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AC Losses of Pancake Coils Made of Roebel Cable

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***Abstract*—Roebel cables are a promising solution for high-current, low ac loss conductors for various applications, including magnets, rotating machines and transformers, which generally require the cable to be wound in a coil. We recently assembled and characterized a 5 meter long sample and wound it into a pancake coil. In this contribution, we investigate the ac loss behavior of such pancake coil by means of numerical simulations based on two complementary models: the finite-element model based on the H-formulation and the minimum magnetic energy variation method based on the critical state. These two numerical models take into account the axis-symmetric geometry of the coil and its detailed structure, simulating each strand composing the cable. Local current density and magnetic field distributions are shown and the ac losses for various current amplitudes are computed. The influence of the number of turns and of their separation on the coils ac losses is investigated. The results of the computations are compared with the measurements and the main reasons for the observed discrepancy are discussed.**

***Index Terms*—Roebel cables, coils, ac losses, numerical simulations.**

I. Introduction

REOEBEL cables made of R*E*BCO coated conductors are an attractive possibility for having compact, high-current conductors with low ac losses. For a variety of applications, like magnets, rotating machines and transformers, conductors need to be wound in coils and a first example of a pancake coil assembled from a Roebel cable has been reported in [1]. Before committing to manufacturing coils for applications, it is important to be able to have a precise idea of how the geometry of the winding (e.g. the number of turns and the separation between turns) affects the magnetic field distribution and, ultimately, the ac losses. Numerical models can be very helpful for this purpose as they can give an accurate description of the structure of the coil and take into account the individual tapes in the cable.

In this paper, we simulate four different pancake coils assembled from the same 5 meter long Roebel cable, manufactured at KIT [2]. Simulations are performed in 2-D with two different models: the finite-element method (FEM) model based on the H-formulation and the minimum magnetic energy variation (MMEV) model. Both models take into account the cylindrical symmetry of the considered geometry.

The paper is organized as follows: first we describe the geometry of the coils and the numerical models; then we show the computed ac losses for different coil samples, and we interpret the results with the help of magnetic field and current density distributions; finally, we compare the computed losses to the measured one, discussing possible reasons for the observed discrepancy.

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II. Coil geometry and Numerical Models

The coils are assembled from the same 5 meter long Roebel cable, composed of 10 strands obtained from 12 mm wide tape from Superpower, Inc. and with a dc self-field critical current of 936 A at 77 K. Due to the important self-field effects in a tightly packed structure as a Roebel cable, this critical current is much lower than the value obtained by multiplying the critical current of each strand (about 140 A) by the number of strands (10) composing the cable [3]. Winding the cable into a coil further reduces the critical current. Table I summarizes the main properties of the coils: the number of turns, the spacing between the turns, the measured self-field critical current, and the total number of strands in the cross-section of the coil used for simulations. As expected, the critical current of the coil decreases by reducing the spacing between the turns, due to an increased self-field.

TABLE I
Properties of the different coils.

Turns	Spacing	I_c	# of simulated strands
13	0.1 mm	456 A	130
9	4 mm	661 A	90
9	10 mm	744 A	90
6	20 mm	829 A	60

For our calculations we used two models: the finite-element method (FEM) model based on the H-formulation and the minimum magnetic energy variation (MMEV) model. These models have been already used for simulating individual Roebel cables [4], [5]. This time we use them for the more complicated geometry of coils made of Roebel cables, which needs to take the cylindrical symmetry into account and results in the simulation of up to 130 thin superconductors. A schematic view of the considered geometry is shown in Fig. 1. With the MMEV model, each strand is meshed with 100 uniformly distributed elements along the width and 1 element along the thickness. Since the FEM model is generally slower, it is important to try to save as many elements as possible: therefore, we simulated only one half of the width of each Roebel turn (so that the numbers of simulated tapes are halved with respect to those indicated in table I), and each strand is meshed with 50 elements distributed more densely near the edges of the strands.

