ITER magnets [1,2]; in particular, the current distribution (CD) amongst the conductor's strands is an important issue as it may influence the performance of a CICC [4,3,5]. Unfortunately, direct measurements of CD inside a CICC are not possible. An indirect approach for the current profile estimate can be based on the measurement of the magnetic self-field around the CICC. The measurement system used for CD reconstruction in Poloidal Field Insert Sample (PFIS), tested in the SULTAN test facility under various working conditions [2], is based on Hall probes (HP) annular arrays (called "heads"), suitably placed around the cable [5]. First results about CD measurement are reported here. Two approaches to the CD reconstruction inverse problem are presented and

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doi:10.1016/j.fusengdes.2005.06.075

compared [6,7]. Both models are based on magnetostatic equations; the first one takes into account the internal 3D structure of the cable. The second model uses a somewhat simplified 2D geometry of the conductor, thus saving time for modelling and computation.

2. Description of the experimental layout

In the PFIS experiment, six heads with 10 HP each have been placed around the two cable sections to be tested. For construction ease, the heads have been paired in such a way that, at each sample cross-section, two heads simultaneously measure the field produced by the two parallel legs constituting the sample (see Fig. 1). The left leg had insulating tapes wrapped around the highest level substructures of the cable (the "petals"), while the right one had un-wrapped petals. The three couples of heads have been placed close to the upper termination (heads 1 and 2), in the SULTAN field peak region (heads 3 and 4), and close to the bottom joint (heads 5 and 6). The acquisition and signal

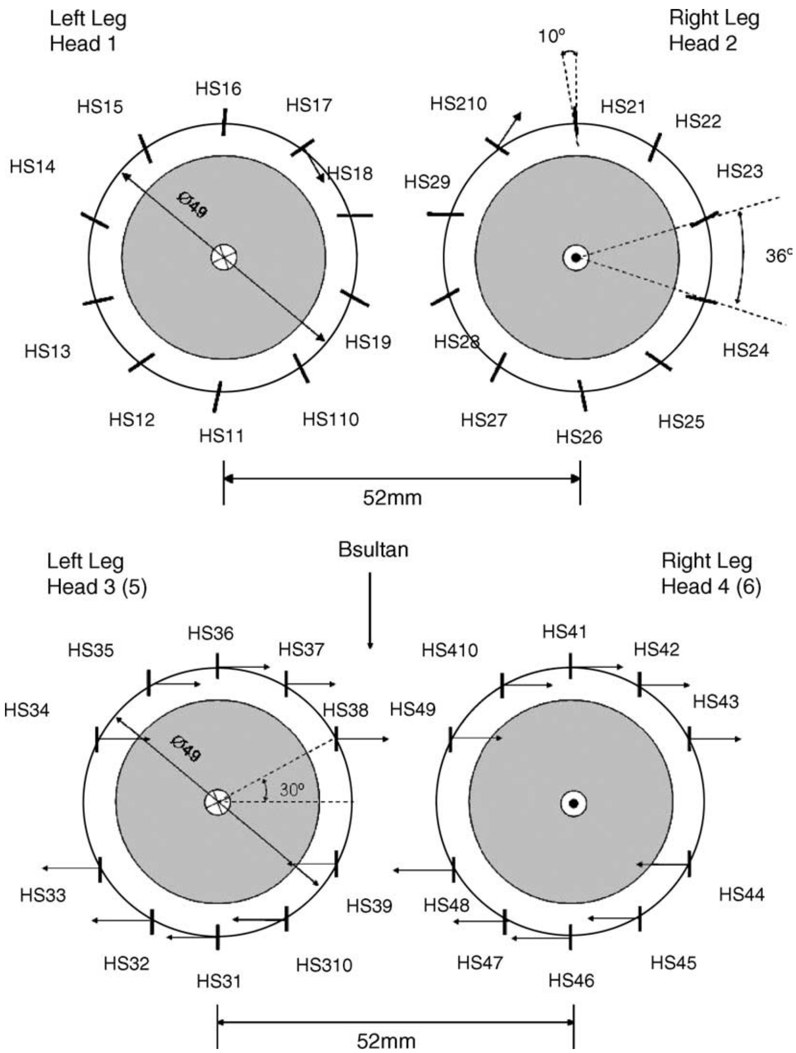

Fig. 1. Layout of heads 1 and 2 (upper) and 3 and 4 (lower). Heads 5 and 6 are identical to heads 3 and 4. Heads 1, 3 and 5 are on the 'Left' (wrapped) leg; heads 2, 4 and 6 are on the 'Right' (unwrapped) leg [2].

conditioning system allows to detect the field with an overall nominal accuracy better than 1%; the observed white noise on the Hall probe traces turned out to be of the order of ±0.1 mT.

