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ABSTRACT

In the frame of the International Tokamak Experimental Reactor (ITER) program, multistage superconducting Cables-In-Conduit (CIC) conductors have been developed. These cables were designed assuming a uniform current distribution among strands. A basis for this assumption in DC operation is that the strands are fully transposed inside the conductor within a connection length (equal to a cable twist pitch). A geometrical analysis of a conductor and a detailed numerical modelling of an ITER CIC have refuted this hypothesis. This implies that the current sharing among strands inside a connection is non-uniform and thus that the DC current distribution in the conductor is also non-uniform. Moreover, it is well known that the critical current of a strand is dependent on the perpendicular component of the magnetic field. Therefore, because of the twisting pattern, the self-field gradient inside a cable cross section due to the transport current leads to a field gradient along every strand length. Calculations of the voltage drop along conductor length taking into account the connection and the field gradient are compared to the critical current measurements on the first European Full Size Joint Sample (SS-FSJS) for ITER.

INTRODUCTION

For designing multistrand cables, the usual way is to calculate the cable critical current from the critical current of a single strand at the peak perpendicular magnetic field experienced by the conductor in the coil. Such a calculation implicitly assumes:

1. All strands carry identical currents
2. All strands are subjected to the same field

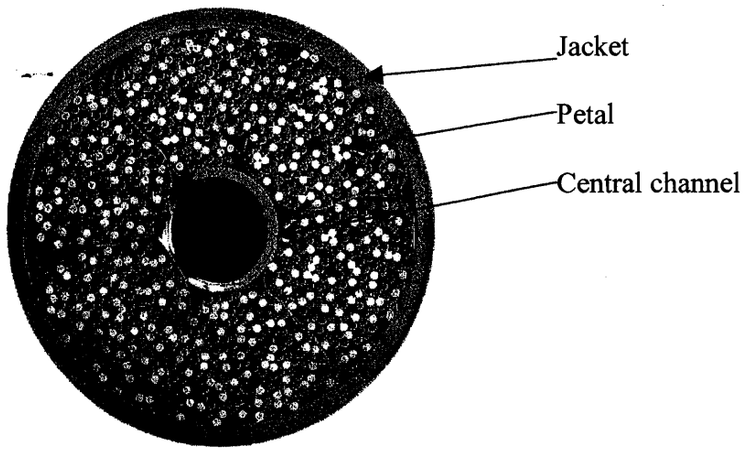

Figure 1. ITER type conductor cross-section (ITER TFMC conductor)

In a coil under DC operation, the current distribution among strands along a unit length of the winding is purely driven by the two connections located at both ends. As an example, doubly unconnected strands (i.e. at both ends) will not carry any current. In case of non-insulated strands, this statement is valid only at low operating current, because current redistribution occurs as soon as strand currents approach their critical values. Thus hypothesis No.1 assumes either that the distribution of strand connecting resistance is homogeneous in the joints, or that interstrand resistance are low enough. In case of an EU-ITER connection, a detailed connection modelling and a destructive analysis of a connection have been performed to check this hypothesis.

Thanks to a newly developed geometrical model, the actual strand trajectories in the cable have been estimated. Thus it has been possible to calculate the voltage drop along the cable by integrating the local electric field, taking into account the actual field experienced by every strand for a given transport current. The critical current calculation then becomes free from the second hypothesis. This law has finally been inserted into a conductor model (electrical network) taking into account the uneven distribution of strand connecting resistances inside the joints as well as the interstrand resistances.

Eventually, the predictions given by the model have been cross-checked with critical current measurements performed on the first European Full Size Joint Sample for ITER (the so-called SS-FSJS).

ACTUAL CABLING MODELLING

ITER conductors are multistrand cables embedded in a structural jacket (see Figure 1). The cabling pattern for the cable shown in Figure 1 is 3x3x5x4x6 with respective twist pitches of 50-70-120-180-450 mm. Our goal is to find a geometrical model giving the actual trajectories of the strands along the conductor length. A first assumption is that all the main sub-cables (so-called petals) are identical, so the trajectories of "only" 3x3x5x4 strands have to be found.