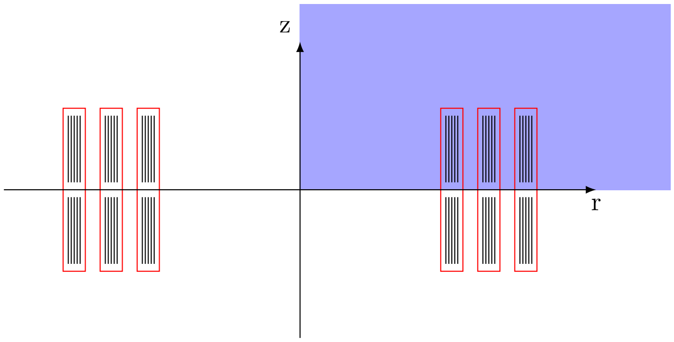

Fig. 1. Schematic view of the cross-section of a coil considered in the simulations (for better readability only three turns are shown). Each red rectangle enclosing ten thin strips represents a turn of the Roebel cable composed of ten strands. For the FEM calculations only one quarter of the full cross-section of the coil (shaded area) is simulated. Not drawn to scale.

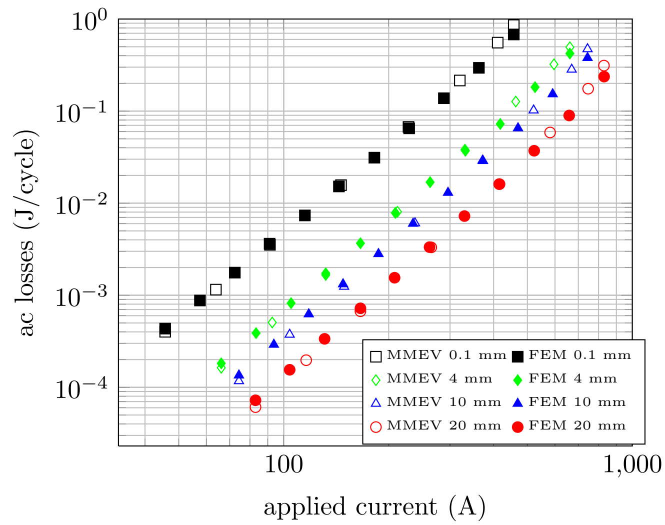

Fig. 2. Computed ac losses as a function of current for the different coil samples.

Differently from earlier works of ours, for this work we implemented the H-formulation in the 2-D axis-symmetric AC/DC module of the Comsol Multiphysics software package. That module solves the following equations:

$$\sigma\frac{\partial \mathbf{A}}{\partial t}+\nabla\times\mathbf{H}=\mathbf{J_e} \tag{1}$$

$$\mathbf{B}=\nabla\times\mathbf{A}, \tag{2}$$

where $\mathbf{J_e}$ represents an externally imposed current density. These equations correspond to those we want to solve

$$\mu\frac{\partial \mathbf{H}}{\partial t}+\nabla\times\mathbf{E}=0 \tag{3}$$

$$\mathbf{J}=\nabla\times\mathbf{H} \tag{4}$$

once the following associations are made: $\mathbf{A}\rightarrow\mathbf{H}, \sigma\rightarrow\mu, 1/\mu\rightarrow\rho, \mathbf{B}\rightarrow\mathbf{J}$ and $\mathbf{J_e}=0$. The main advantage of this approach over the conventional one [6] is that this implementation can be used with different software packages and numerical codes designed for electromagnetic field computation, as it was already pointed out in [7]. In the case of Comsol Multiphysics, the axial symmetry can be included automatically, without the need of modifying the equations.

In the FEM model the superconductor is modeled with a non-linear resistivity $\rho=\frac{E_c}{J_c}\left|\frac{J}{J_c}\right|^{n-1}$, where $E_c=10^{-4}$ V/m, $n=35$, and J_c is derived from the measured critical current of the coil divided by the superconductor's cross section. The same value of J_c is used for the simulations with the MMEV method. This approach allows, at least to a certain extent, to take the self-field effects of the Roebel cable into account.

III. Results

A. AC Losses of Different Coil Samples

Figure 2 presents the ac losses (in Joule/cycle) as a function of the transport current, computed with the FEM (at 50 Hz) and MMEV models. Similarly to what we found in previous works of ours [4], [5], the agreement between the two models is very good. This is a further confirmation of the complementarity of the two approaches and an important mutual verification that the electromagnetic quantities are computed correctly, also in the case of complex geometries (hundreds of tapes) and of problems with cylindrical symmetry. The observed slight discrepancy at high currents is to be ascribed to the fact that the MMEV model is based on the critical state model and, as a consequence, the local current density cannot exceed J_c, which causes a rapid increase of the losses as soon as the critical current of the conductor is approached.

