First Results of a Parametric Study on Coupling Loss in Subsize NET/ITER Nb_3Sn Cabled Specimen

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Abstract- **The cable in conduit conductor for the ITER coils is 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 necessary to identify the quantitative impact of manufacturing parameters on the coupling loss and to find out more precisely the value of the coupling loss time constant to be used in the ac loss computation.**

Here we present the first results of the ac coupling loss measurements on jacketed sub size conductors with variations in type of cabling, cabling stage, twist pitch and void fraction. The ac loss is determined mainly by calorimetric way but partly also using a magnetometer. A sinusoidal ac field amplitude of 15-400 mT, superposed on a dc background field of B_{dc}=0, 1 or 1.5 T, is applied to determine the coupling loss time constants for different specimen. The results up to now show large coupling current time constants especially for braided cables, for which n.τ can reach more than 1000 ms. For twisted cables with 81 strands n.τ values up to 300 ms are attained.

I. INTRODUCTION

The performance of the CIC conductor under ITER operating conditions will be verified by the construction and operation of model coils. Before assembly of the conductor for the model coils begins it is essential to confirm some of the design criteria used for the conductor. The behaviour of the coupling current loss in cabled superconductors has been investigated since twenty years. Up to now no basic experimental activity is considered necessary for technological relevant issues. The main part of the results of the work published is carried out on unjacketed subcables or jacketed full size prototype conductors [1,2]. The contact pressure between the strands is hardly taken into account but may possibly play an important role [3,4,5]. Recent results of coupling current tests on a jacketed 48 (Cr coated) strands subcable without load, show a time constant of 27 ms [6] and no explanation is given for this high value.

A parametric study, restricted to a limited variation of the reference cable lay out, is necessary to identify the quantitative impact of manufacturing parameters on the coupling loss and to enhance the basic knowledge on interstrand resistances to be used in the ac loss computation. An extensive part of this work is carried out in the scope of a NET/ITER contract by the 'Applied Superconductivity Centre' at the 'University of Twente'. The aim of the work is to investigate the AC coupling loss measurements on jacketed sub- and full size conductors with variations of twist pitch, void fraction, chromium coating thickness, substage wrap extent, the influence of fatigue effects (transverse loads) and the effect of the inclusion of pure copper strands. The first results of this work are gathered in this report.

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A. Coupling loss investigations

The ac loss per volume strand, per cycle are expected to show an increase with the frequency. From the results of the measurements of the total loss versus 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 taken proportional to the frequency f and to B_a^2. This is usually formulated as:

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

The time constant $\tau = \frac{1}{2}\cdot\mu_0\cdot(L_p/2\pi)^2\cdot\sigma_\perp$ [s] in which L_p is the twist pitch, and $\sigma_\perp$ is the effective electrical conductivity in the transverse direction.

The slope of the linear section of the curve, α, provides the coupling current constant, n·τ, following:

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

where the applied field is $B_a.sin(2\pi.f.t)$ and the shape factor n=2 for wires with circular cross sections.

B. Test set up

All the tests are carried out at liquid He temperature (atmospheric pressure bath). The time varying field is applied perpendicular to the specimen axis. The AC field is taken sinusoidal and the main amplitude for testing is B_a=400 mT. The perpendicular DC background field is taken B_{dc}=1 T in

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most of the cases. The ac losses per cycle are measured as a function of the frequency at a constant amplitude of the applied ac field, B_a generated by a superconducting dipole magnet. The calorimeter is made of a vertical glass fibre/epoxy tube and it is performed as an insert.
The test set up for magnetisation measurements is described in [3]. Some additional measurements are carried out to check the results found with the calorimetric method.
The samples are electrically insulated with paper sheets in order to create space stacked units of cables.

II. SPECIMEN DESCRIPTION

In Table I the specifications are given of the specimen subjected to the experiments.

TABLE I
SPECIFICATIONS OF THE SUB CABLES USED IN THE EXPERIMENTS

Cable #	Identity	No. of strands	Twist / cabling pitches [mm]	Void fraction
# 1	S	1	10	-
# 4	27 T	1x3x3x3	10x25x60x105	0.28
# 5	27 T	1x3x3x3	10x25x60x105	0.337
# 6	27 T	1x3x3x3	10x25x60x105	0.388
# 7	27 T	1x3x3x3	10x25x60x105	0.444
# 8	81 T	1x3x3x3x3	10x25x60x105x160	0.247
# 9	81 T	1x3x3x3x3	10x25x60x105x160	0.283
# 10	81 T	1x3x3x3x3	10x25x60x105x160	0.352
# 11	81 T	1x3x3x3x3	10x25x60x105x160	0.397
# 12	28 B	1x28	10x374	0.256
# 13	28 B	1x28	10x374	0.301
# 14	28 B	1x28	10x374	0.35
# 15	28 B	1x28	10x374	0.418
# 16	84 BT	1x28x3	10x374x160	0.219
# 17	84 BT	1x28x3	10x374x160	0.245
# 18	84 BT	1x28x3	10x374x160	0.328
# 19	84 BT	1x28x3	10x374x160	0.379

