Electromagnetic and Mechanical Characterisation of ITER CS-MC Conductors Affected by Transverse Cyclic Loading, Part 2: Interstrand Contact Resistances

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Abstract- **A special cryogenic press has been built to study the mechanical and electrical properties of full-size ITER multi-strand Nb3Sn cable-in-conduit conductor samples under transverse, mechanical loading. This simulates the transverse magnetic force that occurs when the conductors are used in a coil. The cryogenic press can transmit a variable (cyclic) force up to 650 kN/m to a cable section of 400 mm length at 4.2 K. The jacket is opened partly in order to transmit the force directly onto the cable. The various interstrand contact resistances (R_c's) between stands selected from sub-cables at different positions inside the cable are measured. A summary of the results obtained with up to several tens of full loading cycles is presented. The cables consist of six last stage sub-cables (petals) which are wrapped with an Inconel 600 ribbon. A significant increase of the intra-petal R_c after several cycles is observed. An opposite effect is noticed for the inter-petal R_c. Upon applying a load of 650 kN/m, the R_c drops for the intra-petal as well as for the inter-petal resistance with respect to zero load.**

I. INTRODUCTION

Transverse loading of the ITER conductors due to Lorentz forces is the cause of mechanical effects and variations in the transverse electrical resistivity and contact patterns in the cable. These variations may affect the total AC loss and the stability of a CICC. A distinction can be made between electromagnetic and mechanical AC losses in a conductor. The influence of transverse loading on the coupling loss is described in Part 1 [1]. The results of these investigations on the mechanical AC loss are presented in Part 3 [2].

In a strand bundle the interstrand contact resistance R_c, plays a very dominant role in the total effective electrical resistivity in the transverse direction, $\rho_\perp$ from relation 2 in [1]. This is confirmed for by AC loss and R_c measurements on Nb_3Sn prototype conductors subjected to cyclic bending up to a strain level of 0.4 % [3]. This treatment caused a considerable increase of the R_c from 14 nΩm in the virgin state (after the heat treatment) up to 1200 nΩm after cycling, accompanied by a decrease of $n\tau$ from 390 ms to about 2 ms. The R_c before the heat treatment was 6600 nΩm.

The decrease in R_c during the heat treatment may be due to the diffusion of the oxygen from the strand surface deeper into the strand and the depletion of the oxide layer at the sealed crossover [3]. A mechanical loading of the heat-treated conductor or the electromagnetic load in operation causes an increase of the R_c and a corresponding decrease of the coupling loss. This is likely due to micro-movements resulting into disengagement of the strand crossovers in a loaded cable. The effect of cable mechanical loading on the coupling loss seems to be much larger than the influence of variations in Cr thickness, void fraction, cable pitches, Cr vendors, etc.

The resistance of these crossover contacts not only determines the total coupling loss, but also has an important influence on the stability of the conductor by influencing the potential level of current sharing and redistributing the current among strands.

Local disturbances like transient field loss and strand movement can produce a small normal zone in a strand or a particular part of the cable which eventually evolves into a quench of the whole cable. The current in the normal zone region transfers to other strands by the crossover contacts. If the normal strands can recover the superconducting state and the currents are redistributed while the other superconducting strands carry the current, then the cable is stable against local disturbances. Therefore the R_c should not be too high. Experiments investigating the minimum quench energy (MQE) in relation to the R_c have pointed out the dominant role of R_c in the stability of multistrand cables [4]-[6].

A transverse force acting on strands of a virgin conductor (no stresses after the reaction heat treatment) affects the R_c and thereby the stability regime of the conductor. For this reason the relation between the contact resistance among strands in varying locations of the cable and the applied force must be examined for a number of cycles until a reproducible behaviour has been reached.

II. EXPERIMENT AND CABLES

The aim of this part of the study is to measure the transverse inter-strand and -stage R_c's of full-size cable samples under transverse, mechanical loading.

The AC loss measurements are discussed in [1] using the data obtained from the R_c measurements, which are presented here. The details of the cryogenic press, the sample preparation and its instrumentation are reported in [7] and the

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main parameters of the specimens provided by the NET team can be found in [8]. The Central Solenoid Model Coil (CSMC) uses two grades of conductors, CS1 which is all superconducting strands and CS2, where one superconducting strand in the first triplet is replaced by a Cr coated copper wire. The CS1.1B-EU and CS2-US conductor, taken from the prototype CS model coil production, are prepared for measurements in the cryogenic press.

The R_c is measured with a four-probe-method, using a current of 50 A supplied to a selection of strands in sub-cables and petals (last stage cabling step) of the ITER conductors, according to the network as schematically presented in Fig. 1, assuming the 3x4x4x4x6 cabling geometry of the CS1 conductor [8].

