Effect of Cyclic Loading and Conductor Layout on Contact Resistance of Full-Size ITER PFCI Conductors

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***Abstract*—An evolution of the contact resistances (R_c) of two full-size ITER (International Thermonuclear Experimental Reactor) cable-in-conduit conductors (CICC) aimed for the Poloidal Field Conductor Insert (PFCI) was studied in the Twente Cryogenic Press. The conductors are distinguished by the presence of stainless steel wraps around the last stage sub-cables in one of the conductors. The R_c and AC loss were measured on the conductors being in the "virgin" state and after they have been loaded 40,000 times with a peak force of 315 kN/m. The test results are compared with those, obtained on sections from the same conductor lengths, in the SULTAN test facility. The consequences of the cyclic loading and the sub-cable wraps on the R_c and the coupling AC loss are discussed in view of the previously published results on full- and sub-size ITER NbTi CICCs. Special emphasis was paid to the measurements of the contact resistances between individual sub-cables and the conduit, since the knowledge of them is important for proper interpretation of the DC test results. As a final goal, the test outcome will be used as a reference for calibration of the PFCI AC loss performance.**

***Index Terms*—AC loss, cable-in-conduit conductor, contact resistance, ITER, PF conductor insert.**

I. Introduction

The test of short length full-size (FS) conductors aimed for the Poloidal Field Conductor Insert [1] have been carried out in the SULTAN test facility [2]. The sample preparation and instrumentation details can be found in [2], [3]. The sample is named PFIS (Poloidal Field Insert Sample) and comprises two sections joined at one end by a hairpin joint. One section is the regular PF Ni-plated NbTi CICC with sub-cable wraps ($\mathrm{PFIS_W}$) and the other one is "de-wrapped" section ($\mathrm{PFIS_{NW}}$). The experimental program in SULTAN includes DC performance test, AC loss test, current distribution test and testing of the joint. In parallel, the test on AC loss and contact resistance on both $\mathrm{PFIS_W}$ and $\mathrm{PFIS_{NW}}$ specimens was carried out in the Twente Cryogenic Press. Since the number of loading cycles is limited in the SULTAN test program (to 100 bipolar load cycles), a further investigation of the influence of a large number of load cycles on the conductors' performance is possible in the press in a relatively short time. The press [4] can deliver a variable (cyclic) transverse force of at least 800 kN/m directly to a cable section of 400 mm length at temperatures between 4.2 K and 300 K. The results of R_c and AC loss measurements for both samples and their comparison with the test results in SULTAN are reported here.

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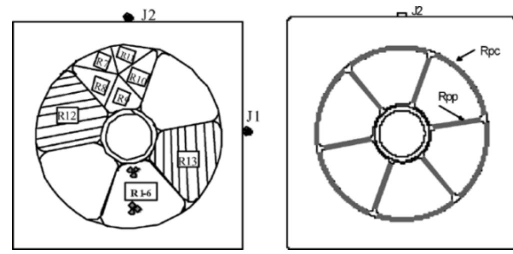

Fig. 1. Left—schematic representation of the strand and strand bundle connections for R_c measurements: 1–6 are single strands for inter-strand (IS) R_c, 7–13 are strand bundles for inter-bundle (IB) R_c; right—geometrical 2D model for solving the R_{pp} (petal-to-petal) and R_{pc} (petal-to-conduit) resistances.

II. Press Sample Preparation

Two short pieces of both PFIS conductors were tested in the press [4] following a procedure described in detail in [5]. The strands and strand bundles for resistance (R_c) measurements are selected according to the network presented in Fig. 1 left. In order to evaluate the contact resistance between a petal and the conduit (R_{pc}) in the $\mathrm{PFIS_{NW}}$, two superconducting strands (NbTi, ∅ 1 mm) were soldered to the outer surfaces of the conduit along the whole length of 400 mm (J1 and J2 in Fig. 1 left). These SC strands represent equipotential lines on the conduit. The AC loss of the conductors in the press is monitored by a magnetization pick-up coil method [4], [5], calibrated by means of boil-off AC loss measurements. In order to compare the cables' performance in the press and in SULTAN, the maximum force applied in the press is 315 kN/m, which is the same as the EM peak force in SULTAN (±45 kA @ 7 T) used for cyclic loading of the conductors [2].

