Evolution of Contact Resistance and Coupling Loss in Prototype ITER PF NbTi Conductors Under Transverse Cyclic Load

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***Abstract*—Cyclic energizing of a magnet coil with Cable in Conduit Conductors (CICC), as for fusion applications, results in an anomalous change of the interstrand contact resistance (R_c) and coupling loss ($n\tau$) due to the alternating transverse forces. Previously, three Nb_3Sn ITER conductors have been tested in a cryogenic press, up to 40 cycles. Now, for the first time, the behavior of NbTi conductors under cyclic load is investigated and results are presented for three full-size prototype ITER Poloidal Field (PF) Coil conductors. One conductor has bare copper strands and no petal wrapping while the others have a Cr and solder strand surface coating. The press can transmit a maximum transverse force of 800 kN/m directly to a cable section of 400 mm length at 4.2 K. Each conductor is tested up to 220 kN/m and 40,000 full loading cycles. The magnetization of the conductors and the R_c between combinations of strands and strand bundles is measured at various number of cycles. It appears that the R_c can vary for up to orders of magnitude during cyclic loading.**

I. Introduction

THE ITER CICC conductors [1] are subjected to heavy transverse loading due to the Lorentz forces in the coils causing a deformation of the cable inside the conduit. This deformation is interrelated with mechanical, electromagnetic and thermohydraulic effects. A cryogenic cable press was built at the University of Twente to simulate the impact of the Lorentz forces on a conductor equivalent to ITER magnet operating conditions [2]. The press can transmit a variable transverse (cyclic) force of more than the Central Solenoid conductor peak load (650 kN/m) directly to a cable section of 400 mm at 4.2 K. The evolution of the magnetization (coupling loss time constant $n\tau$) and the R_c between various strands and strand bundles inside the cable can be followed along its loading history, starting at virgin condition. Knowledge of the evolution of the R_c is crucial for evaluation of the coupling current loss, the stability, the ability of current redistribution and the cable axial voltage-current trace in combination with the nonuniformity of the joints [3]. In previous experiments with the press, two Central Solenoid Model Coil conductors (CS1 and CS2) and a TFMC (Toroidal Field) conductor were tested, all containing Nb_3Sn strands [4], [5]. It was observed that $n\tau$ declines and R_c increases substantially with the number of cycles and it seemed that after roughly 40 cycles saturation in R_c was reached.

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TABLE I
SPECIFICATIONS OF THE NbTi CONDUCTORS

	EM/CRPP bare Cu	VNIIKP Cr / solder
No of strands	1152	1152
Twist pitch strand [mm]	18	12
Diameter strand [mm]	0.81	0.81
Cabling stages	3 x 4 x 4 x 4 x 6	3 x 4 x 4 x 4 x 6
Cabling pitches [mm]	45x85x125x160x410	51x86x121x156x407
Subcable Wrapping	Non	SS tape
Jacket material	SS type 1.4429	Incoloy 908
Bundle void fraction [%]	38	36

The interstrand contact surfaces interfere by micro-sliding, which results in friction and anomalous R_c behavior versus applied load [6]. It seemed possible that the R_c could reduce again substantially after a significant number of micro-sliding cycles [7]. In order to examine this effect for ITER type of conductors, the press was modified recently for fully automatic cycling.

II. Conductor Samples

Three full size prototype ITER NbTi CICC's are selected for the first series of measurements with 40 000 full loading cycles. The layout is practically similar to that of the CS1 conductor [1]. One conductor is manufactured by Euro Metalli (EM, Italy) [8] and the others are manufactured by the Russia Joint Stock Company VNIIKP Moscow (Russia). The EM CICC has no high resistive petal (last minus one cabling stage) wrapping and no strand coating and was tested in SULTAN at Centre de Recherches en Physique des Plasmas CRPP (CH). Both VNIIKP CICC's contain petal wraps, one having the strand surface coated with Cr and the other with solder. The solder (PbSnSb) coated conductor is identified as FS-1152 S and the Cr coated conductor as FS 1152 C. The samples are specified in. After splitting the conduit, the void fraction is obviously determined by the press. The AC loss of the conductors in the press is monitored by a magnetization pick-up coil method [2]. The magnetization system is calibrated by means of boil-off AC loss measurements.

The R_c is measured with the four-point-method, using a current of 50 A and is defined as:

$$R_c = \frac{V}{I} \cdot l \; [\Omega\text{m}] \tag{1}$$

in which V is the measured voltage, I is the applied current through the selected strand or strand bundle combination and l is the length of the jacketed section.

