2D finite element modelling of the AC transport power loss in multi-layer Bi-2223 cables

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Abstract. A simple model is proposed which can estimate the total AC transport power loss of a multi-layered Bi-2223 cable, with the effect of the twisted geometry approximated in 2D, thus greatly decreasing the required computational resources. The model operates by applying a modified current value on the cable’s cross-section. This can be achieved mathematically by taking into account the layer’s twist angle. Several multi-layer cable models with varying layer pitch lengths and magnitudes of transport current were simulated, and the power loss estimated using 3D models; the same was done for their corresponding 2D models and then the results were compared. Furthermore, the 2D model was used to simulate a real 4-layer Bi-2223 cable, where the difference between the simulated power loss and loss presented in literature was under 10%. It was shown that due to the favourable results, the methodology has sufficient basis for further investigation and implementation.

1. Introduction
The majority of AC loss studies of power cables focus on employing analytical methods, or the circuit model. Hence, there is limited literature on the 2D modelling of power cables, particularly those with layer twisting. Several second generation cables are modelled in [1] in the 2D domain, as a reference to further 3D studies, where a simple cross-section is taken without further considerations. Helicoidal symmetry is explored in [2] where a methodology is introduced for simulating the twisted filaments of a superconductor in 2D. However, the possible application in the modelling of systems of tapes is not explored. A reduced 3D model proposed in [3] utilizes a conductivity matrix with anisotropy to model a multi-layer first generation HTS power cable, where the conductivity matrix uses trigonometry to influence the direction of current flow based on the twist angle of each layer. However, the underlying construction of the model appears to rely on a monoblock, which would be insufficient to model both normal operation and overcurrent situations.
In [4] it is simply stated that simulation of the AC loss in Bi-2223 cables requires a 3D model (such as in [5]). Using a cross-section is argued can only be used for conductors of infinite length and geometries with cylindrical symmetry. In the remainder of this paper it is shown that this is not necessarily correct when suitable considerations can be employed.

The proposed model in this paper seeks to provide an easy-to-build and fast-to-simulate tool to estimate the AC loss in such cables by utilizing a previously published homogenization technique for 1G multifilamentary tapes. The computational and time cost of finite element
modelling can then be greatly reduced, enabling FEM to be easily used for AC loss calculations, and establishing a base for further multiphysics studies.

2. Modelling technique

The $H$-formulation was coded in the "General PDE" module of COMSOL 5.4 [6] and discretized using first order curl elements [7]. A Time-Dependent Direct Solver, using backward differentiation formulas (BDF) and free time stepping was utilized.

The 2D simulations were performed on an Intel i7-6700 CPU, 3.4 GHz, 16 GB of RAM; the 3D simulations were performed on the computing nodes of IRIDIS 4 at the University of Southampton — 2.6 GHz Intel Sandybridge, 64 GB of RAM per node.

2.1. $H$-formulation

The $H$-formulation [8] has been successfully used to model current density and electromagnetic fields in superconducting tapes [6,9,10].

Ampere’s Law at power frequency, and therefore without a displacement field [11]:

$$\nabla \times H = J$$

(1)

Faraday’s Law:

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

(2)

Combining both Ampere’s and Faraday’s Laws with $J = E/\rho$ [12]:

$$\nabla \times (\rho \nabla \times H) + \mu_0 \mu_r \frac{\partial H}{\partial t} = 0$$

(3)

where $H$ — magnetic field strength, $\rho$ — resistivity of the material, $\mu_0$ — magnetic permeability of free space, $\mu_r$ — relative permeability of the material. A well-rounded description of the $H$-formulation can be found in [11].

The initial conditions are:

$$H = \begin{bmatrix} H_x \\ H_y \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

(4)

$$\frac{\partial H}{\partial t} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

(5)

A Neumann boundary condition on the outer boundaries is set as per [9]:

$$\frac{\partial H}{\partial t} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

(6)

To introduce a given AC transport current, the current density on the entire conducting surface is integrated (in COMSOL, via a pointwise constraint [10]):

$$\int_S J_n dS = I_T$$

(7)

where $S$ — surface on which the current is applied to the model, $J_n$ — normal component of the current density on this surface (in 2D, the off-plane z-direction), $I_T$ — total transport current.