The R_c value is represented as:

$$R_c = \frac{V}{I} \cdot l, \qquad [\Omega \mathrm{m}], \qquad (2)$$

in which V is the measured voltage, I is the applied current through the selected strand combination and l is the length of the specimen. The resistance between strands is measured on one end of the cable and the other end has a clear cut by electric erosion.

The jacket is cut along its length, with a space of 4 mm between both halves so that the load from the press is applied homogeneously to the cable. If the maximum transversal magnetic forces are taken into account for the ITER conditions, then the transversal peak force on one side of the cable is F_y=650 kN/m (I=50 kA, B=13 T).

A superconducting dipole coil provides a stationary bias field that is required to avoid the possible influence of the low field superconductivity of the diffusion barrier inside the strand on the interstrand resistance.

III. Contact Resistance Measurements

The R_c's of selected strand combinations are measured in one of the petals (intra-petal, petal=last but one cable stage wrapped with resistive metal ribbon) and among strands selected from different petals (inter-petal). The results of the measurements in virgin condition and with a load of 650 kN/m after 38 cycles are presented in Fig. 2.

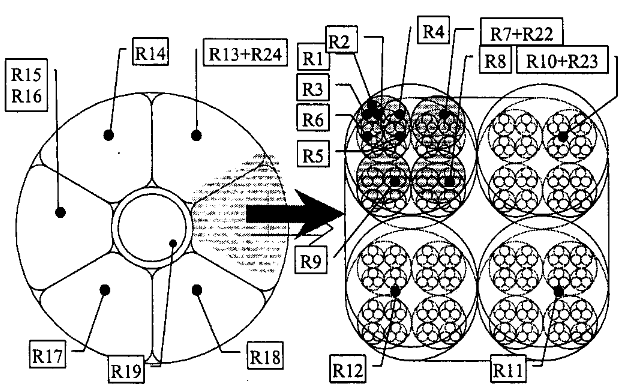

Fig. 1. Schematic view of the selected strands in topologically different positions of the cable (the total cable left and a petal right).

A. History effects

Fig. 3and Fig. 4 show the evolution of the average value of the measured R_c's for different strand combinations versus the number of loading cycles (between brackets) and the load for the CS1.1 and CS2 type of conductor respectively. The average inter-petal R_c without load after 38 cycles saturates at 37 μΩm for the CS1.1 but the value of 13.8 μΩm for the CS2 specimen is probably not the final level. It seems that in the case with load a full saturation has also not been reached after 38 cycles and the average value of the inter-petal R_c is then 4.2 μΩm (CS1.1) and 2.1 μΩm (CS2).

After 38 cycles there still seems to be a rise of the intra-petal R_c with cycling in the case of an unloaded CS1.1 conductor, while the CS2 type is already beyond a maximum. The level of 330 nΩm seems to be the upper limit of the intra-petal R_c for a loaded CS1.1 cable. The intra-petal R_c of the CS2 cable under full load has reached a maximum after 6 cycles and is still decreasing after 38 cycles. Some average R_c values are summarised in Table I and Table II.

The R_c between strand R1 and the jacket under full load amounts to approximately 300 μΩm for the CS1.1 specimen. This R1-jacket resistance gradually decreases from 440 to 350 μΩm for the CS2 conductor and has not reached any saturation after 38 cycles.

The measured R_c for strand combinations between R1 and a copper strand in the CS2 cable amounts to 9 μΩm in the case with full load (intra- and inter-petal) and is 15 μΩm (intra-petal) and 25 μΩm (inter-petal) with zero load.