Ideal strand trajectory

A first step is to assume that any strand trajectory is only dependent on the twist pitch pattern and on the radii of the different cabling stages, which means the trajectory is only a combination of helical curves. Each cabling stage radius is calculated knowing the sub-

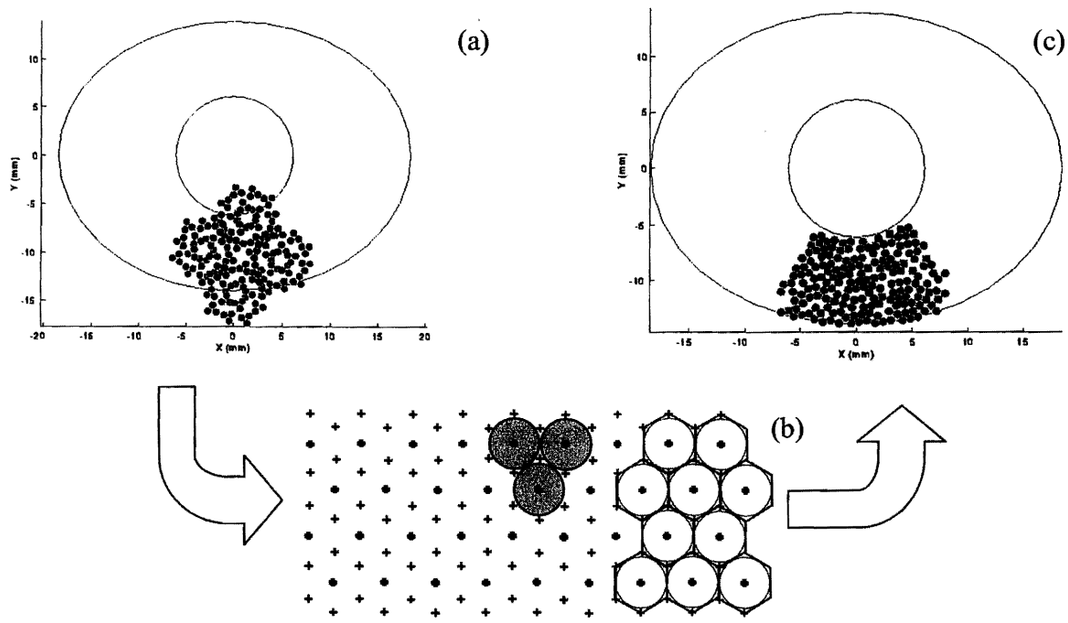

Figure 2. Ideal cross-section (a) is fitted into a mesh (b) to give the "actual" cross-section (c)

stage radius and the number of included sub-stage. For instance, the radius of a triplet of strands of diameter d is $\sqrt{3}d$. This method is not limited to a round conductor, indeed it is possible to use a helix with a square or an ellipsoidal basis instead of a circular one.

Figure 2.a shows the cross-section of an EU connection for ITER (see also Figure 3.b) with the "ideal" strand trajectory. This connection has already been described elsewhere[1]. For our purpose, it has to be noticed that the outer frame of the strand area is roughly an ellipse and the inner frame is a circle. Thus the last but one stage follows a helix with an ellipsoidal basis. It is clear that the "ideal" geometrical area of the petal does not fit into the available space in a real connection (in which the cable void fraction is about 25%).