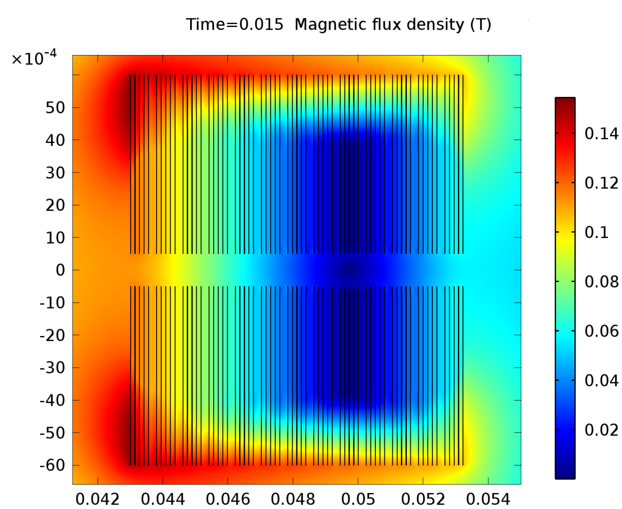

Fig. 3. Magnetic flux density distribution in the coil with turn separation of 0.1 mm. The transport current is 288 A and the distribution refers to the current peak.

From the figure it can be seen that the more tightly the coil is wound, the higher the losses are. This is due to the fact that the produced self-field is higher and penetrates the superconducting strands more deeply when the coil is tight, as can be seen from Figs. 3-4. The figures show the distribution of the magnetic flux density at the peak of the current in the two most extreme coils, with a turn separation of 0.1 mm and 20 mm, respectively, and for a transport current of 288 A. It

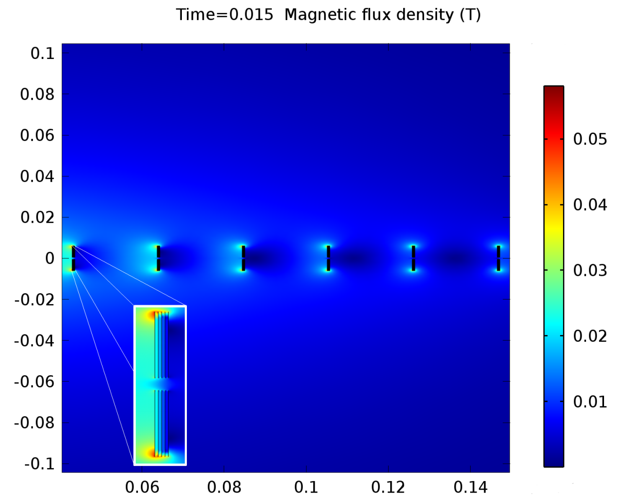

Fig. 4. Magnetic flux density distribution in the coil with turn separation of 20 mm. The transport current is 288 A and the distribution refers to the current peak.

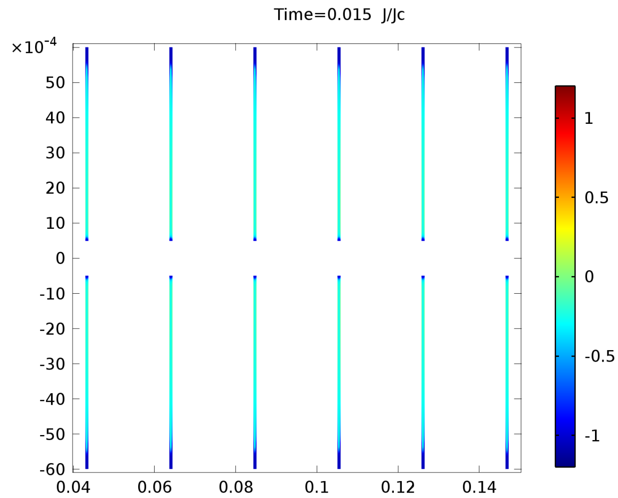

Fig. 6. Current density distribution in the coil with turn separation of 20 mm. The transport current is 288 A and the distribution refers to the current peak.

can be noted that in the case of the tighter coil, the maximum flux density reaches 140 mT, whereas in the case of the looser coil, the maximum is only about 60 mT. This clearly shows the influence of the self-field on the ac losses of coils made of Roebel cables and the importance of the separation between turns for assembling such coils.