After 38 cycles the intra-petal R_c decreases roughly to a

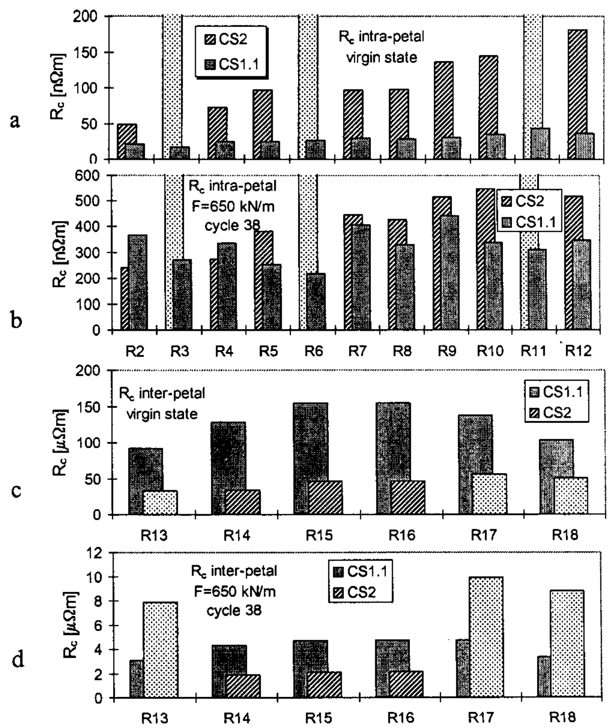

Fig. 2. The intra- and inter-petal contact R_c's in the virgin state (a and c) and after 38 loading cycles (b and d) versus the selected strand combination for the CS1.1 and CS2 type of conductor. The light grey bars represent combinations with copper strands of the CS2 conductor.

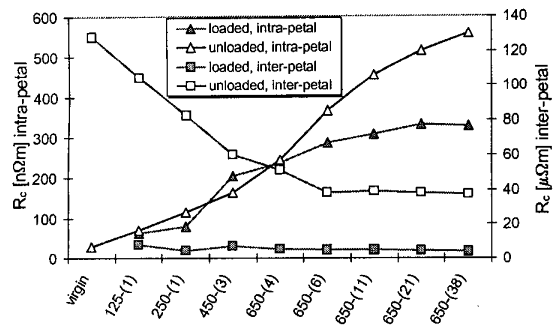

Fig. 3. Average intra- and inter-petal contact R_c's with F=0 and 650 kN/m versus the peak force and the number of loading cycles between brackets for the CS1.1 conductor.

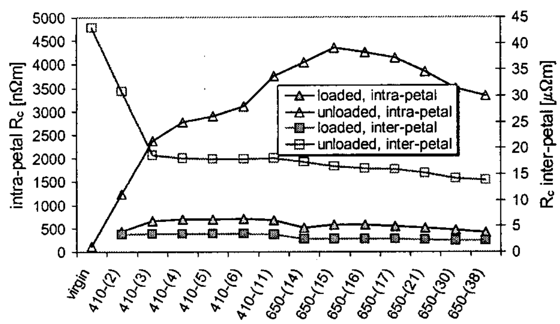

Fig. 4. Average of the intra- and inter-petal contact R_c's with F=0 and 650 kN/m versus the peak force and the number of loading cycles between brackets for the CS2 conductor.

Table I. Summary of average R_c values CS1.1 Conductor

stat e	F [kN/m]	R_c Intra-petal [nΩm]			R_c Inter-petal [μΩm]		
		ave	min	ma x	ave	min	ma x
virgin	0	29	17	43	129	92	154
38 cy	0	560	320	770	37	30	41
38 cy	650	330	220	440	4.2	3.1	4.8

Table II. Summary of average R_c values CS2 Conductor

state	F [kN/m]	R_c Intra-petal [nΩm]			R_c Inter-petal [μΩm]		
		Ave	min	max	ave	min	Max
virgin	0	109	48	181	43	34	47
38 cy	0	3340	1390	4510	13.8	13.4	14.1
38 cy	650	420	240	550	2.1	1.9	2.2

factor of 1.5 for the CS1.1 cable when a load of 650 kN/m is applied. A similar behaviour is noticed for the CS1.1 inter-petal resistance with a decrease to a factor of 9.

Lp2/Rc can approach the relevance of the contribution of the last cabling stage to the total coupling loss production with respect to the intra-petal loss. However it should be considered that this R_c is measured under DC conditions also including the parallel resistance through a number of paths, so it is not completely identical to the case of induced coupling currents loops. The last but one cable stage pitch of a CS1.1 petal is 147 mm and the average R_c amounts to 330 nΩm, so L_p^2/R_c=65 km/Ω. The CS1.1 petal pitch is 397 mm and the average inter-petal R_c is 4.2 μΩm resulting into L_p^2/R_c=38 km/Ω. This implies that the last cabling stage of the CS1.1 conductor contributes significantly to the total coupling loss. This behaviour is also confirmed by the magnetisation measurements combined with the multiple time constant (MTC) analyses as presented in [1]. The low inter-petal Rc may lead to the saturation in current in parts of the conductor already at very low field rates.

B. Pressure effects

After 38 cycles the intra-petal R_c declines by a factor of 8 for the CS2 cable when a load of 650 kN/m is applied. The CS2 inter-petal resistance in turn decreases by a factor of 7. For the inter-petal loss for the CS2 cable the L_p^2/R_c amounts to 74 km/Ω and for the intra-petal loss 160 km/Ω.