The strand material and cables are manufactured by LMI. The wire is an internal tin Nb_3Sn type and the diffusion barrier is made of V-Nb. The specifications of single strand specimen #1 are:

d_{strand}=0.73 mm, $n_{fil.}$=5832, $d_{Cr\text{-}layer}$= 2 μm,
Cu:nonCu=1.7, l_p~10 mm, $d_{fil.}$=3 μm.

After cabling N strands, the cable is put into a SS tube and drawn down to a smaller diameter D in order to create different void fractions, $(1-(d_{strand}/D)^2.N)$. The influence of the twist pitch of the different types of cabling on the length is neglected. The sample length for twisted specimen amounts to 320 mm and for braided specimen 330 mm.
All specimen are heat treated in one batch, according to the following schedule: 175 h @ 220 °C, 96 h @ 340 °C, and 155 h @ 650 °C carried out under vacuum conditions.

III. EXPERIMENTAL RESULTS

A. Influence of the diffusion barrier

The results of the measurements of the coupling loss of specimen #1, maintained with different amplitudes B_a, without dc background field shows that the coupling loss as well as the hysteresis loss strongly depends on the amplitude of the applied ac field. The amplitude dependence of the time constant is caused by the influence of the Nb-V diffusion barrier material [7]. The critical field and temperature of $Nb_{1/0}V_{0/1}$ are between B_c=96 mT (T_c=4.0 K) and B_c=189 mT (T_c=9.2 K). The barrier is shielding each subelement consisting of a bundle of Nb_3Sn filaments, from the applied field as long as its critical field is not exceeded.
To determine relevant coupling loss time constants a dc background field must be applied of B_{dc}=1 T, for which the influence of the shielding of the barrier material is eliminated and the time constant is on a constant level.
The behaviour showing different coupling loss time constants and hysteresis loss, is verified with an electrical magnetisation loss measurement on specimen #1 [7]. The time constant finally found for the single strand for $B_{dc}\geq 1$ T amounts to $n\cdot\tau$=4 ms.

B. Coupling loss

The total loss as a function of frequency for specimen #4 up to #19, are presented in the Figures 1 to 4. The volume of a sample is taken as the sample length times the number of strands multiplied by the area of the strand cross section. The Q_{hys}, found with the calorimetric method for the cabled specimen and electrical magnetisation method for the single strand, are the same and can be considered as an indication for the reliability of the used methods. Both methods result in a loss at f=0 Hz of Q_{hys}=27 ± 1 mJ/cm^3/cycle for an ac field amplitude B_a=400 mT and a dc background field of B_{dc}=1 T. The coupling loss time constants of all measured specimen are gathered in Table II, as determined for an ac field B_a=400 mT.
All time constants measured without dc background field are higher than those measured with B_{dc}=1 T, (except for specimen #9). Specimen #16, measured with different background fields B_{dc}=0, 1 and 1.5 T, shows a decrease of the coupling loss time constant from $n\cdot\tau$=1520, 1350 to 1210 ms respectively. The relation between the time constant and the void fraction is presented in Fig. 5. The time constant increases significantly with declining void fraction. This proves that the interstrand contact resistance plays an important role in spite of the chromium plating. This confirms the results published before [5], about the influence of Lorentz forces on the interstrand contact resistance on current carrying cables with Cr coated strands.
The braided cables show an $n\cdot\tau$ value at least about a factor 2 above the twisted specimen. This is qualitatively in agreement

with the results on 27 strands twisted and 29 strands braided cables as described before [3,4].

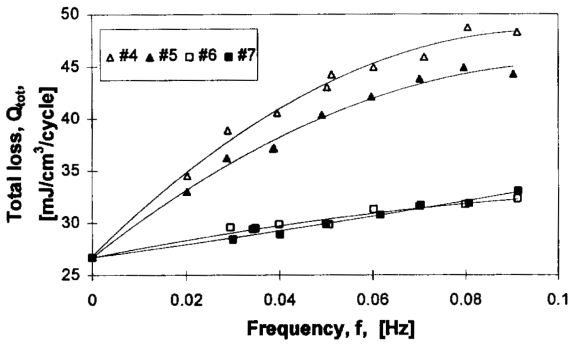

Fig. 1. Total loss versus frequency for 27 strands, twisted specimen, with different void fractions, B_a=400 mT and B_{dc}=1 T.