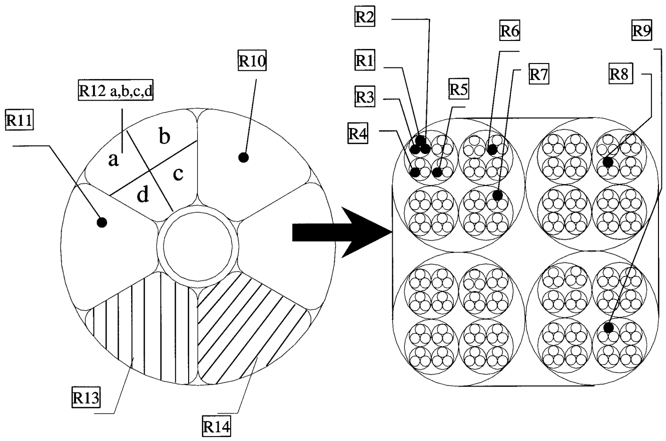

Fig. 1. Schematic representation of the strand and strand bundle connections for R_c measurements.

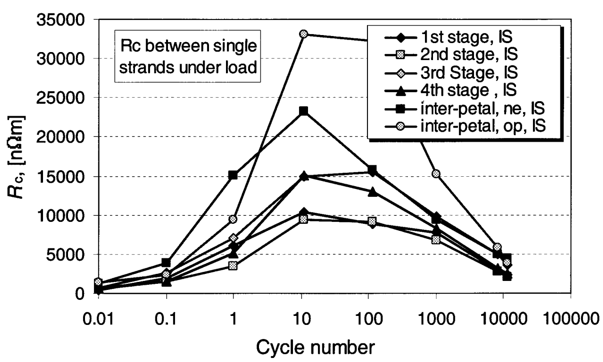

Fig. 2. R_c for single strand (IS) combinations from different cabling stages (EM/CRPP) versus number of cycles, with $F = 220$ kN/m, $B_{dc} = 0$ T (ne = neighboring, op = opposite strands or bundles).

The R_c between a pair of sub-cables or strands is measured according to the network connections as schematically presented in Fig. 1. The connections indicated with $R1$–$R2 \ldots R11$ refer to single strands (IS) from different locations in the cross section. While R12a-d, R13 and R14 are strand bundles for inter-bundle (IB) R_c measurements. For these strand bundles (IB) all strands belonging to the bundle are soldered in parallel at one end.

III. EM/CRPP Conductor Without Petal Wraps

The $n\tau$ of the EM/CRPP conductor is determined only in the virgin state and amounts to 135 ms. The transverse peak load for the NbTi conductors is chosen as 220 kN/m. This is roughly a factor of two lower than the peak force for the Nb_3Sn conductors, because the operating magnetic field is lower for the NbTi PF coils. After 11 130 full loading cycles, a mechanical defect emerged in the cryogenic press and so it was brought back to room temperature in air environment. The results of all the interstrand (IS) intra-petal and inter-petal R_c's versus the number of loading cycles from the virgin state to 11 381 cycles are presented in Fig. 2 (full load). A comparison of the R_c values for triplet (IS), sub-petal (IB) and petal level (IB) under load is made in Fig. 3. No clear saturation was reached after 11 381 cycles and so after repair of the press the experiment was continued proceeding up to 41 581 cycles. The most characteristic R_c results

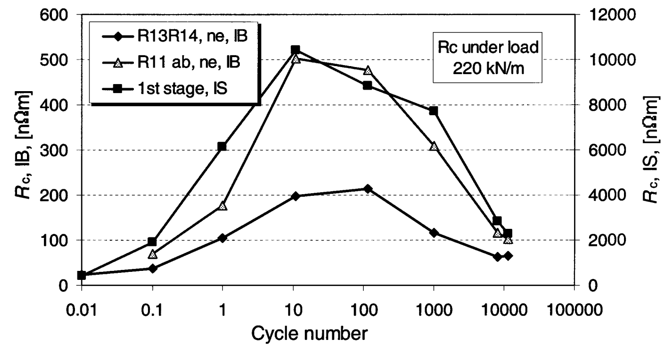

Fig. 3. The average R_c for triplet (IS) sub-petals (IB) and petals (IB) with $F = 220$ kN/m versus the number of loading cycles, 1st series.

