Utilising full angle-dependent critical current data in the electromagnetic modelling of HTS coils

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***Abstract*—A methodology is presented for modelling HTS coils using full angle-dependent critical current data. The results are contrasted with those obtained using more common techniques such as a minimum critical current method or a field magnitude-dependent approximation. Several interesting design consequences that emerge only when the full anisotropy of the wire is taken into account are outlined and discussed.**

Keywords—electromagnetic modelling, critical current data, anisotropy, hybrid windings, coil orientation, inclined substrate deposition

I. Introduction

Common approaches to the modelling of HTS coils involve either assuming a minimum critical current (I_c) value for the wire or adopting a field dependent $I_c(B)$ characteristic, which conveniently lends itself to an approximate functional form. Often the underlying values are taken from real wire data measured at the desired operating temperature (T) and possibly for fields applied both parallel and perpendicular to the wire surface to account in a minimalistic (and unrealistic) manner for the true I_c anisotropy of the wire. Less common is the use of full angle-dependent critical current data $I_c(T,B,\theta)$ due to issues of both the availability of such data and the perceived difficulty of modelling using real data tables in place of functional approximations.

Here we discuss both aspects of the data-driven approach and highlight the benefits that can be obtained in the design of real devices when actual wire data is utilised. In particular this leads towards several novel approaches to device design and construction that are worthy of deeper investigation.

II. Modelling Method

A. Data Sources

One data source that allows convenient investigation of the implementation and benefits of these methods is the freely accessible Robinson HTS wire database [1], and we will use example data from this database to illustrate the modelling approach. Of course, at the point of real device construction it is better – if not essential – to re-run the models on the basis of sample data acquired on the actual wire to be used, and internally we typically adopt this approach. However, for educational purposes, any available dataset can be utilised to good effect.

B. Modelling Method

To demonstrate the method, we restrict ourselves to a simple two-dimensional axisymmetric electromagnetic model formulated in the open-source software FEMM [2]. Again, it is recognised that this is not the cutting edge of electromagnetic modelling, but it serves to exemplify the method, provides a no-barrier route to access and experimentation, and it is anticipated that all the techniques described can as easily be implemented in more advanced tools, including three-dimensional simulation packages.

The method is straightforward enough. For each element in the mesh that lies within the conductor, the field magnitude and orientation at that point is determined. For an axisymmetric two-dimensional model, we benefit from the convenience that the field components B_r and B_z fall naturally in the commonly measured out-of-plane (maximum Lorentz force) geometry relative to the wire. In a three-dimensional model, it will be necessary to decompose the field vector into an in-plane and an out-of-plane component and to then choose to neglect any in-plane variation.

Once this is done, it is a simple computational step to interpolate the $I_c(T,B,\theta)$ dataset to obtain the I_c of the wire under the particular field conditions (magnitude and orientation) pertaining to the given element. The coil I_c is then dictated by the minimum I_c element (with whatever engineering margin is desired). For a given operating current, the result can trivially be replotted as a percentage of the wire I_c at the operating temperature. By way of example, a simple model of a coil pack comprising ten double-pancakes is shown in Fig. 1, operating at two different temperatures while generating the same 2.5 T central field. It is seen that

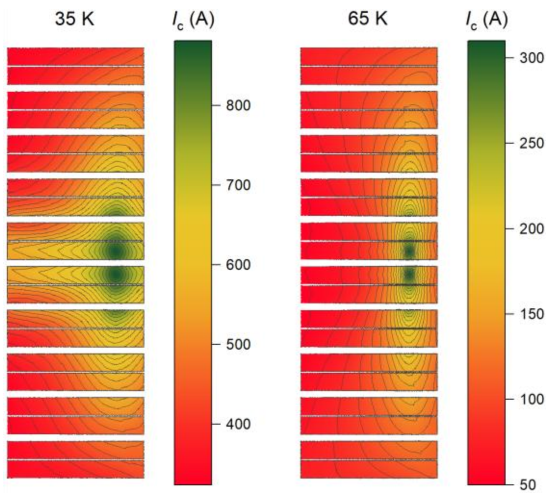

Fig. 1. Critical current maps of a ten double-pancake coil pack operated at different temperatures but generating the same 2.5 T central field. The bore is to the left. Notice that the point of lowest I_c is at the end of the bore when operated at 35 K, but shifts to the centre of the bore at 65 K.