III. Results and Discussion

A. Contact Resistances R_c

The R_c results versus the number of loading cycles for both conductors are presented in Figs. 2–4, and summarized in

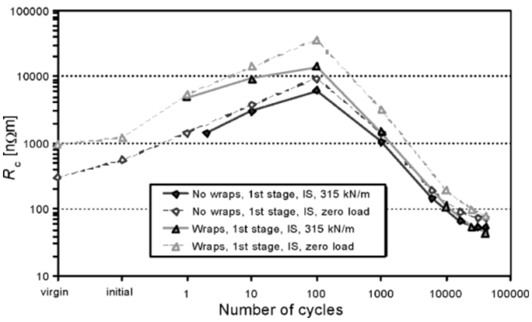

Fig. 2. R_c between single strand combinations within a first triplet, for both conductors versus the number of cycles, with $F = 0$ and 315 kN/m, $B_{dc} = 0$, (for all figures, ne = neighboring, op = opposite strands or bundles).

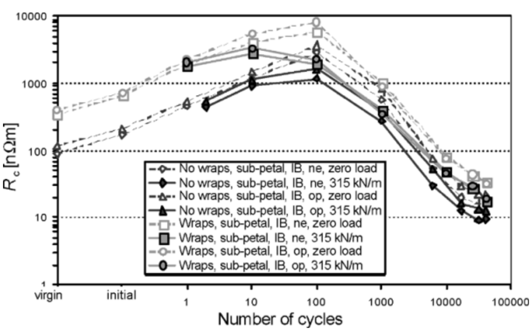

Fig. 3. R_c between sub-bundles belonging to the same last cabling stage, for both conductors versus the number of cycles, with $F = 0$ and 315 kN/m, $B_{dc} = 0$.

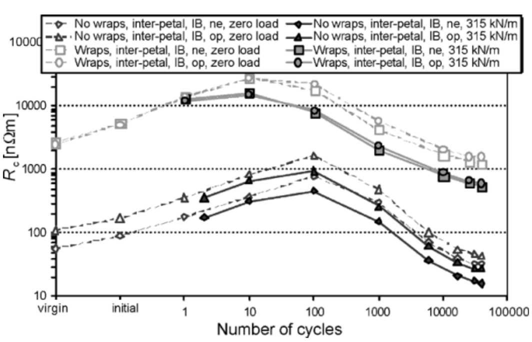

Fig. 4. R_c between the last stage sub-bundles (petals), for both conductors versus the number of cycles, with $F = 0$ and 315 kN/m, $B_{dc} = 0$.

Tables I and II. At first the R_c is measured on the conductors being in virgin state. The "initial" values of R_c are measured in the press before any force is applied on the conductors. An increase of the "initial" R_c by 20–50% compared to the virgin R_c is caused by a relaxation of the conductors after splitting their jackets [5].

The presence of petal wraps in the $\mathrm{PFIS_W}$, strongly affecting the values of inter-petal R_c, seems to be also responsible for higher values of the virgin IS and sub-petal R_c in $\mathrm{PFIS_W}$ compared to $\mathrm{PFIS_{NW}}$, despite the same coating, cabling pattern and void fraction of both conductors. Similar enhance of the virgin IS and sub-petal R_c in a sub-size (SS) conductor with wraps was observed in [7]. Apparently, the paths to redistribute the current are limited within a petal by the high resistivity of the wraps.

The values of virgin IS and sub-petal R_c in $\mathrm{PFIS_W}$ are bigger by approximately a factor of 5 compared to those of the FS NbTi

TABLE I
R_c RESULTS IN FIRST STAGE TRIPLET AND STRAND BUNDLES UNDER FULL AND ZERO LOADS, FROM ZERO TO 40 000 CYCLES FOR $\mathrm{PFIS_W}$

Average R_c [nΩ·m] for neighboring strands and bundles					
	315 kN/m		0 kN/m		
stage	max.	end	virgin	max.	end
single strands (1st stage)	14,200	45	940	36,300	80
sub-petal (4th stage)	2,750	18	340	5,730	33
petal (5th stage)	16,600	552	2,700	28,100	1,240

TABLE II
R_c RESULTS IN FIRST STAGE TRIPLET AND STRAND BUNDLES UNDER FULL AND ZERO LOADS, FROM ZERO TO 40 000 CYCLES FOR $\mathrm{PFIS_{NW}}$

Average R_c [nΩ·m] for neighboring strands and bundles					
	315 kN/m		0 kN/m		
stage	max.	end	virgin	max.	end
single strands (1st stage)	6,140	54	304	9,430	74
sub-petal (4th stage)	1,170	10	90	2,830	16
petal (5th stage)	470	22	57	793	33

Ni-plated conductors with wraps from [5], while the virgin inter-petal R_c is by a factor of 5 lower in the $\mathrm{PFIS_W}$. Together with the results from [8] it suggests that in Ni plated conductors the R_c is very sensitive to the manufacturing process and at present can not be controlled within a narrow span.

