Reconstruction of Current Unbalance in Full-Size ITER NbTi CICC by Self-Field Measurements

Yu. A. Ilyin, A. Nijhuis, H. H. J. ten Kate, P. Bruzzone, and B. Stepanov

***Abstract*—Methods have been developed to study the distribution of the transport current among the strand bundles of cable-in-conduit conductors (CICC) by using self-field measurements with Hall probe arrays. The unbalance in the transport current is mainly caused by the unavoidable nonuniformity of the joints and can be a reason for a change in the voltage-temperature characteristic and consequently of the temperature margin. In the present study we focus on the reconstruction of the current unbalance in a full size NbTi CICC tested in the SULTAN test facility. The crucial point in the reconstruction procedure is the proper choice of the reference self-field profile corresponding to a uniform current distribution. To achieve this uniform distribution, the conductors were driven far into the current sharing regime. The self-field profile corresponding to the highest achieved voltage level was taken as a reference. This assumption is supported by the modeling of current-sharing runs in the CUDI-CICC network model. Furthermore, local redistribution effects were observed in the conductors at high currents. The current transfer associated with this redistribution is analyzed as well.**

***Index Terms*—Cable-in-conduit conductor, current distribution, ITER, PF conductor, self-field measurements.**

I. INTRODUCTION

IN THE framework of the R&D program on ITER Poloidal Field coils [1], a full size conductor sample was tested in the SULTAN facility [2]. The sample comprises two straight specimens of the NbTi CICC connected by a hairpin joint [2]. The two conductors are identical except for the presence of stainless steel wraps around the last stage subcables (petals) in one of them, while the other conductor has no wraps. The conductors are named $\mathrm{PFIS_W}$ (Poloidal Field Insert Sample with wraps) and $\mathrm{PFIS_{NW}}$ (without wraps). The DC performance of both conductors, especially at high current level, appeared to be somewhat below predictions [2], [3]. It is argued then, that underperformance of both conductors could be a consequence of an unbalanced current distribution among the strands. The aim of the present work is an attempt to reconstruct the current unbalance in both conductors by using the measurements of the self-field profile around the conductors together with the earlier developed algorithm of current reconstruction [4]. Particularly we focus on the steady state current unbalance caused by the nonuniformity of the joints. The results of the calculations will be used for interpretation of the PFIS DC performance.

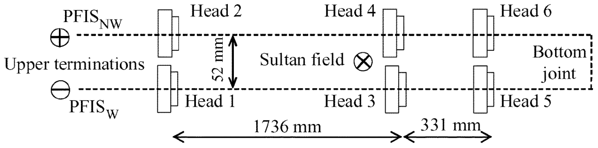

Fig. 1. Sketch (not in scale) of the PFIS sample with the Hall sensor heads and main dimensions. The directions of the transport current and the SULTAN field are indicated as well.

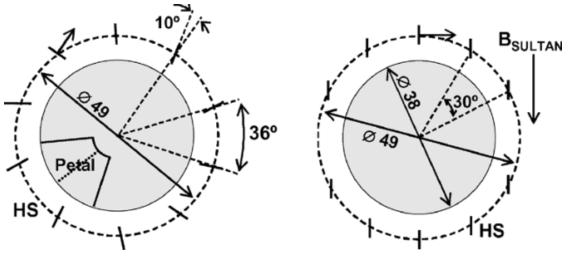

Fig. 2. Hall probes orientation and basic geometry in the heads #1, 2 (left) attached close to the upper termination and #3,4,5,6 (right) attached in the high field region and near the bottom joint.

II. EXPERIMENTAL ARRANGEMENTS

A. Instrumentation

In total six Hall probe (HP) arrays (heads) are attached to the PFIS to sense its self-field (see Fig. 1). The heads #1 and #2 are fixed close to the upper termination, heads #3 and #4 are installed in the high field region, and the other two heads #5 and #6 are installed close to the bottom joint. For better sensitivity, the HP's are placed as close to the cable as possible. For that, the conduit is turned round to a constant wall thickness of 3 mm at the location of the heads. Each head includes 10 HP's. Next to the upper termination, where the stray field from SULTAN is weak, the sensors are symmetrically distributed over the perimeter, making a 10 degree angle between their plane and normal line to the cable surface, see Fig. 2 left. This particular angle has been chosen with the aim of minimizing the conditioning number of the coefficient matrix related to the inverse problem of current reconstruction [5]. At the other four locations, the 10 sensors are oriented parallel to the background field (Fig. 2 right) to minimize its influence and to increase the signal/noise ratio [5]. The sensors were calibrated at room temperature and in liquid helium. The instrumentation noise in the HP signals is within $+/-$ 0.12 mT, which is at least an order of magnitude lower compared to the expected change during current redistribution. A detailed description of the heads can be found in [6].

