A NEW TEST SETUP TO MEASURE THE AC LOSSES OF THE CONDUCTORS FOR NET

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Abstract

This paper describes the design of a new test system. It is under construction now and will be used to measure the AC losses of subcables from NET conductors. A special feature of the test arrangement is that the losses will be determined while the sample carries a transport current and is at the same time subjected to changing magnetic fields in transverse and longitudinal directions. Several aspects of the design such as magnetic fields, forces and losses will be discussed.

Introduction

In co-operation with NET (Next European Torus), the University of Twente is studying the AC losses of cables that will be used in the NET fusion machine. During the operation of such a tokamak, the currents in several toroidal coils, poloidal coils and the plasma produce a magnetic field that changes in magnitude and orientation in a rather complex way. In the toroidal coils the alternating field will in general have transverse as well as longitudinal components with respect to the cable. In the poloidal coils the magnetic field is oriented perpendicular to the jacket of the cable, but since the subcables are strongly twisted inside the jacket a significant component parallel with the subcables will exist.

The separate problems of multifilamentary wires in transverse or longitudinal changing fields have been solved theoretically by a number of authors.^{1,2,3} It is questionable whether these losses can simply be added when both components are simultaneously present. The presence of a transport current is often taken into account by multiplying the hysteresis loss by a general factor $(1 + \alpha(I/I_c)^2)$, where $\alpha=1$ for a constant current and $\alpha=1/3$ if the current varies in phase with B . In the case of cables in rapidly changing fields an extra loss contribution occurs caused by coupling currents flowing between the strands. This interstrand coupling loss depends strongly on the geometry of the cable and it has hardly been dealt with theoretically. It is clear that experimental verification of calculated losses is essential.

Requirements

Theoretical and experimental investigation of the AC loss in the NET conductors is of course an issue at various research institutes related to NET. An important aspect of the experimental programme carried out in Twente is that the losses will be measured under conditions that are comparable to the actual situation in the coil system of NET during regular operation or plasma disruptions. Therefore, the sample should be exposed to a combination of transport current, DC background field and rapidly changing transverse and longitudinal fields. Also, the sample length has to be at least one cabling length of conductor in order to have reliable results for the interstrand losses.

It was decided to develop a special test system in which the above conditions can be realized. The requirements are as follows:

- 1) transport current of up to 40 kA,
- 2) DC background field of 5 T,
- 3) AC transverse field of at least 1 T at 2 T/s,
- 4) AC longitudinal field of at least 0.5 T at 10 T/s,
- 5) suitable for sample diameters of 8 mm,
- 6) test length of at least one cable pitch (0.46 m).

The samples to be measured do not correspond to a final design of the NET conductors. They are the subcables of different pre-designs. A subcable is 1/21 of the full cable and consists of either 27 strands twisted in three-stage triplets or 29 strands braided according to a special technique developed at ABB. The basic conductor is a TWCA Nb₃Sn wire produced with the modified jelly roll method. The diameter of a strand is 0.96 mm and the diameter of the slightly compacted subcables is just below 8 mm. The braid has a periodicity of 0.46 m. In the twisted subcables, three characteristic twisting lengths play a role, but they are all significantly shorter than 0.46 m.

The expected critical current of the sample at 5 T can be estimated using I_c measurements on the single strand. At 5 T a strand will carry about 1100 A. This yields 25 kA at 5 T for the 29 strands subcable after correction for the self field (≈ 1.3 T).

General outline of the design

The magnet system consists of three concentric coils, about 0.6 m long. The inner coil is a solenoid generating the longitudinal AC field at the sample. This solenoid is enclosed by a dipole coil for the AC field and a second dipole coil providing the DC background field. The three coils are energized by separate

Figure 1. Electrical scheme of the test system.

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power supplies. If the voltage of the power supply (100 V) becomes insufficient to drive one of the AC coils, capacitors will be included to create a resonance circuit. A u-shaped sample, about 1 m long, is inserted into the solenoid. Its overall loss is measured calorimetrically using the well-known boil-off method. The calorimeter surrounds 0.46 m of the two straight legs of the sample, so the actual test length is 0.92 m. The transport current is generated by means of a superconducting transformer that is connected to the sample by 20 cm long soldered joints. The current can be measured with a superconducting current meter. This setup is shown schematically in figure 1.