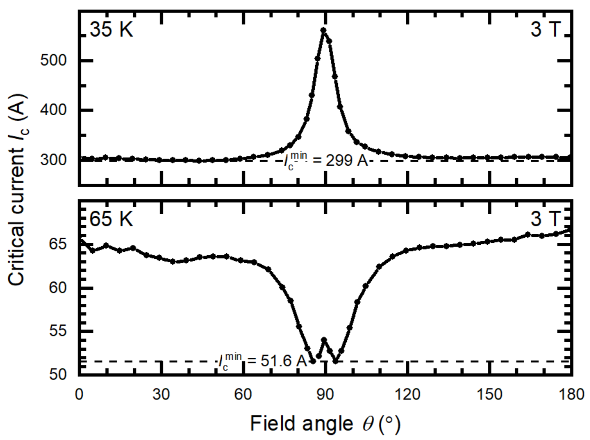

Fig. 2. Field angle dependences of the critical current of the wire used [3] for modelling the coil shown in Fig. 1 at the two operating temperatures and the highest field (3 T) experienced by the coils.

the weakest point of the coil can vary from the point of greatest field magnitude (as at 65 K) to the point at which the field lies perpendicular to the plane of the wire and through intermediate points where field magnitude and orientation combine to become least favourable (as at 35 K). It depends entirely on the complex behaviour of the wire and is not static but varies in dependence on the operating temperature.

The explanation for this seemingly unusual behaviour is apparent upon inspection of the angle-dependent I_c curves of this wire at the two example temperatures (Fig. 2). Such a behaviour will never be predicted by a mathematical model based on a monotonic decay of $I_c(B)$ at all temperatures.

C. Comparison with Other Approaches

The comparison with the minimum I_c model is trivial. We simply identify the highest field at any point on the conductor and note its minimum I_c value at that field. These values are labelled on Fig. 2, although note that in practice the I_c value at the perpendicular field angle of 0° is often taken as a proxy for I_c^{min}, and the data for 65 K shows clearly how faulty this assumption can be. In the 35 K case where we have a simple anisotropy with close-to-minimum I_c for fields perpendicular to the wire and maximum I_c for fields in-plane, we can obtain a substantial performance benefit by taking advantage of the enhanced in-plane performance of the wire, in this case operating at 325 A vs 299 A, a gain of almost 10%. Of course, this is heavily dependent on the exact features of the wire and the device design as exemplified by the behaviour at 65 K where the wire performance is insufficient to support the desired current. However, if a 0° I_c^{min} value were to be assumed here, this would overrate performance by a disastrous 30%.

Any attempt to account in some superficial way for the anisotropy of the wire using a geometrical combination of parallel and perpendicular field dependences is clearly going to fare no better. Only by properly accounting for the real anisotropy of the wire do we reach an optimal device design.

III. Novel Device Designs

These considerations suggest several avenues towards the development of novel device designs taking advantage of the unique characteristics of coated conductor wires.

A. Hybrid Windings

Once the critical region of a given coil pack is accurately identified, it becomes an obvious option to substitute a higher-performance wire for the most critical coils, or indeed to simply arrange the coils on hand in such a way as to optimise available wire usage. Often, as in the 35 K case here, there can be a significant difference in the performance of wire required in, for example, the end coils (I_c^{min} = 335 A) and the mid coils (I_c^{min} = 420 A). Such an arrangement has been termed a hybrid winding [4].

B. Flipped Coils

Likewise, when the full anisotropy of the wire is properly taken into account, it can often be found that an otherwise overlooked asymmetry between field directions either side of the wire normal (not strongly evident in the data presented here) can lead to performance differences. In this case, simply taking care of the orientation of the coils as they are stacked can produce significantly enhanced performance [5].

C. Inclined Planarity Coated Conductors

Coated conductors prepared by a method such as inclined substrate deposition [6] which results in a strongly offset in-plane peak I_c offer a unique opportunity to accommodate conventionally unfavourable field orientations. Together with point B above, coils formed from such wires have the potential to entirely obviate the issues associated with field divergence at the end coils. To our knowledge, no such attempt has been reported to date. Such a dataset [7] provides an excellent case study as a starting point for investigation.

IV. Conclusion

Modelling utilising actual wire data and in particular full angle-dependent critical current characterisation offers many opportunities to optimise devices and exploit features of real wires that are missed when mathematical approximations to their real-world behaviour are adopted. Existing techniques can be relatively easily adapted to make use of such data as it becomes more widely available.

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