3. Current distribution reconstruction procedures

The ITER type CICC are composed of more than 1000 superconducting strands and it is not realistic to reconstruct the current in each of them; consequently, in usual CD reconstruction procedures, a simplified representation base is adopted to describe the current carrying elements of the cable. The most diffused base, adopted here, is represented by currents associated to the petals. If no magnetic materials are present, the relationship among source currents and probes measurement can be stated, in the nominal configuration, as:

$$\mathbf{G}I = \boldsymbol{b} \times \boldsymbol{s} = \boldsymbol{m} \quad (1)$$

where $\mathbf{G}$ is the system Green matrix, whose elements g_{ij} provide the magnetic field component of the j-th base current at the i-th probe location along the sensing direction $\boldsymbol{s}_i$. $\boldsymbol{m}$ is the known terms vector, obtained as dot product of $\boldsymbol{b}_i$ (total field at i-th HP location) and $\boldsymbol{s}_i$ for each probe [5–7].

In the 3D model, g_{ij} is computed by evaluating the Biot-Savart superposition integral along the "current path" associated to the j-th base current. The current is then reconstructed using a truncated singular value decomposition (TSVD) of $\mathbf{G}$. In the simplified 2D model [7] the petals are assumed to be straight, infinitively long segments with uniform current density over the petal cross-section. The corresponding overdetermined system of linear equations similar to (1) is solved in the least squares sense by using the same TSVD technique. It should be noted that in reality the current is not necessarily distributed uniformly within a petal [8], and the assumption of the intra-petal uniformity is forced by the limited number of the available input data. Much care must be taken in the assembling of matrix $\mathbf{G}$ and vector $\boldsymbol{m}$, as the ill-posed nature of the problem causes errors on data to heavily impact on the solution. In fact, in the actual layout, (1) must be corrected as:

$$(\mathbf{G} + \Delta\mathbf{G})I = (\boldsymbol{b} + \Delta\boldsymbol{b}) \times (\boldsymbol{s} + \Delta\boldsymbol{s}) \Rightarrow \mathbf{G}I = \boldsymbol{m} + \boldsymbol{\varepsilon}_0 + \boldsymbol{\varepsilon}(I) \quad (2)$$

In (2), ΔG, Δb and Δs represent the uncertainty on the related variables (due to assembling tolerances, model errors and measurement noise), and $\varepsilon(I)$ and $\boldsymbol{\varepsilon}_0$ represent the overall uncertainty terms, depending or not depending on I, respectively. Note that $\boldsymbol{\varepsilon}(I)$ can be reduced by "tuning" $\mathbf{G}$ and $\boldsymbol{m}$ on a reference experiment for which I is known (e.g. with uniform CD). Unfortunately, in the case of the PFIS experiment, it was not possible to charge the sample with high enough current in the resistive state; consequently, a situation in which the current can be supposed uniformly distributed must be identified in other ways. It must be noted also that the particular geometry of the measurement system exposes the HP in heads 3–6 to a rather strong field along the plane of the sensors, causing a relevant planar Hall effect [9] that can alter significantly the sensor's linearity. Calibration experiments on the HP have been performed with the sample being in the normal state at $T > 10$ K and SULTAN field raised up to 8 T, with the aim to check alignment, linearity and calibration of the HP in heads 3 and 4. As shown in Fig. 2 for head 3, a non-linear, partly non-monotonous behaviour is observed versus the SULTAN field. In order to check the effect of this non-linearity on the measurement of transversal fields, a trapezoidal shaped perpendicular field of 0.4 T amplitude has been applied by means of a dipole coil, at different SULTAN field levels (between 0 and 8 T), observing variations of Hall coefficients up to 30%. It was also demonstrated that the response of the HP to the perpendicular field is rather linear, though some hysteresis was present. The

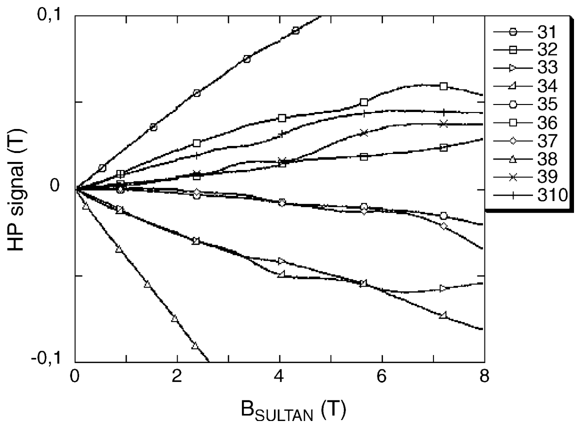

Fig. 2. Response of the HP in head 3 to the SULTAN background field.

exposed issues suggest to choose separate calibrations for each run, considering the differences in HP response and reconstructing current unbalances rather than petal currents themselves.