Cross-section meshing

A new arrangement of strands into the section, taking into account the twisted pattern and the available space, has to be found. The basic idea is to use a finite meshing of the space available for strands (in our case a "trapezoidal" shape for a petal). The mesh is triangular so that the triplet is naturally formed (see Figure 2.b). The location of a strand

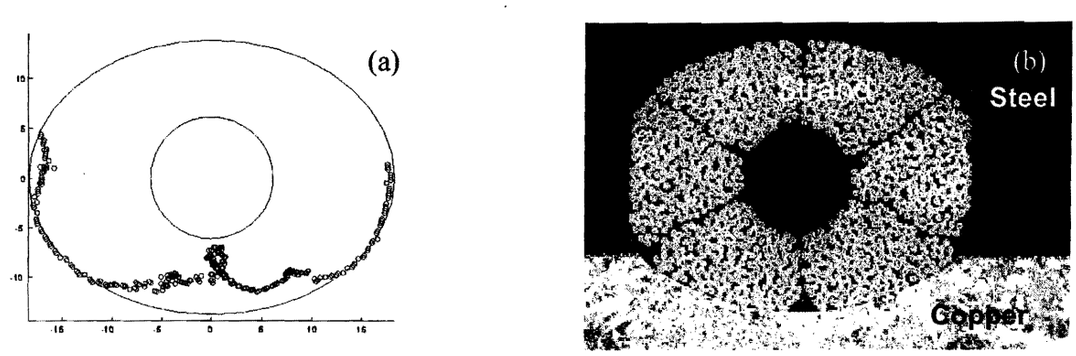

Figure 3. "Actual" strand trajectory (a), and Actual connection cross-section (b)

Table 1. Contact statistic for the modelled and real connection

Contact Numbers per strand	0	1	2	3	4	5
Measured	60	60	47	11	1.5	0
Modelled	60	58	37	17	6	2

into the mesh is the nearest free spot in the mesh. The initial location is calculated with the ideal trajectory (Figure 2.a). Figure 2.c gives the results of such a calculation. It is clear that all strands fit now into the available connection space.

Checking of the model with a real connection

However, the weak point of our model is that it does not really impose the continuity of the strands along the cable axis direction, since each cross-section is arranged separately. Nevertheless, Figure 3.a shows that trajectories calculated for strands are not broken by unexpected jumps provided length step is small enough.

Secondly, a connection has been especially manufactured in order to check the validity of our model. The connection box has been manufactured by ANSALDO (Italy), the sample prepared by CEA and the final compaction performed by ANSALDO. This connection was fully impregnated, and then dismantled. It was then possible to count the number of contact points between the copper sole of the connection (see Figure 3.b) and every strand. These measurements are summed up in Table 1. The model is in rather good agreement with measurements except for 4 and 5 contact point strand, which are overestimated by the model.

Conclusion

Our geometrical model gives a rather simple method to get the actual strand trajectory of every strand in a CIC. This model has been tested on an EU connection with success. This model, as well as the measurements, shows that strands are not fully transposed inside the conductor. Besides, it is shown that the contact distribution in a connection is uneven, which means that in DC operation a current unbalanced among strands must be expected.

CRITICAL CURRENT OF A CIC

A model has been developed to calculate the cable critical current taking into account the actual magnetic field experienced by strands, the unbalanced distribution of strand connecting resistances, as well as the interstrand resistances.

Effect of the actual strand trajectory on strand voltage drop

Theoretical basis

The electric field, **E**, along a superconducting strand carrying a current density J under a magnetic field **B** is given by the usual formula (1) where $\mathbf{E}_{c0}$ and n are constant.

$$\mathbf{E}(\mathbf{B}) = \mathbf{E}_{c0}\left(\frac{J}{J_c(\mathbf{B})}\right)^n \tag{1}$$

In this case, J_c is only dependent on **B**, as the temperature T_{op} is kept constant. The relation between J_c and **B** is usually described using the pinning law:

$$\|\mathbf{J}_c \wedge \mathbf{B}\| = F_p(T_{op}, b), \text{ with } b = B/B_{c2}(T_{op}) \tag{2}$$

F_p is the so-called pinning force. F_p can be written in the following way, where f is a function independent of b.

$$F_p(T_{op}, b) = f(T_{op})g(b) \tag{2'}$$

This law shows the effect of the field orientation on the critical current density J_c. However, it has to be noted that previous experiments[2] have shown that the expression given here is only a first order approximation for Nb_3Sn strands, indeed the pinning force is also dependent on the field orientation.