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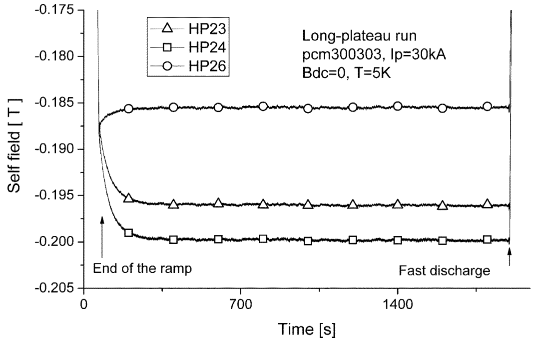

Fig. 3. Self-field in the high field region around the $\mathrm{PFIS_{NW}}$ as measured by the HP's during the LP run. Clearly seen is the redistribution process in the cable.

B. *Experimental Runs Analyzed*

All runs performed during the DC test campaign for the PFIS can be classified in three groups: critical current run ($\mathrm{I_c}$ run), current sharing temperature run ($\mathrm{T_{cs}}$ run) and long-plateau run (LP). In the $\mathrm{I_c}$ runs the current is increased at constant temperature and magnetic field until the quench occurs. In the $\mathrm{T_{cs}}$ run, the current is ramped up to a constant level and, after sufficient time for currents to redistribute, the temperature was increased in the conductors until it quenches. In the LP runs, the current is increased in the conductor with the maximum possible ramp rate (~400 A/s) and is kept constant then for at least 30 min to observe the redistribution process (from mainly inductive to resistive distribution, governed by the connection resistances between strands in the joints), and finally the current is ramped down.

An example of the LP run is shown in Fig. 3. A characteristic time constant of the redistribution process is about 200~300 s.

III. ANALYTICAL MODEL FOR CURRENT RECONSTRUCTION

A. *Formulation and Assumptions*

The conductor is modeled by means of a 2D six petal approximation with uniform current distribution within the petals [4]. (A comparison between the 2D and 3D models with the preliminary results on PFIS current reconstruction can be found in [7].) A petal is represented as a circular ring sector as shown in Fig. 2 left. Since both conductors are close to each other (Fig. 1), the HP's in each head are almost equally sensitive to the self-field created by both legs. For each location we seek the closest approximation to the solution of the over-determined system of linear equations (20 HP's and 12 currents) in the least squares sense. The equation to solve is often called a 'normal equation', in matrix form given as: $G^TGI = G^TB$, in which I is the vector of unknown currents in 12 petals (assumed straight, and infinitively long), B is the vector of measured self-field in 20 locations, G—is the coefficient matrix $(\mathrm{m} \times \mathrm{n})$ related to the geometries of the model [5]. Since in our case matrix G has a full rank (n), the G^TG is nonsingular and a unique solution exists to the least squares.

As said, we assume that the current distribution inside the petals is uniform and this is used as a boundary condition. This is done because no interpretative tools (cable models) exist that can handle the complexity of a large number of strands and not sufficient knowledge of all electrical contacts is available. Above all, in practice the solution of the inverse problem is limited by the number of HP's that is used. A larger number of HP's would not improve the solution because the accuracy is limited by the experimental conditions. So we still have to keep in mind that all methods of current reconstruction based on self-field measurements can give solutions with even larger uncertainty when local nonuniformities are present inside the bundles. A cable having the size of a petal has no homogeneous current distribution, even when all the strands are connected by very low resistance at the joint. This was demonstrated with the analysis of the self-field measurements on the so-called SeCRETS conductors in SULTAN [9]. In principle, the full-size ITER conductors can be considered as having six of such conductors in parallel.