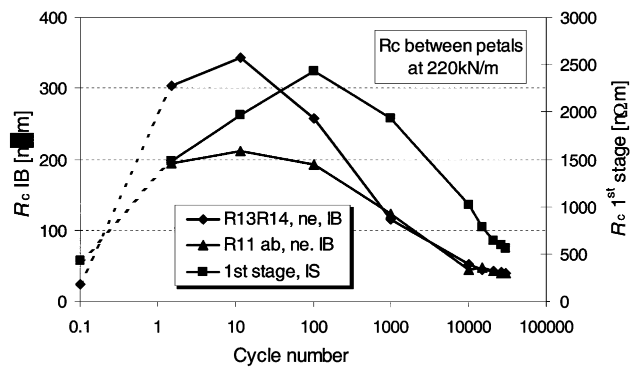

Fig. 4. The average R_c for triplet (IS) sub-petals (IB) and petals (IB) with $F = 220$ kN/m versus the number of loading cycles, 2nd series.

TABLE II
R_c Results in Fist Stage Triplet, Sub-Petal and Petal Strand Bundles Under Full and Zero Loads, From Zero to 41 581 Cycles

R_c [nΩm] for neighbouring strands and bundles					
	virgin	220 kN/m		0 kN/m	
stage		max.	final	max.	final
(1st stage triplet) IS	420	10,400	560	123,000	7,000
sub-petal (4th stage) IB	<70	500	39	1,190	220
petal (5th stage) IB	24	210	39	900	730

the 2nd series are gathered in Fig. 4 and all results are summarized for both series of cycling in Table II. A relaxation in the R_c after unloading for a one-month period is clearly observed. The maximum in R_c, under full load, for both series appears already between 10 and 100 cycles, just as it was found for the Cr-plated Nb_3Sn CS and TF CICC's. The increase is about one order of magnitude compared to the virgin level, which apparently is the minimum value. The data in 'virgin state' are taken before separating the jacket because some effect on conductor handling cannot be avoided when inserting the sample into the press. Beyond the peak, between 100 and 10 000 loading cycles, the R_c gradually decreases and saturates after 10 000 cycles toward roughly again the virgin level. In the second series, again the same characteristic behavior is observed. The relatively strong stresses in the cable, during the cable manufacture, could possibly be responsible for creation of low resistive contacts in the virgin state. The drastic increase in R_c during the first 100 cycles, may then be related to disruption of the low resistive contacts due to strand micro-sliding. During relaxation

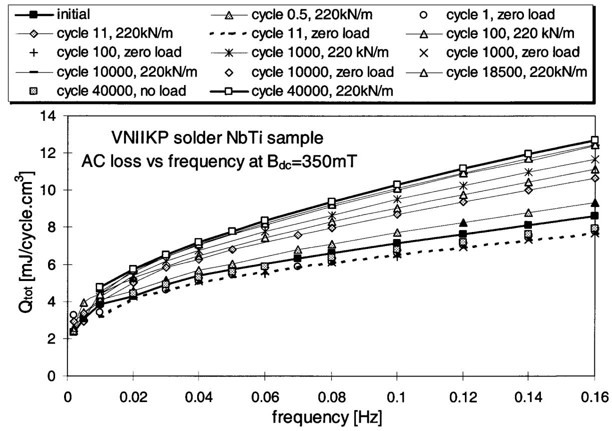

Fig. 5. Evolution of the AC loss in the FS 1152-S specimen in initial state, under load (220 kN/m) and without load up to 40 000 cycles.

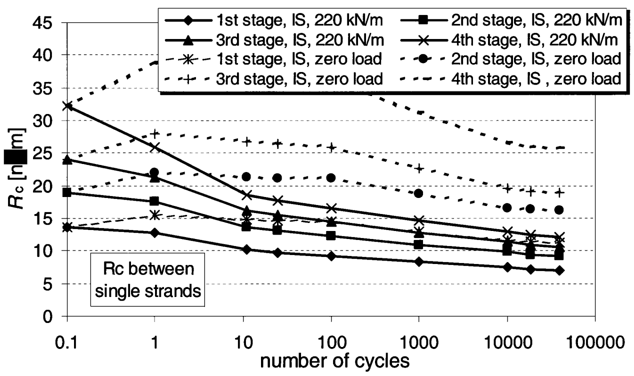

Fig. 6. R_c for single strand combinations (IS) from different cabling stages (FS 1152-S) versus cycling, $F = 0$ and 220 kN/m, $B_{\rm dc} = 0.35$ T.

of the cable in between the two series of measurements, the R_c might be increased due to oxidation of the polished spots or due to further dislocation of the strand positions.