The different loss behavior of the coils can also be understood by looking at the current density distribution for the two cases, which is shown in Figs. 5-6. It can be noted that, due to the high self-field, in the case of the tight coil the current penetrates deeply inside the strands, filling most of its width, whereas for the looser coil the penetration occurs only in a limited region from the edges.

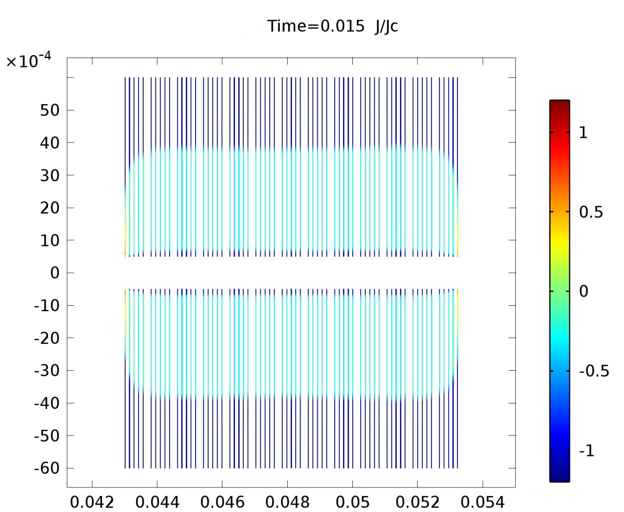

Fig. 5. Current density distribution in the coil with turn separation of 0.1 mm. The transport current is 288 A and the distribution refers to the current peak.

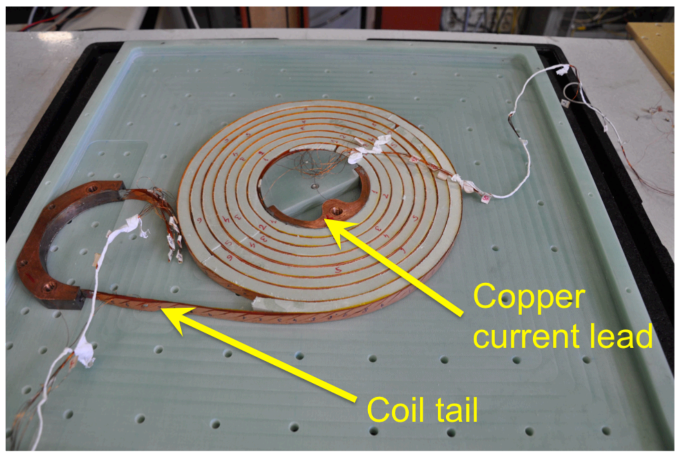

Fig. 7. View of the coil with 10 mm separation between the turns.

B. Comparison with Experiments

We measured the ac losses of the coil by putting the voltage taps on the copper contacts, which is expected to provide sufficiently accurate results [1], [2]. When we compared the results of computations with measurements, in general we found that the agreement is not so good. More specifically, the measured losses are higher than the computed ones, and the curves of the losses vs. current have a lower slope, typically between 2.4 and 2.7, whereas the computed curves have a slope of about 3.5. An example of measured and computed losses is given in Figs. 8-9 for a frequency of 18 and 72 Hz, respectively. Different factors have to be taken into account while comparing experiments and simulations:

- The utilized model with constant J_c is not very precise and a model including the angular dependence on the local magnetic field $J_c(B, \theta)$ would be more appropriate. However, it is unlikely that this reason alone can account for the drastic change of slope of the loss curves.
- We simulate the idealized case of a perfectly axis-

symmetric problem. In reality, the coil sample has a relatively long "tail" (whose length depends on the particular coil sample), which breaks the symmetry of the problem – see Fig. 7. This cable part contributes to the losses in a different way than the part spirally wound, however its contribution to the losses should be superconductor-like, and as such it should have a slope similar to the one coming from the rest of the coil.

- The copper leads might have an important influence on the measured losses. Since the losses in a metal have a slope +2 contribution, this might be the reason for the observed behavior.

