Parametric Study on Coupling Loss in Subsize ITER Nb₃Sn Cabled Specimen

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Abstract- The cable in conduit conductors for the various ITER coils are required to function under pulse conditions and fields up to 13 T. A parametric study, restricted to a limited variation of the reference cable lay out, is carried out to clarify the quantitative impact of various cable parameters on the coupling loss and to find realistic values for the coupling loss time constants to be used in ac loss computations. The investigations cover ac coupling loss measurements on jacketed sub- and full size conductors with variations in type of cabling, twist pitch, void fraction, and thickness of the chromium coating. The results are summarised and conclusions regarding the ITER cable design are presented. Scaling laws for coupling loss versus void fraction and number of cabling stages are presented.

I. INTRODUCTION

The performance of the cable-in-conduit, (CIC) conductor under ITER operating conditions will be verified by the construction and operation of model coils. Before assembly of the conductor starts, it is essential to confirm some of the design criteria used for the conductor. The main part of the results of the work published before the start of this study is carried out on unjacketed subcables or jacketed full size prototype conductors [1]. Only a few studies have been carried out on the influence of the chromium coating thickness and variation in void fraction [2,3]. In recent studies it was demonstrated that the contact pressure between the strands caused by Lorentz forces in multistrand conductors carrying transport current in a background field, plays an important role in the coupling loss [4]. For this, a parametric study restricted to a limited variation of the reference cable lay out, is necessary to identify the quantitative impact of the manufacturing parameters on the coupling loss and to enhance the basic knowledge of interstrand resistances also required for ac loss computation. It was demonstrated that the coupling loss time constant increases significantly with declining void fraction [5]. The increase of loss due to twisting from the 0 to the 4th stage gradually progresses to time constants of at least 300 ms. Twisting three braids results

in time constants of more than 1300 ms, at the lowest void fractions. Braided cables show a time constant value at least about a factor 2 more than in twisted specimen.

II. COUPLING LOSS

The ac loss per volume strand, per cycle increases with the frequency. The hysteresis and coupling losses can be determined assuming that the hysteresis loss per cycle is independent from the frequency (which is true for low frequencies and when no internal shielding is present). The coupling loss per cycle, as a first and simple approximation, is proportional to the frequency f and to B_a^2 :

$$Q_{cpl} = v \cdot (\pi/\mu_0) \cdot B_a^2 \cdot \omega \cdot n \cdot \tau \quad [J/m^3/cycle]. \quad (1)$$

The time constant $\tau = 1/2 \cdot \mu_0 \cdot (L_p/2\pi)^2 \cdot \sigma_{\perp}$ [s] in which L_p is the twist pitch, and $\sigma_{\perp}$ is the effective electrical conductivity in the transverse direction. The volume fraction of the total amount of strand volume involved in the power dissipation is expressed by v . The shape factor is represented by n , which amounts to $n=2$ in wires with circular cross sections and in uniform transverse field [5]. For intrafilament coupling loss, this volume is approximately the volume of the closely packed multifilamentary zone. The non-Cu fraction of the strand is 0.37 which means that the effective volume fraction v , is about 0.4. This effective volume fraction is difficult to estimate for higher cabling stages and is not necessarily the same for every stage. The slope α of the linear section of the curve, representing the total loss per cycle versus the frequency of the applied field, provides the coupling current constant $v \cdot n \cdot \tau$:

$$v \cdot n \cdot \tau = \alpha \cdot \mu_0 / 2\pi^2 \cdot B_a^2 \quad [s], \quad (2)$$

where the applied field is $B_a \cdot \sin(2\pi \cdot f \cdot t)$. In the following the $v \cdot n \cdot \tau$ will be indicated just by $n \cdot \tau$, because v and n are unknown and the $n \cdot \tau$ value is related to the total strand volume.

III. SPECIMEN DESCRIPTION

The specifications of strand and cables are given in [5]. After cabling N strands, the cable is put into a SS tube and drawn

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to an inner diameter D in order to create different void fractions δ , and $\delta=(1-(d_{\text{strand}}/D)^2)N$. The void fraction is determined after the heat treatment, by measuring the weight before and after filling the jacketed cables with ethanol. The relative spread in f among specimen with identical void fraction is less than 0.3 % and the absolute accuracy is better than 2 %.

IV. EXPERIMENTAL RESULTS

A. Coupling loss

To determine the right coupling loss time constants a one tesla dc field must be applied, to eliminate the influence of the shielding by the barrier material is [5]. The test set up and experimental conditions are described in a previous paper [5]. The coupling loss time constants are gathered in Table I. The relation between the time constant and the void fraction is presented in Figure 1. The left vertical axis scales the time constant for cable type T27, and the right vertical axis scales $n \cdot \tau$ for the T81 type. The time constant increases significantly with declining void fraction between 0.45 and 0.30. Below $f=0.30$ the $n \cdot \tau$ value has reached a plateau. Apparently the interstrand contact resistance becomes constant for low void fractions. This can be either caused by reaching the minimum possible resistance by compression or by a release of the original contact pressure in the cable. The copper stabiliser is softened during the heat treatment and this may possibly release the pressure. In the case of a transverse load by Lorentz forces, the plateau can probably be a on a

Fig. 1. Coupling loss time constant as a function of the void fraction, for $B_a=400$ mT, $B_{dc}=1$ T for twisted specimen T27 and T81.

higher level. The coupling loss time constant is less dependent on the void fraction above 0.45. This agrees with the relation between contact resistance and void fraction or contact pressure found by others [2,3]. The interstrand contact resistances play an important role. It confirms the results published before [4,5] on the influence of Lorentz forces on the interstrand contact resistance on current carrying cables with Cr coated strands.