IV. Results Solder Coated CICC (FS1152-S)

A. AC Loss Measurements on FS 1152-S

The AC loss results obtained by magnetization on the solder coated VNIIKP conductor FS 1152-S are shown in Fig. 5. Every time when releasing the load along cycling, the loss returns to a level, which is slightly below what was found in the 'initial state' and does not further depend too much on the loading history (dotted line). The 'initial state' of the sample, after insertion in the press, is not equal to 'virgin' as some handling of the conductor is required after releasing the clamps from the splitted conduit halves. Nevertheless, for this AC loss case also a virgin specimen was measured. Under full load, the loss increases with the number of cycles but saturates when approaching 10 000 cycles. The loss versus frequency behaves strongly nonlinear below 0.05 Hz but seems rather linear above 0.05 Hz. For frequencies higher than 0.05 Hz the $n\tau$ amounts to 170 ms in the virgin state.

B. Contact Resistance Measurements on FS 1152-S

The R_c strongly depends on the background field as the solder is superconducting below 0.2 T. Hence a DC field of

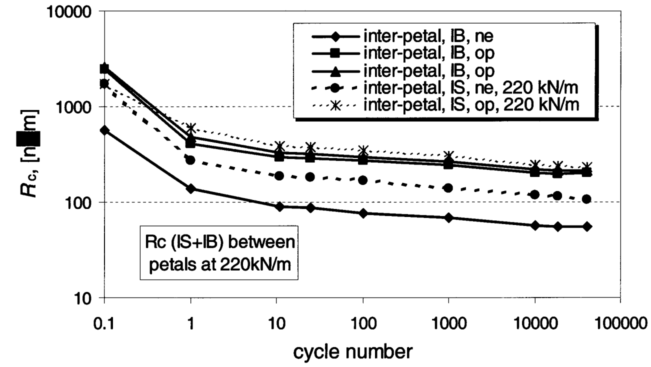

Fig. 7. Interstrand (IS) and interbundle (IB) R_c for petal combinations (FS-1152 S) versus number of cycles, with $F = 220$ kN/m, $B_{\rm dc} = 0.35$ T.

TABLE III
R_c Results in 1st Stage Triplet, Sub-Petal and Petal Strand Bundles Under Full and Zero Loads, From Zero to 40 000 Cycles

R_c [nΩm] for neighbouring strands and bundles					
	220 kN/m		0 kN/m		
stage	max.	end	initial	max.	end
(1st stage triplet) IS	14	7	14	15	11
Sub-petal (4th stage) IB	8	2.2	8	10	7
petal (5th stage) IB	570	55	570	1080	550

0.35 T is required to keep the solder permanently in the normal state. The results of all the interstrand (IS) intra-petal R_c's for full load and zero load, versus the number of loading cycles from the initial state to 40 000 cycles, are presented in Fig. 6. The R_c within a petal decreases gradually by a factor of two within 40 000 cycles. The sub-petal inter-bundle R_c (IB) under load reduces by a factor of three to four within 40 000 cycles. Without load there is hardly any change in the R_c with cycling. The evolution of the inter-petal R_c for single strand combinations (IS) and full bundle combinations (IB) under load is compared in Fig. 7. The major part of the reduction in R_c occurs during the first loading cycles and amounts to one order of magnitude, while there is hardly any difference between IS and IB. The most important results from the evolution of the R_c versus cycling are summarized in Table III. The maximum R_c under full load is already in the initial state and then gradually decreases with cycling. Without load the R_c passes a maximum and decreases again after 100 cycles.

The final saturation level of R_c (under load) is reached after 10 000 cycles and is plainly below that in the initial state, in contradiction to the EM/CRPP conductor with bare copper strands. The effect of transverse cable loading on the R_c for intra-petal combinations with solder coated strands is moderate. Still, for the inter-petal R_c changes up to one order of magnitude with cycling are observed under load. It is obvious that the coupling loss is mainly generated inside the petals and this is well in agreement with the measured results. The level of coupling loss with and without load corresponds well to the intra-petal R_c. Analysis of the $n\tau$ and R_c in the virgin, initial and final state, suggests that the virgin R_c should be roughly similar to the final R_c. And so the conductor handling likely already caused an increase in R_c.

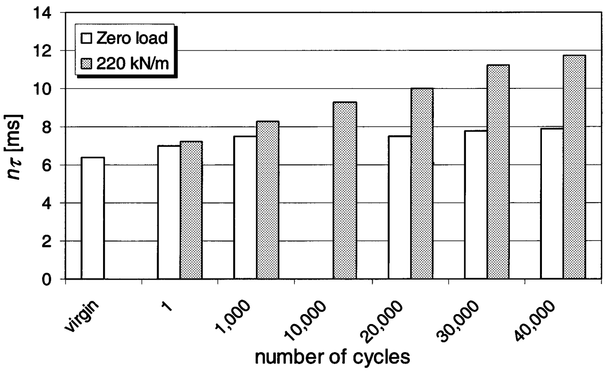

Fig. 8. The AC loss of the FS1152-S specimen in the virgin state, under load (220 kN/m) and without load up to 40 000 cycles.