B. *Choice of the "Reference Profile"*

A reference self-field profile corresponding to a uniform current distribution in the conductors is essential for the current reconstruction [5], [7], [8]. Because of the unavoidable geometrical uncertainties (HP's orientation and location of their sensitive zone, position of the cable bundle relative to the conduit etc) and influence of a stray field, the 'uniform' profile can not be simply calculated and should be determined experimentally. Such 'calibration experiment' can be performed by supplying a current to the conductor being in the resistive state (above $\mathrm{T_c}$), see for example [9], [10]. However, in the present experimental conditions such an experiment is impractical due to limitations from the power supply and a cryogenic system. Instead a 'resistive-uniform' approach is proposed. It is assumed that at a high level of voltage (above 100 $\mu\mathrm{V/m}$) in the part of the conductor in peak field, the current is distributed mainly according to the resistances built up in the conductor, which are believed to have much smaller dispersion compared to the contact resistances in the joints. It is supported by the modeling of a $\mathrm{T_{cs}}$ run in the PFIS with the CUDI-CICC code [11] that the current distribution at high level of electric field ($> 100\ \mu\mathrm{V/m}$) becomes rather uniform compared to the one governed by nonuniform joints, see Fig. 4. A sufficiently high voltage in the conductors can be achieved in the $\mathrm{T_{cs}}$ runs, see Fig. 5. Unfortunately, the high level of voltage could only be reached in both conductors below 35 kA [2]. To evaluate the current unbalance at higher currents, the reference self-field profile determined at 10–35 kA had to be scaled to high current.

IV. RESULTS AND INTERPRETATION

A. *Six-Petals Problem, Low Current*

Two $\mathrm{T_{cs}}$ runs are considered here, both at 10 kA, performed before and after cyclic loading of the conductors [2]. The self-field profile corresponding to the nonuniform current distribution is chosen at an instant of constant current and before the temperature in the conductor starts rising. In principle, the solution of the concerned 'normal equation' depends on the choice of an annular position of the petals inside the conduit. Since this position is unknown (and correlation between locations is poor due to variation in the cable twist pitch with length [12]), the solution in all three locations has been found for any combination

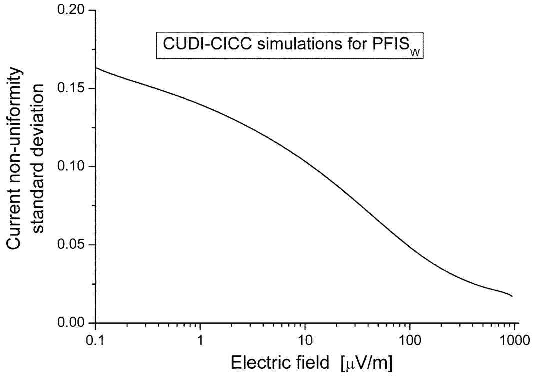

Fig. 4. Current nonuniformity vs. the electric field in the high field region during the T_{cs} run as simulated by CUDI-CICC on the $\mathrm{PFIS_W}$.

TABLE I

CURRENT UNBALANCE IN THE MOST OVERLOADED PETALS AS MAXIMUM AND MINIMUM DEVIATION FROM THE AVERAGE CURRENT PER (SUB-)PETAL, IN %

6-petals Problem						
	Upper joint		High field		Bottom joint	
Type of run	$\mathrm{PFIS_W}$	$\mathrm{PFIS_{NW}}$	$\mathrm{PFIS_W}$	$\mathrm{PFIS_{NW}}$	$\mathrm{PFIS_W}$	$\mathrm{PFIS_{NW}}$
T_{cs} run, 10kA, before cycling	21 (15)	25 (10)	25 (13)	54 (20)	26 (15)	27 (15)
T_{cs} run, 10kA, after cycling	20 (14)	36 (21)	33 (19)	55 (17)	32 (19)	28 (18)
I_c run, 60kA, before cycling	10 (7)	31 (17)	22 (14)	32 (16)	37 (20)	36 (21)
12-sub-petals Problem						
T_{cs} run, 10kA, before cycling	23 (19)	45 (36)	53 (37)	53 (50)	32 (27)	62 (49)