The average electric field, $\overline{E}_i$, over a length L of conductor for strand i with trajectory C_i inside the cable is given by (3).

$$\overline{E}_i = 1/L \int_{C_i} \mathbf{E}(\mathbf{B})d\mathbf{s} \tag{3}$$

During a conductor critical current measurement, in DC condition, the electric field measured corresponds, in a first approximation, to the average electric field over all the strands, $\langle \overline{E}_i \rangle$.

Application of the real strand trajectory model

Knowing the "actual" strand trajectory, it is possible to calculate $<E_i>$. However, for a cable composed of hundreds of strands such a calculation is rather long and a simplified formulation is needed for a use as a subroutine in an electric network.

Usually, for a sample critical current measurement, an external field $\mathbf{B}_{ext}$ is applied to the conductor. The local magnetic field on strand i at curvilinear abscissa s_i is thus given by (4), where α is a vector dependent on the strand trajectory and I is the transport current through the conductor sample.

$$\mathbf{B}(s_i) = \mathbf{B}_{ext} + \boldsymbol{\alpha}(s_i)I \tag{4}$$

Note that the current distribution is assumed to be uniform among strand for calculating α. We restrict our study to the case when $\mathbf{B}_{ext}$ is predominant (i.e. $B_{ext} >> \alpha I$), which is the usual case when testing high field conductors. Then the magnetic field direction is constant and is given by the direction of $\mathbf{B}_{ext}$; thus (4) can be projected on this direction leading to (4').

$$B(s_i) = B_{ext} + \gamma(s_i)I \tag{4'}$$

Now, using (2) and (2'), it is possible to write (5).

$$J_c(s_i) = \frac{1}{\sin(\beta(s_i))} F(T_{op})G(b) \tag{5}$$

where F is equal to $f(T_{op})/B_{c2}(T_{op})$, and G is equal to $g(b)/b$. Introducing (5) into (1) leads to (6), where J_i is the current density in strand i.

$$E_i(s_i) = E_{c0} J_i'' \sin''(\beta(s_i)) F^{-n}(T_{op}) G^{-n}(b) \tag{6}$$

Then developing $Q^{-n}(b)$ by a MacLaurin series in the vicinity of b_{ext} ($=B_{ext}/B_{c2}$) (see Equation 4'), one gets the following series expansion according to I.

$$E_i(s_i) = E_{c0}\left(\frac{J_i}{J_{c\perp}(B_{ext})}\right)^n \left[\sin^n(\beta(s_i))\right]\left[1+\sum_{q=1}^{\infty}\frac{A_q(b_{ext})\gamma^q(s_i)}{q!B_{c2}{}^q}I^q\right] \quad (7)$$

where $J_{c\perp}$ is the strand critical current density under a perpendicular field of amplitude B_{ext}.

Equation (7) shows that the coefficients of the series expansion are constant. They depend on the external field (B_{ext}), on the operating temperature (T_{op}) and on the strand trajectory (γ). For a given strand i, $\overline{E}_i$ is then calculated using (3), last $\langle\overline{E}_i\rangle$ can be calculated by averaging $\overline{E}_i$ over all the strands, which leads to (8).

$$\langle\overline{E}_i\rangle = E_{c0}\left(\frac{J}{J_{c\perp}(B_{ext})}\right)^n \left[\sum_{q=0}^{\infty}\frac{A_q(b_{ext})\Gamma_q}{B_{c2}{}^q}I^q\right] \quad (8)$$

Note that Γ_q, which is the sum of the terms containing si, is only dependent on the strand trajectories, and that J is the current density assuming a uniform current distribution. Thus, for a given conductor configuration and a given b_{ext}, the electrical field along the conductor is given by the same development in power expansion of I. It has to be noted that our model simulates an average strand carrying a current density J. I is the transport current inside the cable, and the expansion is in fact a global corrective factor due to the self field effect (for $q \geq 1$) and the strand trajectories (for $q \geq 0$).