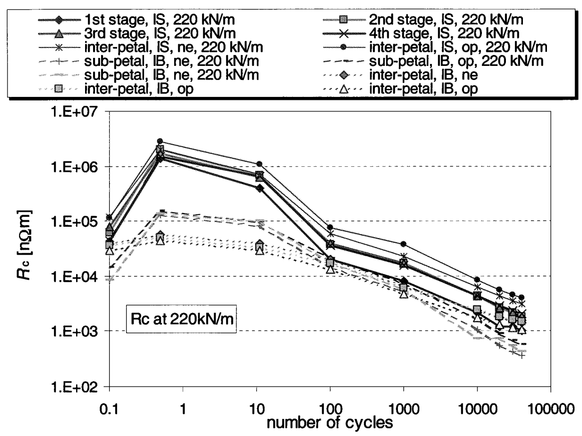

Fig. 9. R_c for single strand combinations (IS) from different cabling stages (FS 1152-C) versus cycle number, $F = 220$ kN/m, $B_{dc} = 0.35$ T.

V. Results Chromium Coated CICC (FS1152-C)

A. AC Loss Measurements on FS 1152-C

The coupling loss time constants obtained on the chromium coated VNIIKP conductor are shown in Fig. 8. The coupling loss is mainly from intra-strand origin but with cycling an additional interstrand component is coming up.

B. Contact Resistance Measurements on FS 1152-C

The results of all the IS and IB, petal and sub-petal R_c's for full load versus the number of cycles are presented in Figs. 9, 10 and Table IV (Note that the R_c in Table IV is in $\mu\Omega$m instead of nΩm). The evolution of the R_c without load is not presented because it is similar to the case with load except that the level is about one order of magnitude higher. The R_c reaches a maximum already before ten cycles, after which it gradually decreases for three orders of magnitude without showing clear saturation after 40 000 cycles. The final R_c level is not far from what is observed for the previously tested Nb_3Sn CS and TF CICC's [5]. Besides electromagnetic forces, the strands need sufficient freedom to move and so the void fraction might play a significant role.

VI. Summary

Cyclic cable loading, simulating electromagnetic forces for NbTi ITER type of CICC's, can have a severe impact on the interstrand contact resistance R_c. There is a tendency for increase of R_c along the first decade of loading cycles. For bare copper strands the maximum in R_c is one order of magnitude above the virgin R_c. Beyond the peak, the R_c saturates toward again that of the virgin state. The R_c within a petal of a CICC with solder coated strands changes up to a factor of two within 40 000 cycles. The Cr-plated specimen reaches its maximum R_c already during the first cycle and then decreases with three orders of magnitude.

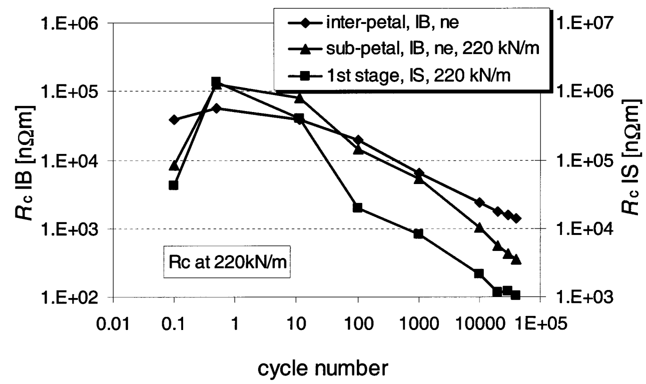

Fig. 10. The average R_c for triplet (IS), sub-petals (IB) and petals (IB) with $F = 220$ kN/m versus the number of loading cycles, (FS 1152-C).

TABLE IV
R_c Results in 1st Stage Triplet, Sub-Petal and Petal Strand Bundles Under Full and Zero Loads From Zero to 40 000 Cycles

R_c [μΩm] for neighbouring strands and bundles					
	220 kN/m			0 kN/m	
stage	max.	end	vigin	max.	end
(1st stage triplet) IS	1350	1.0	43	4160	5.0
Sub-petal (4th stage) IB	129	0.36	8.5	470	1.6
petal (5th stage) IB	57	1.42	39	200	7.4

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