The evolution of the R_c during cyclic loading is qualitatively similar for both conductors with maximum between cycles 10 and 100, just as it was observed many times in the FS and SS conductors tested in the past [5]–[7]. The increase in R_c is an order of magnitude for both conductors compared to their virgin level. Beyond the peak, between 100 and 40 000 loading cycles, the R_c gradually decreases toward below the virgin level. Still no saturation of the R_c was observed after 40 000 cycles. The final values of IS and sub-petal R_c after 40 000 cycles for both conductors deviate within 50%. Conversely, the difference between final inter-petals R_c of both conductors remains rather high, about 30 times.

For both $\mathrm{PFIS_W}$ and FS NbTi Ni-plated conductors with wraps from [5], the difference between their IS and sub-petal R_c also becomes less after 40 000 cycles and amounts to 30%.

The values of R_c not only determine the AC loss (as discussed below), but also the ability of the current to redistribute and thus the stability of a conductor against current nonuniformity. It was demonstrated in [9] that in a SS SULTAN sample without inter-stage wraps, the unbalanced current, caused by connecting only 75% of total strands to one current lead, is able to redistribute along the cable before it reaches the high field region, where the I_c is measured (at about 2 m). While a conductor with petal wraps is unable to redistribute this current unbalance over the same length. Both SS conductors have 288 SC strands and are to some extent similar to a petal in the PFIS (though the cabling pattern is different). It was reported in [7] that inter-petal R_c for the SS conductor without wraps was $\sim 100\ \mathrm{n\Omega m}$, and $\sim 3500\ \mathrm{n\Omega m}$ for the SS conductor with wraps in virgin condition. Comparing this SS data with the sub-petal R_c of the present FS conductors, we can conclude that a current redistribution between the petals and even within a petal, is easier in the $\mathrm{PFIS_{NW}}$. If the current nonuniformity were only caused by the

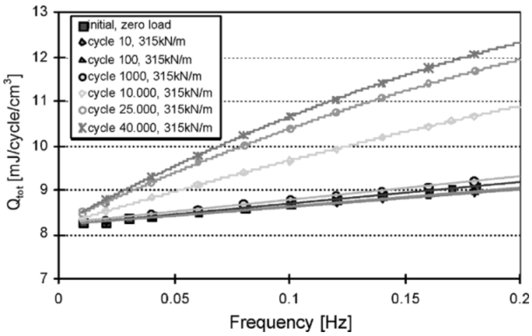

Fig. 5. Evolution of AC loss in conductor with wraps in virgin condition and with $F = 315\ \mathrm{kN/m}$ up to 40 000 cycles; $Ba = 150\ \mathrm{mT}$, $Bdc = 350\ \mathrm{mT}$.

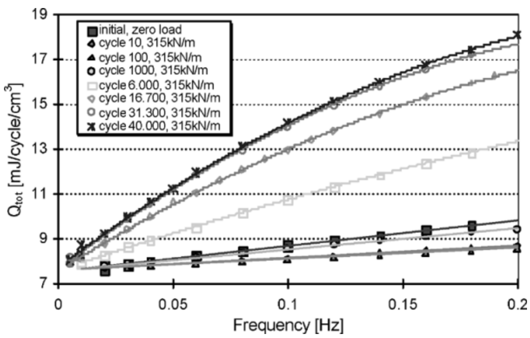

Fig. 6. Evolution of AC loss in conductor without wraps in virgin condition and with $F = 315\ \mathrm{kN/m}$ up to 40 000 cycles; $Ba = 150\ \mathrm{mT}$, $Bdc = 350\ \mathrm{mT}$.

upper termination of the PFIS sample, just as in the case of the SS-samples, the current unbalance would be improved at least in the $\mathrm{PFIS_{NW}}$ over the length between the termination and the high field region (about 2 m). However, if the nonuniformity of the current is caused by the bottom PFCI joint, with the distance to the high field region significantly shorter than for the SS samples, an effective redistribution is not expected, even not for the $\mathrm{PFIS_{NW}}$.

B. AC Loss in Cryogenic Press

The AC loss results obtained in the press are shown in Figs. 5 and 6. The total loss is normalized to the NbTi strand volume in order to match the hysteresis loss at zero frequency. The development of the AC loss during cycling nicely correlates with the change of R_c. Initially there is a decrease of the loss but after cycle 100 the loss starts increasing.