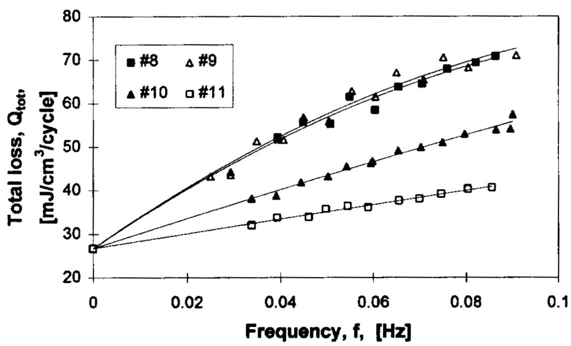

Fig. 2. Total loss versus frequency for 81 strands, twisted specimen, with different void fractions, B_a=400 mT and B_{dc}=1 T.

TABLE II

COMPARISON OF THE COUPLING LOSS TIME CONSTANTS.

Cable #	void fraction [%]	n.τ [ms] for B_{dc}=0 T	n.τ [ms], for B_{dc}=1 T	n.τ [ms] for B_{dc}=1 T, remeasured
# 1	-	4-100	4	-
# 4	28	-	180	-
# 5	34	-	140	-
# 6	39	96	35	-
# 7	44	91	27	-
# 8	25	370	290	350
# 9	28	260	300	440, 350
# 10	35	190	140	-
# 11	40	130	68	-
# 12	26	-	1240	-
# 13	30	-	330	-
# 14	35	-	310	-
# 15	42	-	150	-
# 16	22	1640, 1520	1350	-
# 17	25	1220	1100	-
# 18	33	790	620	-
# 19	38	650	550	-

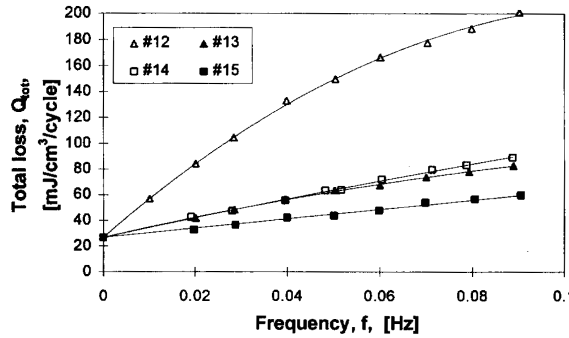

Fig. 3. Total loss versus frequency for 28 strands, braided specimen, with different void fractions, B_a=400 mT and B_{dc}=1 T.

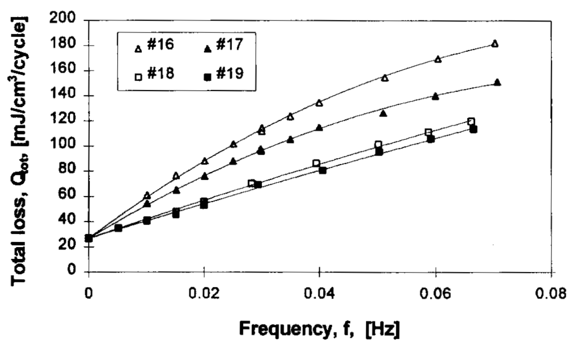

Fig. 4. Total loss versus frequency for 84 strands, twisted braids, with different void fractions, B_a=400 mT and B_{dc}=1 T.

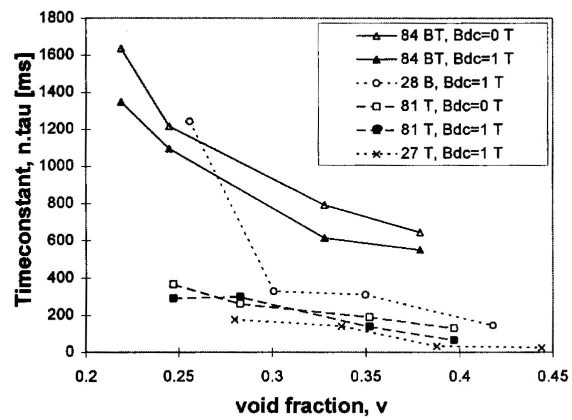

Fig. 5. Coupling loss as a function of the void fraction, for B_a=400 mT for twisted specimen #4, to #11 and braided specimen #12 to #19.