Fig. 5 and Fig. 6 clearly show that the intra-petal R_c among strands not only decreases when the applied force is raised but above that a hysteresis behaviour of the resistance versus applied force is noticed. A relaxation of the resistance value after unloading of the force is clearly observed. No change of resistance in time (creep) under a full load of 650 kN/m was observed for several tens of hours.

The R_c value found in the triplet stability experiment from [4] amounts to 7 μΩm. In this case the MQE of a cable appeared to be much larger than the MQE of the single strand. For the CS1.1 conductor the R_c of the first triplet <750 nΩm and for the CS2 conductor R_c<1400 nΩm. As a result the stability conditions for current redistribution regarding the R_c seem to be rather favourable, although the R_c's of all parallel circuits should not be neglected.

The evolution of the R_c with the number of cycles (Fig. 3 and Fig. 4) is clearly relevant for the initial loading cycles of a magnet. In general it is recommended to complete several loading cycles at slow rate for a magnet wound from Nb_3Sn CICC's, in order to reach more stable conditions regarding the R_c and $n\tau$ before serious operation.

V. Discussion

The evolution of the R_c at a specific location in a cable is correlated to the maximum Lorentz force at that particular position. In other words, the local field and the history determine the local R_c. In the CSMC the inner turns experience the maximum field and thus the strongest Lorentz force. In this high field region the R_c is on its minimum level, on one hand creating optimal conditions regarding current redistribution during local disturbances, but on the other resulting in an increase of the coupling loss [1]. For the low field regions in the magnet the R_c is at a relatively higher level but the demand for current sharing among neighbouring strands is of a lower level.

In order to determine the consequences with respect to stability and AC loss a larger number of cycles have to be performed to obtain the final values of the R_c. and to evaluate the possible effects of wearing. The conductor should be subjected to fatigue tests i.e. loading the conductor from zero up to 400 kN/m for a much larger number of cycles than 38, in order to examine the evolution of $n\tau$ and R_c under realistic ITER lifetime conditions.

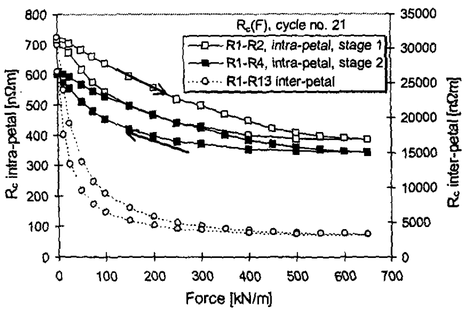

Fig. 5. R_c versus load for two different strand combinations of the first two cabling stages inside a petal and between two petals after 21 cycles up to 650 kN/m, B_{dc}=0.6 T and I=50 A, CS1.1 conductor.

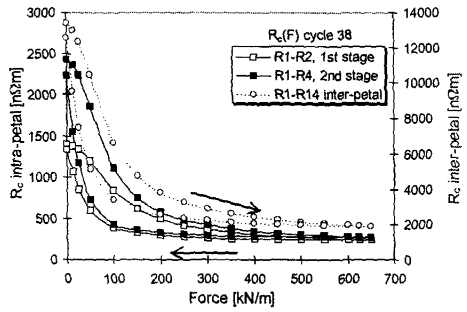

Fig. 6. R_c versus load for two different strand combinations of the first two cabling stages inside a petal and between two petals after 38 cycles up to 400 and 650 kN/m, B_{dc}=0.6 T and I=50 A, CS2 conductor.

VI. Conclusions

After cyclic loading the intra-petal R_c (no load) increases significantly with the number of cycles from 30 nΩm in the virgin state to 560 nΩm (CS1.1) and from 110 to 3300 nΩm (CS2). Upon applying a transversal load the intra-petal R_c drops again to values between 200 and 500 nΩm for both types of CS conductors. The inter-petal R_c in the virgin state amounts to 130 μΩm (CS1.1) and 40 μΩm (CS2). After cyclic loading it decreases to a 4 μΩm (CS1.1) and 2 μΩm (CS2) (650 kN/m).

The last cabling stage (inter-petal) may contribute significantly to the total coupling loss production.

The R_c clearly declines with the applied force and is accompanied by hysteresis and relaxation effects. This may explain the big difference found between the high $n\tau$-values of Nb3Sn CIC conductors in the virgin state and the lower $n\tau$'s as for example in the DPC magnets and the ENEA coil.

The R_c's after 38 cycles are not likely the final values after a larger number of cycles. Therefore further study is required by which a much larger number of cycles must be performed in order to find the ultimate performance of the ITER CS conductors.

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