The characteristic time constant $n\tau$ of coupling currents is determined by linear regression along the low frequency range. The evolution of the $n\tau$ with cycling for both conductors is depicted in Fig. 7. As mentioned, the $n\tau$ reaches its minimum around cycle 100 and amounts to ∼10/8 ms (load/ no load) for $\mathrm{PFIS_W}$ and 15/12 ms for $\mathrm{PFIS_{NW}}$ (the main part of the loss comes from the intra-strand loss). Decreasing of the R_c with number of cycles leads to increase of $n\tau$ toward 246/141 ms (load/no load) in $\mathrm{PFIS_{NW}}$ and 64/41 ms in $\mathrm{PFIS_W}$ after 40 000 cycles. The $n\tau$ in the $\mathrm{PFIS_W}$ remains within the target range (for PF conductors, see [10]) of 100 ms due to the presence of the petal wraps. It should be noted, nevertheless, that using a single $n\tau$ approach to evaluate the coupling loss in multistage FS conductors at higher frequencies can be fallacious.

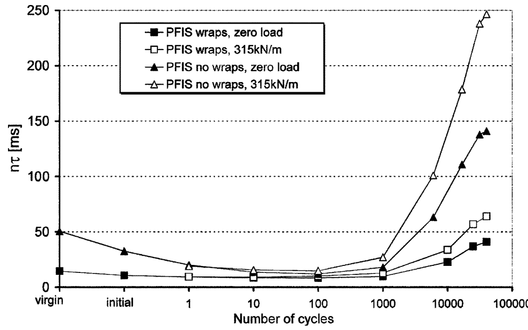

Fig. 7. Evolution of the coupling AC loss time constants in the virgin state, with $F = 0$ and 315 kN/m as measured in the Twente Cryogenic Press and in SULTAN.

Qualitatively, the presence of wraps in the $\mathrm{PFIS_W}$ limits the AC loss. Quantitative comparison between both conductors might not be fully correct as the presence of wraps is not the only difference. It was reported [11] that during unwrapping of the cable for the $\mathrm{PFIS_{NW}}$ conductor preparation, its last stage twist pitch substantially increased from the average 490 mm (regular for the $\mathrm{PFIS_W}$) to an average of 540 mm with the maximum of 650 mm at the tail of the cable. The twist pitch of the $\mathrm{PFIS_{NW}}$ conductor piece tested in the press was checked afterwards and appeared to be 600 mm. As the contribution of the last stage loss to the $n\tau$ is dominant at low frequencies [5], an expected $n\tau$ with the regular twist pitch would be by a factor of $(600/490)^2$ lower compared to the measured one in $\mathrm{PFIS_{NW}}$. On the other hand, the effective length of the sample in the press is limited to 400 mm. This means that another correction for the $\mathrm{PFIS_{NW}}$ coupling loss is required as the loss of a section much shorter than one pitch is not fully representative for long lengths (20 to 30%) [12]. Thus, the expected $n\tau$ of the $\mathrm{PFIS_{NW}}$ with the 490 mm twist pitch would be about 200 ms (under load). Note, that this correction is only about five percent for the $\mathrm{PFIS_W}$, giving adequate precision for $\mathrm{PFIS_W}$.

In [5] an empirical relation to calculate the $n\tau$ of the FS CICC was proposed. Applying this relation to the $\mathrm{PFIS_W}$ will result in $n\tau$ of 12 ms in virgin conditions and 44 ms after 40 000 cycles and under full load. The correlation with the measured values is within 30%.

It is likely that different cabling pattern of the PFIS conductors compared to the previously tested FS CICCs is the reason for the lower than predicted $n\tau$ in the $\mathrm{PFIS_W}$. For the case of $\mathrm{PFIS_{NW}}$ the calculated $n\tau$ (with the twist pitch of 600 mm) are 174 ms for the virgin condition and 621 ms after 40 000 cycles and under full load. A correction for the length in the press would result in lower $n\tau$ of 116 and 414 ms correspondingly. Still these values exceed the measured ones by a factor of 1.7∼2.3. Apparently, the mentioned relation from [5], verified on 10 FS CICCs with identical cabling pattern and sub-cable wraps [5], is no longer valid for conductors without sub-cable wraps.