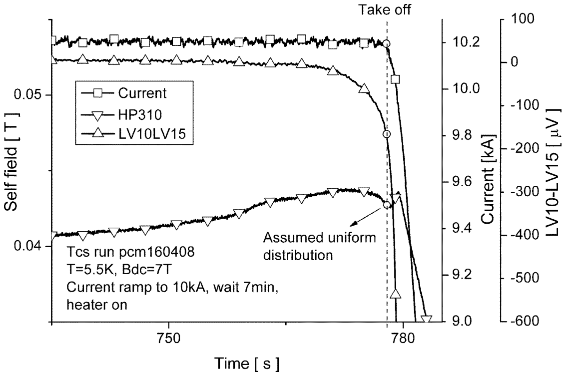

Fig. 5. Example of the T_{cs} run in the $\mathrm{PFIS_W}$ and definition of the self-field 'reference profile' for HP 310. The total transport current and voltage in the high field region (LV10-15) are shown as well.

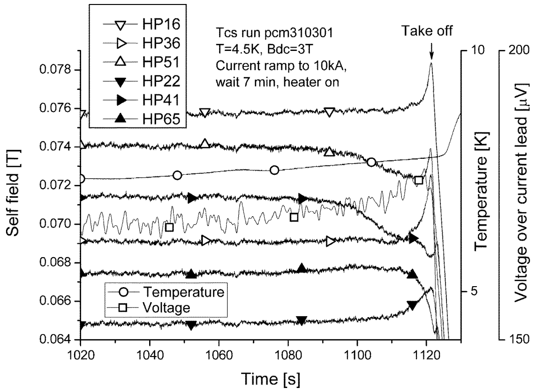

Fig. 6. T_{cs} run in the $\mathrm{PFIS_W}$ $\mathrm{PFIS_{NW}}$. The HP's in all three locations are sensitive to the current redistribution.

of the rotation angles between 0° and 60° (the limits are due to periodicity of the solution) in both conductors. Then for each angle we have found an overloaded petal with the maximum deviation from the average current per petal. Finally, the least and the most overloaded ones have been chosen among the selected petals, and the results are gathered in Table I. An estimated error in current unbalance is within ±15%. The numbers in brackets correspond to the minimal degree of current unbalance in the least overloaded petals. For both conductors the maximum unbalance does not exceed 55 ± 15% from the average current per petal. There seems to be no change in the current distribution before and after cyclic loading of both conductors.

As can be seen from Fig. 6, the temperature increase causes a change in the self-field profile in all three locations along both conductors. Most likely the current redistribution happens through the joints as having lower contact resistances compared to inter-petal contact resistances [12] and hardly along the length, in particular for the sample with petal wraps. It is also confirmed by the resistance rise over the termination in the $\mathrm{PFIS_W}$ (see Fig. 6) and by simulations with CUDI-CICC [11]. Subsequently we may assume that six petals are isolated and thus in three locations along the conductor's length the degree of current unbalance should be identical. Based on the results in Table I we may conclude that the maximum current unbalance of about 25% in both conductors satisfies this condition.

B. Six-Petals Problem, High Current

The third line in Table I corresponds to the I_c run with the take off at 60 kA. The duration of the run exceeds the characteristic time constant and we may assume that at the end of the ramp the current is redistributed mainly according to the resistance distribution in the joints. The results of calculation show that at high currents the current distribution caused by the nonuniform joints is not more uneven than at lower currents. It is also confirmed by the measurements of the transversal voltages on the conductors (Fig. 7) [2], [11]. Transversal voltage is measured by potential taps attached to the opposite sides of the conduit surface in the same conductor's cross-section. If the current balance between the petals changed, it would also change the slope of the curves in Fig. 7, but it remains the same for both runs.