In order to check the validity of this development, the coefficients of the series in (8) have been calculated numerically using a direct calculation performed with equation (3) without approximation for different values of B_{ext} and of operating temperature leading to the same b_{ext} (see Equation (2)). The agreement between the series expansion values and the direct calculation has confirmed the validity of our calculations, but note that for practical applications (8) must be expanded up to q equal to 11.

Effect of the uneven current distribution among strands and "interstrand" resistance: discrete electrical network

The preceding electrical field calculation takes into account the strand trajectory submitted to a uniform field. It gives the electrical field along an "average strand" but it does not take into account an unbalanced current distribution.

Model presentation

A main hypothesis is that all strand contact point resistances have the same value. It means that strands with two contacts will carry twice the current of strands with only one contact. It is then possible to group strands according to the contact distribution given in Table 1. The cable is then modelled with only a few groups of strands. Each group is considered as a unique "big" strand. The electrical field of the group is calculated using the expansion calculated in the preceding section. The number of groups is a compromise between accuracy and computing time (in our case N=8 is a good optimum).

The cable can thus be modelled as a resistive network with 8 conductor groups (see Figure 4). The groups are connected at both ends to a power supply by resistance R_{joint} calculated according to Table 1 and to the resistance of the connection. R_{joint} are different for each group and at each end of conductor. The voltage drop along a group for a given current is calculated using Equation (8).

In order to take into account the current transfer from one group to the other (intergroup resistance), resistances, R_{trans}, between conductor groups are inserted. R_{trans} are different in the joint area, $R_{t\text{-}joint}$, and in the conductor area, $R_{t\text{-}cond}$ (see Figure 1 and Figure

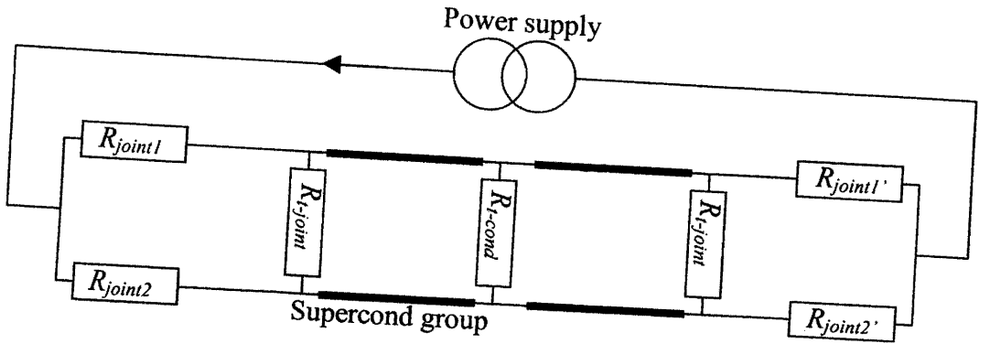

Figure 4. Schematic view of a 2-groups electrical network

3.b) mainly due to the different void fraction. R_{joint} values are calculated with the statistic given in Table 1 and with the total resistance measured on the joint.

It has to be noted that a field profile along the conductor can be introduced to calculate critical values. This model has been fully described elsewhere by D. Ciazynski[3].

Conclusion

A model has been developed taking into account the actual field gradient inside a conductor. This model has been inserted inside an electrical resistive network of a conductor length connected at both ends to a power supply (see Figure 4). The current redistributes between strands through interstrand resistance and the uneven distribution of strand connecting resistance inside the EU-ITER joint. For a given conductor and connection, the input free parameters of this model are:

1. The transverse resistances, $R_{t\text{-}joint}$ and $R_{t\text{-}cond}$.
2. The strand critical current characteristics.

The Summers's law gives the strand critical current[4]. Parameters of this law have been fully investigated for ITER strands[5]. The only free parameter is the strain, ε, in Nb_3Sn filaments inside strands. This value is different in the joint, ε_j, and in the conductor, ε_c. From experimental results on sub-size joints[6], ε_j is taken equal to –0.72% and $R_{t\text{-}joint}$ equal to 6 $R_{t\text{-}cond}$. Then only two free parameters remain: ε_c and $R_{t\text{-}joint}$.