Table 1. Data of the applied conductors.

	solenoid	dipoles & transformer
manufacturer	Alsthom	Alsthom
material	NbTi/Cu/CuNi	NbTi/Cu
bare diameter	0.30 mm	0.30 mm
filament diam.	1.4 μ m	2.3 μ m
η (=sc./total)	0.33	0.40
twist length	5 mm	3 mm

The transformer

To generate the current in the sample, the superconducting transformer and switch are used in the following operation cycle. First the switch is opened and the primary current is swept to $-\hat{I}_p$. Next the switch is closed and the measurement starts. A total primary current sweep of $2\hat{I}_p$ is then available to induce the desired transport current in the sample and to compensate the resistive voltage over the joints for a time Δt . To keep the current in the sample constant at a certain desired level I_s a feedback loop is necessary, as indicated in figure 1. If the resistance of the secondary circuit is constant, Δt can be determined from $2M_{ps}\hat{I}_p = L_s I_s + I_s R_s \Delta t$, where L_s represents the self inductance of the total secondary circuit including sample and M_{ps} the mutual inductance between primary and secondary.

In our transformer, consisting of a 5003 turn primary and a single turn secondary, M_{ps} is 0.50 mH and L_s is 0.3 μ H. The primary will be operated with 20 A so the available flux is 20 mVs. Supposing that the two joints are 1 n Ω each, which is a realistic value for this type of soldered connections, a transport current of 25 kA can be induced and maintained for 250 s.

Figure 2. Lay-out of the magnet system, sample and transformer.

The magnet system

Pulsed field coils

The coils for the AC fields have to be made with an appropriate low-loss superconductor and they should have sufficient cooling. In such a case, the ultimate field rate is usually limited by the power supply rather than by the coil itself. Suppose that a certain pulsed magnetic field B is generated in a volume V . The stored energy of such a magnet is at least $V|B|^2/2\mu_0$, so the power of the supply has to be

$$P(t) > \frac{V}{\mu_0} |B| \frac{d|B|}{dt}$$

This shows that besides keeping the volume of the coils as small as possible, it is also advantageous to have the DC background field and the AC field perpendicular to each other. This was the main reason to rotate the AC and DC dipoles mutually by 90° . The orientation of the different field components at the sample is illustrated in figure 4.

Magnetic coupling

By choosing the appropriate arrangement of the different coils and the sample, undesirable magnetic coupling has been avoided as much as possible. The resulting lay-out is shown in figures 2 and 3. The solenoid does not couple with any of the other coils. The inner dipole is rotated 90° with respect to the outer dipole, therefore they have no magnetic interference. Since the fields of the dipoles are perpendicular, the sample will always couple with one of the dipoles, however coupling with the DC dipole is not problematic. Coupling with the AC dipole should be avoided otherwise the AC field will influence the transport current in the sample. For this reason the plane of the sample has to be parallel to the AC field.

Table 2. Parameters of the magnet system

	Solenoid	AC dipole	DC dipole
number of turns	7552	2x1780	2x6000
self inductance [H]	0.105	3.43	37
field factor [T/A]	0.0206	0.048	0.087
package length [mm]	460	560	560
i.d. of the coil [mm]	28.0	38.0	72.1
i.d. of package [mm]	28.4	42.3	76.1
o.d. of package [mm]	32.4	60.5	106
o.d. of the coil [mm]	34.0	63.5	132

Figure 3. Cross section of the magnet system.

Figure 4. Orientation of the various field components.

Forces

The repulsive Lorentz force between both halves of each dipole is sustained by means of a steel pipe around it. In addition there is a steel pipe inside the coil. To avoid large deformation of the coil these inner and outer supporting pipes need to be rather thick, for example 2 and 12 mm respectively for the DC dipole. Mechanical fixation of the conductor is achieved by vacuum impregnating the winding package between the pipes using an unfilled epoxy.