According to Fig. 5, the 28 B specimen give a coupling loss time constant far exceeding the n·τ of the 27 T. This might be caused by the ratio between the transposition pitch of the 28 B specimen and the last stage twist pitches of the 27 T cables. Note that the square of the ratio of transposition and twist pitches amounts to a factor: $(374/105)^2$=12.7.

The total increase of loss due to twisting the strand from the 0 to the 4th stage with 81 strands gradually progresses to a time constant of at least 300 ms, at the highest void fraction and about 140 ms for the 36 % ITER void fraction. Twisting three braids up to 84 strands, results in time constants of more than 1300 ms and about 300 ms for 36 % void fraction. The 81 T specimen #8 and #9 are remeasured within short time intervals of less than 24 hours. This results in $1.2{\cdot}n{\cdot}\tau_1$ to $1.5{\cdot}n{\cdot}\tau_1$ respectively, for which $n{\cdot}\tau_1$ represents the time constant of the first measurement. Specimen #9 is remeasured a third time after drying and cleaning with helium gas flowing through the jacketed cable at room temperature. The time constant drops from $1.5{\cdot}n{\cdot}\tau_1$ to $1.2{\cdot}n{\cdot}\tau_1$, while the hysteresis loss remains constant. The change in time constant stresses the influence of the interstrand contact resistance in the coupling current path. The presence of condensed air or frozen water is suspected to influence the interstrand contact resistance, but further investigations are necessary.

One of the consequences of a heat treatment is a softening of the Cu stabiliser material after it is hardened during jacketing and reducing the void fraction. As a result, part of the original contact pressure between the strands in the cable, as it was present before the heat treatment, has disappeared. The contact resistance between the strands is certainly different after heat treatment.

For specimen #16 a more extended frequency range is measured in order to compare the measured performance with theory over a large frequency range, by which the correlation between time constants determined by the slope and the maximum of the $Q_{tot}(f)$ curve, and the absolute value of the loss is determined. The hysteresis loss is subtracted from the total loss versus frequency and devided by the square amplitude of the applied ac field, $Q_{cpl}(f)=\{Q_{tot}(f)-Q(f=0)\}/B_a^2$. Relation (1) is applied using the summation of the coupling loss represented by three time constants for each cabling stage from strand (0) and braid (1) to twisted (2), to fit the total coupling loss versus frequency. When using equation (1) the losses per unit volume must be related to the multifilamentary zone (as a first approximation) and not to the strand volume.

The non-Cu fraction of the wire is 0.37 which means that the effective shape factor n for the composite is about 0.37 times the n=2 of a closely packed multifilamentary zone. So, for the coupling loss per volume strand as presented here an effective n value of about 0.8 can be expected.

A possible fit of the measured overall curve and the summation of three times equation (1) for 3 cabling steps is shown in Fig. 6. It can be observed that a satisfactory good solution can be found assuming $n_1=n_2=n_3=0.8$ and time constants of 5, 1200 and 210 ms respectively. Moreover the correct dominant time constant of about 1200 ms is found.

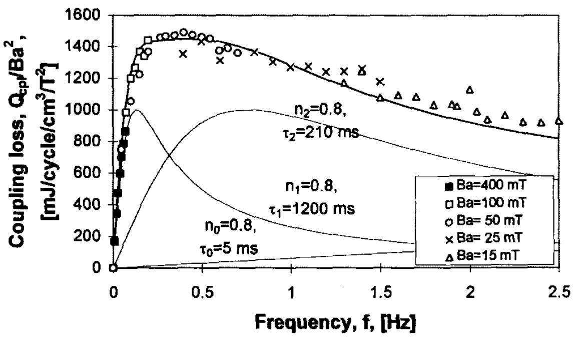

Fig. 6. Coupling loss versus frequency of specimen #16 for several amplitudes of the applied ac field and B_{dc}=1 T, with a best fit of the standard model using 3 time constants.

IV. CONCLUSIONS

Most time constants measured without dc background field are 10 to 20 % higher than those measured with B_{dc}=1 T. The coupling loss time constant increases significantly with declining void fraction. The total increase of loss due to twisting from the 0 to the 4th stage gradually progresses to a time constant of at least 300 ms, twisting three braids results in time constants of more than 1300 ms. The braided cables show an $n.\tau$ value at least about a factor 2 above the twisted specimen. The variation in $n\tau$ after repeated measurements, stresses the importance of the interstrand contact resistance in the coupling current path in spite of the chromium plating. The measured frequency dependence of the scaled coupling loss for various amplitudes of magnetic field coincide very well which proves the accuracy of the method and analysis. A good agreement is found between the measured loss of a three stage cable and theory over a large frequency range. The loss contributions represented by the three subcables can be added and acceptable time constants for the cabling stages are found.

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