APPLICATION TO EXPERIMENTAL RESULTS

Our model can be now cross-checked with critical current measurements performed on the first European Sample for ITER (the so-called SS-FSJS) in the SULTAN test facility.

ITER Full-Size-Joint-Sample description

A sample is composed of two straight conductor bars connected at one end (the sample is tested in vertical position) by an ITER joint and at the other end to the facility superconducting transformer. The maximum applied field in SULTAN is 11 T perpendicular to the conductor bars. For current critical measurements, the voltage drop along 440mm of the bars (the last stage twist pitch length) is measured. The tests performed on this sample have been presented elsewhere[7]. In this paper, a particular critical current test is analysed: B_{ext} is equal to 11 T, T_{op} is equal to 7.7 K.

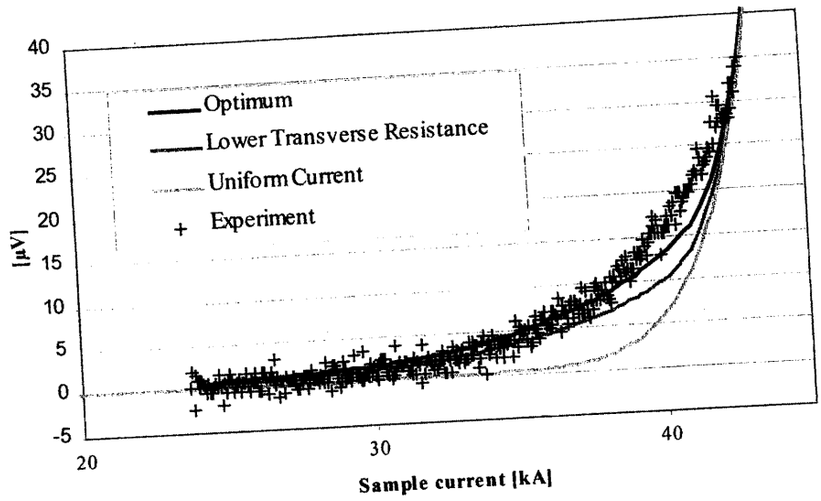

Figure 5. Comparison between model (ε_c=-0.594%, Optimum→$\rho_{t\text{-joint}}$=30µΩ.m, Lower→$\rho_{t\text{-joint}}$=20µΩ.m, Uniform→$\rho_{t\text{-joint}}$=1µΩ.m) and experiment (+)

Modelling results

As explained in the former section, two parameters are adjusted (ε_c and $\rho_{t\text{-joint}}$) using the experimental $V(I)$ curves. Results of such fit are shown in Figure 5. ε_c is found equal to – 0.594% and $\rho_{t\text{-joint}}$ equal to 30 µΩ.m leading a good agreement with measurements.

Two other calculations have been performed to point out the effect of the transverse resistivity inside the joint. The lower is the transverse resistance, the better is the current distribution, and then no current redistribution voltage occurs near the transition. In the $V(I)$ curve calculated for $\rho_{t\text{-joint}}$=1µΩ.m the current distribution is almost uniform.

CONCLUSION

A model has been developed to calculate voltage drop along CIC conductors taking into account the detailed strand trajectory and the resistive network at ends and inside the cable. This model has been partly checked on an ITER joint mock-up and used to analyze a critical current test performed on an ITER FSJS sample. The analysis of this test have led to estimate a quite high interstrand resistivity inside the joint (and thus also inside the cable). It means that current distribution must be unbalanced up to quite high I/I_c ratio. It can then be expected that at the operating current the current distribution inside CIC conductor is still strongly unbalanced, which could lead to an unexpected lower stability margin. Other tests have still to be analysed to check if the same optimisation can be done for different B_{ext} and I.

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