4. Detection and reconstruction of current redistribution

To validate the CD reconstruction procedures, a run in which a transition from the superconducting to normal state is thermally induced at constant current of 10.4 kA has been considered to define a reference current distribution. It is assumed that at high enough longitudinal electric field in the cable (above 100 μV/m, [10]), i.e. in the current sharing regime, the current distribution is close to the uniform one. Consequently, the reconstruction procedures have been calibrated to interpret the measurements at this instant (namely, t = 1121.5 s) as corresponding to uniform CD. By first analyzing the raw HP signals, appreciable variations with respect to the steady state distribution can be observed, indicating current transfer processes among different petals, occurring when approaching the current sharing level. This is shown in Fig. 3, where field variations with respect to the current plateau reference are plotted for some of the HP on head 3 (Left, wrapped leg). This redistribution process at the current sharing has been observed also for the Right, un-wrapped leg, and with higher signal variations. Under the assumption of the uniform current distribution just before the take-off (i.e. during current sharing at the highest measured electric field before a sudden, irreversible voltage development occurs), this may indicate that the current at the steady state, before starting sample heating, is non-uniformly distributed within the cable cross section in both legs, with higher non-uniformity in the Right one. Apparently, the local redistribution is easier in the Right leg thanks to the lower values of interstrand contact resistances.

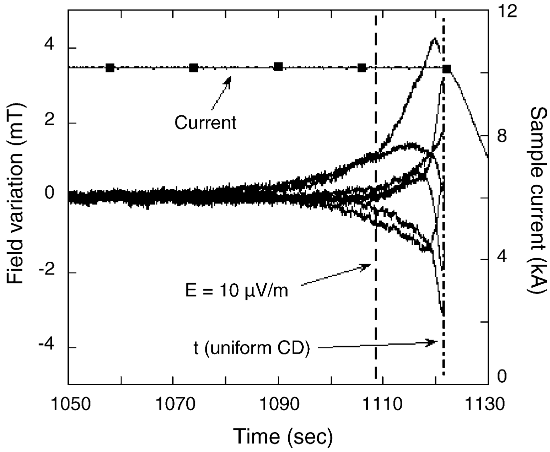

Fig. 3. HP signal variations with respect to the distribution at t = 1050 s for head 3 during current flat top of benchmark experiment. Sample current is also reported (right hand scale). The instant at which the electric field reaches the 10 μV/m value is evidenced for reference, as well as the time instant at which current distribution has been assumed to be uniform.

Using the algorithms for CD reconstruction exposed above, the maximum current unbalances during the temperature rise (since t = 1050 s until t = 1121.5 s) at the various head locations have then been determined, and are reported in Table 1 as a percentage of the petal current corresponding to uniform CD (i.e. 10.4 kA divided by 6, the number of petals). Both approaches use TSVD (10 singular values out of 12). It should be noted that the current unbalance at t = 1050 s (in steady state conditions) is caused primarily by the unavoidable non-uniformity of the joints.

The results obtained by both models are in reasonable agreement. The maximum current unbalance is observed in the conductor section exposed to the peak SULTAN field, and is in the range of 30% for both models. In addition, both models predict higher current unbalance in the right leg of the sample, which is in agreement with the observed signals variations. The discrepancy between the models can partly be

Table 1
Maximum current percentage unbalances at the various head locations reconstructed using 3D and 2D models

Model	Close to upper termination		Peak field		Close to bottom joint	
	Left (%)	Right (%)	Left (%)	Right (%)	Left (%)	Right (%)
2D	16	22	19	33	21	19
3D	17	30	22	29	8	16

explained by the differences in the geometrical description of the cable (e.g. annular orientation of the petals in respect to the HP, impacting up to 10–15% on the results) and the model inaccuracies, producing uncertainties in the reconstructed currents in the range of the relative differences between the models. In addition, the solution is quite sensible to the number of singular values considered in the current reconstruction process. This is a very delicate matter, as the larger is the number of retained singular values, the more sensible is the solution to inaccuracies and errors, but, conversely, a too conservative truncation would lead to the loss of significant details in the CD. At this stage it is hard to conclude that employment of one of the models is more favourable.

5. Conclusions

Results for current unbalance measurement and reconstruction procedure have been presented for the PFIS experiment. HPs, together with appropriate numerical modelling, can be used to detect current distribution in cables, but a reference distribution is needed to get absolute values. In the analysed run, current imbalance and current re-distribution processes can be clearly observed. The current reconstruction with a 2D and a 3D model has been performed. Models predictions are close to each other and the expected current unbalance is within 30% from the average current per petal. Further investigation is needed to assess results on other runs.

Acknowledgements

Authors wish to thank people from EFDA, CREATE, University of Twente, ENEA, IEE for their precious hints and suggestions; the SULTAN staff, and particularly P. Bruzzone, for their support in the experimental activity; and finally people from CEA for the fruitful discussions. This work is done in the framework of EFDA Technology Workprogramme 2004, ref. TW4-TMSP-PFCIAT.

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