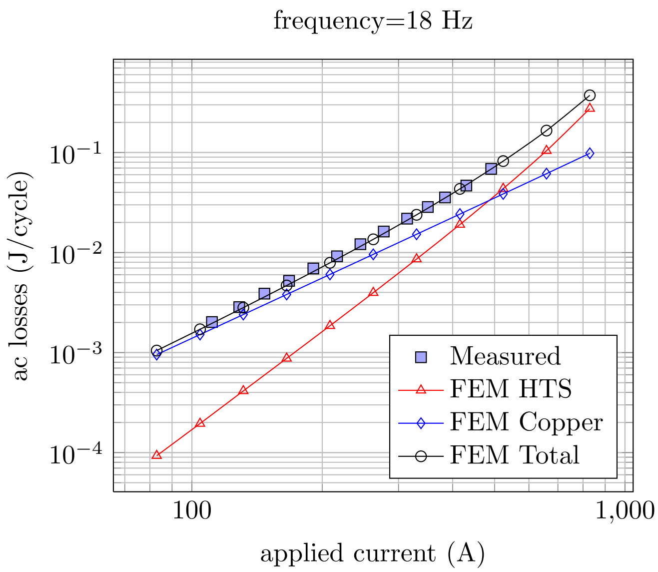

Fig. 8. Comparison of measured and computed ac losses. In the computations, we simulated the presence of a copper turn. The frequency of the current source is 18 Hz.

In order to test the third hypothesis, we simulated the presence of a copper turn inside the coil, with cross-section similar to that of the copper ring (5 mm) and resistivity $2 \cdot 10^{-9} \Omega \cdot \mathrm{m}$. When the loss contribution of the copper is added to the superconductor losses, the total losses are much closer to the experimentally measured ones and the slope is much more similar, as can be seen in Fig. 8-9. However we found that the degree of agreement changes with the frequency, so that a more detailed simulation of the copper current leads is necessary.

IV. Conclusion

With this work we successfully compared two numerical models for ac loss computations in the case of coils assembled from YBCO coated conductor Roebel cables. With respect to previous comparisons of the same models, we analyzed a much more complex geometry (up to 130 tapes) with cylindrical symmetry. The obtained very good agreement confirms the complementarity of the two models.

We calculated the losses of coils of different dimensions, in particular different turn separations and numbers of turns. We found that when the coil is tightly wound the self-field effects

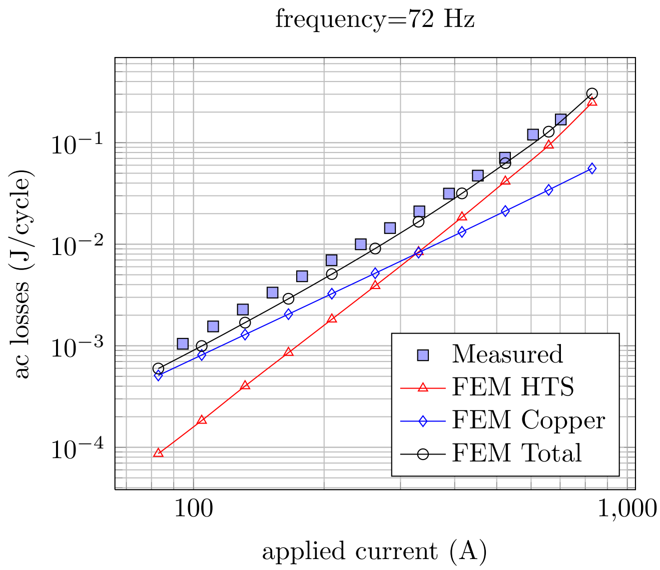

Fig. 9. Comparison of measured and computed ac losses. In the computations, we simulated the presence of a copper turn. The frequency of the current source is 72 Hz.

are very important and the losses are much higher (more than one order of magnitude) that those in a loosely wound coil, made with the same cable. The models are also able to provide detailed information of the current density and magnetic field distributions inside the coils.

The utilized models contain important simplifying assumptions, e.g. a field-independent J_c and a perfect cylindrical symmetry that is not completely realistic. And when we compared the computed losses with the measured ones we found an important discrepancy. However, this discrepancy has most probably to be put in relation with the way ac loss are measured, more specifically with the presence of massive copper blocks used as current leads. When the presence of the inner copper block is taken into account in the model (albeit with an approximated geometry), the computed losses are much closer to the measured ones, both in terms of absolute value and of the slope of the loss curve.

Further studies will include the angular dependence of J_c on the magnetic field and a more accurate simulation of the copper leads.

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