C. Twelve-Sub-Petals Problem

As discussed, in practice there are no grounds to believe that current inside each petal is uniformly distributed between the sub-petal bundles. To investigate the possible unbalance within a petal (intra-petal), a 12-sub-petals model was used. For this, each of six petals was subdivided in two equal area sub-petals (Fig. 2 left). The problem with 12 sub-petals can be classified as underdetermined (24 sub-petals and 20 HP's). In this case a unique solution would be the one having the minimum norm

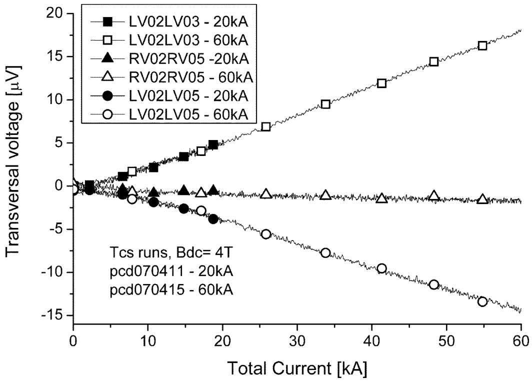

Fig. 7. Transverse voltages in the same cross-section as measured on the conductors' jackets versus sample current in two runs. "R" stands for $\mathrm{PFIS_{NW}}$ and "L"—for the $\mathrm{PFIS_W}$.

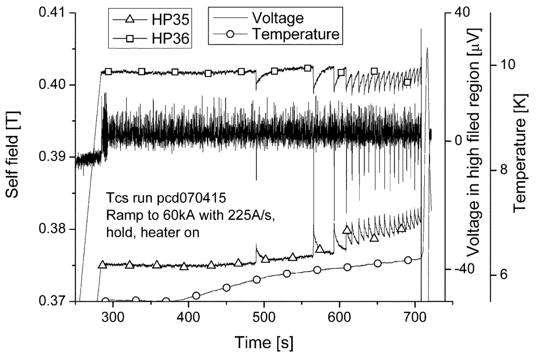

Fig. 8. Spikes on the HP's and voltage traces (in high field region) during the $\mathrm{T_{cs}}$ run in the $\mathrm{PFIS_W}$ can be associated with local quenching of the overloaded strands or strand-bundles.

[4]. This solution is less physically sound because the minimization is not based on any physical properties of the problem, thus can only be justifiable for indication of a minimum current unbalance required to satisfy the problem. The solution to the 12-sub-petals problem is shown in Table I for the same $\mathrm{T_{cs}}$ run at 10 kA. It is seen that the maximum current unbalance between two neighboring sub-petals in the high field region may reach up to 50%.

D. Local Quenches

During the $\mathrm{T_{cs}}$ measurements at high current, spikes were observed on the HP's and voltage traces as shown in Fig. 8. The frequency of the spikes increased with raising temperature. The spikes were observed *only* in the $\mathrm{PFIS_W}$ and *only* in the high field region. The reason for the spikes is likely the local quench of the overloaded strands or strand bundles and corresponding current redistribution. Similar spikes and current redistribution were observed and analyzed in [9], [13], [14]. Applying the 12-sub-petals model, we found that the current transfer between two neighboring sub-petals associated with a spike is ~10% of the average current per sub-petal (or ~500 A at 60 kA total current). The absence of the spikes in the $\mathrm{PFIS_{NW}}$ suggests more uniform current distribution in this conductor. Although the results (6-petals model) in Table I point toward higher inter-petal current unbalance in the $\mathrm{PFIS_{NW}}$, this, however, can not exclude somewhat higher intra-petal unbalance in the $\mathrm{PFIS_W}$. Conclusions on the intra-petal current unbalance based on the 12-sub-petals model can not be definitive since there is a number of uncertainties and assumptions used in the models and thus influencing the results to a great extent. The spikes in the $\mathrm{PFIS_W}$ are believed to be a better argumentation for the higher degree of intra-petal current unbalance in this conductor.

V. CONCLUSION

According to the 6-petal model, the maximum inter-petal current unbalance in the PFIS does not exceed 55% of the average current per petal. Assuming no current transfer along the conductor, the average current unbalance is within 25%. Cyclic loading of the conductors does not enhance the current unbalance. Neither does it change between low and high transport currents. The intra-petal current unbalance in the 12-sub-petals model can be up to 60% from the average current per sub-petal. The local voltage and HP's spikes observed on the $\mathrm{PFIS_W}$ suggest local quenching of strand bundles due to higher intra-petal current unbalance in this conductor and less tolerance to redistribute the excess current due to wraps.

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