C. AC Loss in SULTAN

Unfortunately, the AC loss results of PFIS in SULTAN are unsatisfying. In the calorimetric measurements, the temperature sensors were not reliable. The magnetization signals could not

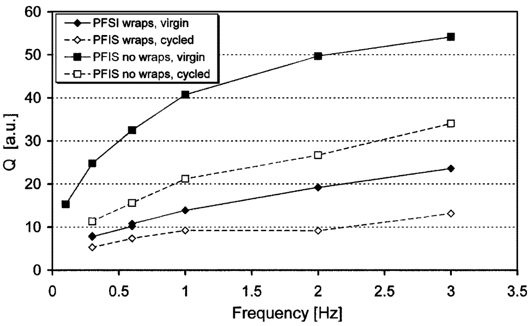

Fig. 8. Test results in SULTAN. Evolution of the AC loss (by calorimetric method) in both conductors in virgin state and after 100 bipolar load cycles; $Ba = 200$ mT, $Bdc = 2$ T.

be properly compensated. A full reliable evaluation of the calorimetric AC loss in absolute units was not possible.

Nevertheless, a qualitative correlation was found between the development of the AC loss with electromagnetic loading of the conductors in SULTAN and in the press. In Fig. 8 the calorimetrically measured AC loss curves are shown for both conductors for the virgin state and after they have been loaded 200 times. The AC loss was measured by applying a sinusoidal field with the amplitude of 0.2 T in the presence of a background field from SULTAN of 2 T. After loading of the conductors, the $n\tau$ (extracted from the initial slope of the loss curves) drops by a factor of 4.5 for $\mathrm{PFIS_{NW}}$ and by a factor of 2.4 for $\mathrm{PFIS_{W}}$. These numbers should be compared to 4.2 and 1.8 correspondingly as measured in the press. Qualitatively the SULTAN results are in line with those obtained in the press.

D. Contact Resistance R_{pc}

For evaluation of the conductor $V - I$ characteristics, potential taps are usually attached directly to the outer surface of the conductor's conduit. The choice of the (angular) position of the potential taps on the conduit, in relation to the cable elements, can strongly affect the evaluation of the cable longitudinal electric field in case when the outer conduit surface is not equipotential and the current in the cable is not uniformly distributed. The potential distribution on the jacket depends, in turn, on the values of the R_{pc}. Especially for the $\mathrm{PFIS_{NW}}$ the R_{pc} is expected to be lower than in the cable with wraps leading to a nonequipotential condition on the outer surface of the conduit. To evaluate the R_{pc}, a simplified 2D model (Fig. 1, right) is built in FEMLAB software, in which the contact resistances R_{pc} and R_{pp} (petal-to-petal) are adjusted in the way to satisfy the experimental results of the *virgin* R_c measurements. In the model, the contact resistances are represented as thin conducting layers on the border separating the conductor's elements. The resistivity within the petals is assumed zero. The measured specific resistivity of the conduit is 540 $\mathrm{n\Omega m}$ @ 4.2 K. First, the R_{pp} resistance is matched to satisfy the inter-petal R_c, resulting in average value of $R_{pp} = 76\ \mathrm{n\Omega m}$. Next, the R_{pc} is chosen to match the voltage measured in the combinations "petal—SC strand on the conduit". For this case the choice of the contact area between the SC strands on the surface of the conduit, or the width of the solder strip, appears essential. For assumed two extreme (though realistic) widths of 1 mm and 5 mm, the calculated R_{pc} is one order of magnitude different (47 and 470 $\mathrm{n\Omega m}$). Thus, the calculation of the voltage distribution should be performed also for two different values of R_{pc} in order to identify the influence of this parameter on the potential distribution.

IV. Conclusion

The contact resistance R_c of both conductors are affected by the cyclic loading and, consequently, so is the coupling AC loss. During the first 10–100 cycles the R_c tends to increase, resulting in a minimum in coupling loss (mainly intrastrand loss) in both conductors. The AC loss results in SULTAN confirm the decrease of the AC loss during the first several hundreds of loading cycles. Beyond the peak, the R_c decreases toward the level quite below the virgin state and no saturation is observed.

A high R_c level during the first several thousands of cycles in both conductors can hamper the current redistribution between the strands in case of nonuniform current distribution. This conclusion is based on the stability analysis of SS conductors.

The coupling loss from the last stage sub-cables contributes considerably to the AC loss. However, the difference in twist pitch of the conductor without wraps impedes regrettably an accurate direct comparison between both conductors. The obtained AC loss results on the short piece of $\mathrm{PFIS_{W}}$ can be used as a reference for a calibration of the AC loss in the PF conductor insert.

A petal-to-conduit R_{pc} is evaluated for virgin $\mathrm{PFIS_{NW}}$ using R_c measurements and 2D finite element modeling of a conductor. Knowledge of the R_{pc} is important for proper evaluation of the longitudinal voltages measured on the conductors.

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