B. Scaling laws

The relation between the coupling loss and void fraction, can be expressed by a third order polynome, for $0.30 < f < 0.45$:

$$n \cdot \tau = C_k \cdot (-1 + 8.956 \cdot f - 24.52 f^2 + 21.35 \cdot f^3), \quad (3).$$

where $C_k=5250$ and 3300 for the T81 and T27 subcables respectively.

This results for 38 % void fraction in $n \cdot \tau=182$ ms for T81 and $n \cdot \tau=109$ ms for the T27 subcable. The data of both cable

TABLE I
COMPARISON OF THE COUPLING LOSS TIME CONSTANTS.

Cable #	Identity	Cabling geometry	void fraction $\pm 2\%$	$n \cdot \tau$ [ms]
# 1	S	1	-	4
# 2	T3	1x3	0.07	6.5
# 3	T9	1x3x3	0.56	14
# 21	T9	1x3x3	0.38	20
# 4	T27	1x3x3x3	0.309	180
# 5	T27	1x3x3x3	0.367	140
# 6	T27	1x3x3x3	0.417	35
# 22	T27	1x3x3x3	0.447	43
# 7	T27	1x3x3x3	0.474	27
# 8	T81	1x3x3x3x3	0.280	290
# 9	T81	1x3x3x3x3	0.301	300
# 10	T81	1x3x3x3x3	0.394	140
# 23	T81	1x3x3x3x3	0.431	100
# 11	T81	1x3x3x3x3	0.449	68
# 24	T81	1x3x3x3x3	0.484	59
# 25	T243	1x3x3x3x3x3	0.38	510

Fig. 2. Coupling loss time constant versus number of strands for all cable stages, with void fraction=0.38. The solid line represents $n \cdot \tau = 2.15 \cdot N$, $B_a=400$ mT and $B_{dc}=1$ T.

TABLE II
COUPLING LOSS TIME CONSTANTS VERSUS NO. OF STRANDS.

Cable #	Identity	n.τ [ms], measured or interpolated ¹⁾	n.τ from 2.15·N[ms] f=0.38	n.τ [ms] from (5)
# 1	S	4	2.2	-
# 2	T3	6.5	6.5	6.8
# 21	T9	20	19.4	20
# 4-#7	T27	109 ¹⁾	58	61
#8-#24	T81	182 ¹⁾	174	183
#25	T243	510	523	548
#29-#30	T27	~75	-	81
ENEA	T144	140	-	142

types are used to find relation 3, when considering all points the accuracy is about 15 %. However it seems that the curve for the T81 cables is more gradual than for the T27 cables.

In Figure 2 the n.τ values of cables with a void fraction of 0.38 are shown versus the number of strands. The n.τ values of the T27 and T81 subcables are determined by interpolation of the curves in Figure 1. Table II and Figure 2 demonstrate that the relation between the time constant and the number of strands appears to behave linear. The loss gradually progresses to a time constant of 510 ms with twisting the strands from the 0 to the 5th stage with 243 strands. Moreover the line crosses the origin within the error bar, (n.τ,N)=(0,0). This would imply that only the time constant of one cable stage is necessary to predict the time constants of multistage cables (provided they are of the same quality without intermediate barriers).

The time constant goes linear with the number of strands which results in the following simple scaling law:

$$n.\tau = \beta \cdot N, \quad (4)$$

with: β =slope, in this case $\beta=2.15$ ms/No. of strands;
N=number of strands.

For at least triplet twisted cables find with acceptable accuracy: $n.\tau = \beta \cdot 3^{k_n}$, with k_n =cable stage. The n.τ value of the 27 strands cable, shows a deviation. For the single strand the model is not correct because the mechanism of intrastrand (or interfilament) coupling loss is different from the interstrand coupling loss. The relations 3 and 4 can be combined, if it is allowed to assume that n.τ is proportional with the number of strands for all void fractions between 0.30 and 0.45:

$$n.\tau = \beta \cdot N \cdot 30.7 \cdot (-1 + 8.956 \cdot f - 24.52 \cdot f^2 + 21.35 \cdot f^3). \quad (5)$$

The n.τ values of the T27 cables coated with 1 and 4 μm, as described further on, can be used to estimate n.τ for a cable with a 2 μm Cr layer thickness at a different void fraction. The n.τ value calculated with relation 6, gives n.τ=83 ms for f=0.350 and n.τ=79 ms for f=0.355. It is striking that the

average n.τ value of the two T27 specimen with varying Cr layers from Table III amounts to n.τ=75 ms. This value fits very well in the scaling law represented by relation (5).