Table 3 shows the expected mechanical interaction between the coils and the sample. In the calculation, a worst case has been assumed where the sample carries 25 kA, the solenoid generates 0.5 T, the AC dipole 1 T and the DC dipole 5 T. The forces acting on the primary coil of the transformer are negligible because it is at sufficient distance from the magnet system. The torque acting on the solenoid is absorbed by the inner steel pipe of the AC dipole by means of spacers. Similarly, wedges in the gap between the inner and outer dipoles have to be present to absorb the 7100 Nm and to prevent rotation of the dipoles.

The torque on the sample is a point of concern because the sample holder can only be fixed at the ends, outside the calorimeter. The sample holder has to be sufficiently stiff to keep torsion within acceptable limits. To handle the 110 Nm alternating torque of the AC dipole, a cross section as shown in figure 5 is necessary. Note that an additional torque caused by the DC dipole may occur if the sample is not properly aligned. Another important point is that the directions of the DC field and the transport current should be such that the sample is pressed inwards, against the sample holder.

Table 3. Calculated torque (in Nm) acting between the various coils and the sample, using $I_s = 25$ kA, solenoid at 0.5 T, AC dipole at 1 T and DC dipole at 5 T.

	sample	solenoid	AC dipole	DC dipole
sample	---	0	110	$580 \cdot \sin \phi$
solenoid	0	---	130	640
AC dipole	110	130	---	7100
DC dipole	$580 \cdot \sin \phi$	640	7100	---

The losses in the magnets

A worst case analysis of losses in the magnet system is given in table 4. The smallest dissipation occurs in the solenoid which is wound with a relatively short length of mixed matrix wire. The solenoid is only

3 mm thick, therefore well cooled, so the temperature rise is negligible. This is not true for the dipoles in which the conductor loss is much larger and the dissipation in the support structure is also significant. Note that the values given in table 4 represent averages over the total coil volume. The local AC loss in the ends of the dipoles will be higher.

Table 4. Calculated dissipation in the magnet system (in W). The two values represent losses caused by the solenoid at 10 T/s and AC dipole at 2 T/s respectively.

		Hysteresis	Eddy current
solenoid :	conductor	0.14 / 0.03	0.1 / ≈ 0
AC dipole:	conductor	0.05 / 0.13	0.2 / 0.7
	inner pipe	-- / --	0.9 / 0.2
	outer pipe	-- / --	0.8 / 0.5
DC dipole:	conductor	0.2 / 0.5	0.1 / 0.5
	inner pipe	-- / --	0.5 / 0.3
	outer pipe	-- / --	1.8 / 1.0

The sample holder

As explained before, the H-shaped cross section of the sample holder is required for mechanical reasons. The sample is folded into the holder after applying an insulation tape which prevents electrical contact with the holder. Then, after the heat treatment, it is soldered to the permanent secondary section of the transformer. A glass fibre tape for protection is wound around the holder in a way that allows access of liquid helium. The tape has no mechanical function because the Lorentz force presses the sample into the holder during the measurement.

The measurements have to be corrected for the eddy current loss occurring in the sample holder, which can easily be calculated. For example if the solenoid generates 10 T/s and the dipole 2 T/s, the eddy currents in the holder dissipate 0.25 W. At these field rates the expected AC loss in 0.9 m of sample is several Watts.

Figure 5. Detail of the sample holder and the u-shaped sample surrounded by the boil-off chamber.

Loss measurement

To determine the AC losses, the boil-off method is foreseen. A distinction between hysteresis and coupling losses can be made in the usual way, by measuring the dissipation over a certain range of frequencies and separating the components proportional to f and $(fB)^2$. Experiment shows that an absolute accuracy of better than 5 % is possible in the range of 10 mW to 2 W.

The total dissipation in the sample has three sources: the current supplied by the transformer, the longitudinal field generated by the solenoid and the transverse field of the AC dipole. In principle it is possible to distinguish between these sources if an electrical method is applied, using voltage taps over the sample and two pick-up coils of a solenoidal and dipole shape. This method has been rejected because of its complexity and the fact that it requires a number of compensation coils that are difficult to accommodate in the magnet system.

Conclusions

A special facility has been designed in which the AC losses of NET subcables will be measured. The objectives are: 1) to verify existing loss expressions quantitatively, 2) to investigate the effect of combined losses of different origins and thus get a better understanding of AC losses. The construction of the facility is in progress and first results are expected by the end of 1990.

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