The loss of the CICC for the EURATOM-ENEA 12 T magnet is also measured in this test set up, and the time constant amounts to n.τ=140 ms. The total number of strands is 144, twisted in a 1x3x3x4x4 geometry with a void fraction f=0.43. The strand material is comparable, and the twist pitches are similar to the ones used for determination of the scaling laws. The time constant predicted by the relation (5) is n.τ=142 ms. This again fits well within the scaling law.

It seems (at least in this parametric study of about 25 samples) that the time constant, determined from the initial slope of the total loss versus frequency, is proportional to the number of strands, and not to the number of cabling stages.

IV. INTERNAL INSPECTION OF JACKETED SUBCABLES

From every series of cabling type, some samples have been unjacketed for visual inspection of the internal condition. A sample of specimen #21, #4, #22, #8, #11, #24, and #25 from the series with twisted triplets and #12, #15, #16, and #27 from the series with braided specimen has were opened [5]. The cabling twistpitch is checked and varies within ±10 %, except for the T243 cable. The last stage twist pitch appears to be 300 mm instead of the specified value of 200 mm. The reason for this elongation is not clear.

No damage of the Cr layer in the inner parts of the cable is found and no sintering have been noticed. At low void fractions large spoon sizes and significant plastic deformation has occurred. On the outer surface of the cables where contact with the jacket occurs the Cr layer is slightly damaged. Since the jacket is not relevant for ac loss it is not affecting the results.

The average weight per unit length of the strand and unjacketed cables is measured in order to investigate whether it is allowed to neglect the influence of the twisting and jacketing in the calculation of the strand volume in a cable. The weight per volume of strand is $8.56 \pm 1\%$ g/cm³. The additional amount of strand compared to the void fraction with straight strands, appeared to be negligible for the T9 type of cable, 1.6 % for the T27, 2.3 % for the T81 and 2.3 % for T243 type of cable. For the braided cables B28 the effect can be neglected and 1.3 % for the twisted B84 type of braid [5]. The correct void fractions are in Table I.

V. VARIATION IN CHROMIUM COATING THICKNESS

One bare strand and two strands with 1 and 4 μm Cr layer thickness were twisted in the T27 geometry (1x3x3x3) and jacketed. The strand diameter amounts to 0.82 mm. All three

specimen are heat treated in one batch, according to: 175 h @ 220 °C, 96 h @ 340 °C, and 180 h @ 650 °C in vacuum. The specifications and the results of the loss measurements are gathered in Table III and Figure 3. The thickness of the Cr layer is checked with micrographs.

The void fractions are slightly different which influences the coupling loss time constant, but according to the scaling law (5) this is only 5 % for both Cr coated specimen. The comparison of time constants shows that the thickness of the Cr layer influences the interstrand contact resistance with a factor 2. This effect is in agreement with previous investigations [2].

On the other hand this type of Cr coating seems to be insufficient for lowering of the coupling loss. Other plating conditions of coating strands with Cr layers may lead to different results. Variations in contact resistance up to a factor 6 are found for the same spoon size, using Ni coatings of different vendors [6]. For Cr this will be investigated in the near future.

It appears that the cable with the so called bare strands has the lowest coupling loss. The strand type is different but this probably has no considerable influence on the time constant of the cable. Low coupling loss for bare strands, has been noticed before in Rutherford cables and it is probably caused by a thin oxide layer on the strand surface [6].

VI. CONCLUSIONS

The coupling loss time constant increases significantly with declining void fraction.

The ac loss increases with the triplet twisting from the 0 to the 5th stage gradually to a time constant of 500 ms.

The relation between the time constant and the number of strands appears to be linear.

Only the time constant of one cable stage is necessary to predict the time constant for all other stages. This results in the following scaling law for triplet twisted cables: $n\tau = N \cdot g(f)$, with N =number of strands and $g(f)$ representing the influence of the void fraction or contact resistance and twist pitch.

No damaged Cr coating, no sintering, and no broken strands have been found in the opened cable specimen.

The variation in $n\tau$ with changing void fraction and chromium coating thickness, stresses the importance to control in a predictive manner the interstrand contact resistance.

The thickness of the chromium layer influences the interstrand contact resistance, but the used coating seems not to be sufficient for lowering of the coupling loss.

TABLE III
CABLES WITH VARYING CR LAYER THICKNESS

Cable Identity	#28	#29	#30
Cr thickness [μm]	0	1	4
Void fraction:	0.370	0.355	0.350
No. of fil. bundles in strand:	36	55	55
Barrier material:	Ta	V-Nb	V-Nb
No. of filaments:	~6000	~9000	~9000
$n\tau$ [ms]:	24	99	50
$n\tau$ calculated with relation (5), if $d_{Cr}=2 \mu\text{m}$, [ms]:	69	79	83
Qhyst [mJ/cycle/cm ²]:	26.8	35.9	36.3

Fig. 3. Total loss versus frequency for 27 strands, twisted braids, with varying chromium coating thickness, $B_a=400$ mT and $B_{dc}=1$ T.

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