Total power losses, in 2D, $Q$ (J/m/cycle) [4] are integrated over the 3rd half-cycle to avoid transient terms that arise from the initial conditions [13, 14] and over the entire surface of the tape $S_t$, then doubled to minimize simulation time:

$$Q = 2 \int_{1/f}^{1.5/f} \int_{S_t} JEdt$$

(8)
2.2. HTS material simulation

The superconducting phenomenon is modelled via the E-J Power Law [15]:

\[ E = E_c \times \left( \frac{J}{J_c(B)} \right)^{n(B)} \quad (9) \]

where \( E \) is the electric field, \( E_c \) is a constant of the electric field at which the DC critical current is defined (\( E_c = 1 \times 10^{-4} \) V/m), \( J \) is the current density, and \( J_c(B) \) and \( n(B) \) are the magnetic flux dependent critical current density and power index, respectively.

The critical current density’s dependence on the magnetic field is expressed:

\[ J_c(B) = J_{c0} \times f(B_\perp)g(B_\parallel) \quad (10) \]

where \( J_{c0} \) is the local critical current density at zero field; \( B_\parallel \) and \( B_\perp \) are the parallel and perpendicular components of the magnetic field in Tesla with respect to the wide face of the tape, respectively.

\( f(B_\perp) \leq 1 \) and \( g(B_\parallel) \leq 1 \) are functions, obtained via a piecewise cubic interpolation of the experimental data in literature, which describe the critical current density’s dependence on the perpendicular and parallel magnetic field component, respectively. Both are normalised by \( J_{c0} \).

The same equation may be applied to the \( n \)-index [16]. This technique has been successfully used in [17].

2.3. Homogenization of 1G multifilamentary tapes

Several papers execute their numerical modelling via a type of homogenization [18–21] with a varying degree of explanation. Homogenization in 1G multifilamentary tapes can be traced back to [22–24] and is redefined for AC power loss modelling in [17].

Appropriate homogeneity can be obtained when the simulated superconducting domain has the approximate shape of the real tape’s multifilamentary region. Since here the cross-sectional area of the homogenized domain is larger than the real area of superconductor, it must be ensured that the current is correctly distributed in the cross-section. This can be achieved by scaling the local critical current density in self-field \( J_{c0} \) in all cases such that:

\[ J_{c0} = I_c/S_{eq} \quad (11) \]

where \( S_{eq} \) is the area of the filamentary-equivalent domain used in the model and \( I_c \) is the critical current for the given tape. An equation similar to the above is mentioned in [21].

3. Proposed method for estimation of the power loss via finite element modelling

3.1. Method description

This method may not predict the current sharing between individual layers — it must be known or calculated separately. As power cables are designed so that the current is equally shared between all layers in order to minimize losses, all models in this work assume that is the case. This is not a substitute for a proper 3D study, but is rather an opportunity to achieve a time-efficient FEM simulation via an approximation.

Mathematics. The essence of the proposed model is applying a current through a 2D cross-section, such that the magnitude of this applied current is equal to the total current flowing through the cross-section, and not the total current of the tape (Figure 1).
Figure 1. A top-down view of a small section of the 3D geometry of a power cable, the piece in blue with striped shading is a twisted tape. This is an illustration of the trigonometric relationship between $I_t$ and $I_{t-2D}$.

If the peak transport current flowing in a twisted tape is $I_t$ and the twist angle is $\alpha$, then the peak applied current in the 2D cross-section is:

$$I_{t-2D} = \frac{I_t \cos \alpha}{\cos \alpha}$$

The critical current density at self field at any point of the 2D cross-section remains the same as if the examined tape was straight.

Additionally, each tape of a particular layer in the 2D model has its width $w_t$ modified by the cosine of the twist angle $\alpha$ of that layer. Displayed in Figure 2, similarly to Equation 12:

$$w_{t-2D} = \frac{w_t \cos \alpha}{\cos \alpha}$$

Constructing the 2D model. A single cross-section in a 2D model cannot represent the various positions a tape from one layer can have in relation with a tape from another layer. It is proposed that the total AC loss in the cable is equal to the average value of the AC loss calculated by the 2D models using two "extremes". It is already known that the AC loss in a practical cable must fall between the losses in these two extremes [25].

The first "extreme" is the tape-on-gap cross-section, where each layer is rotated such that the center of each tape will be above the gap between the tapes of the layers above and below (Figure 6).

The second "extreme" is the tape-on-tape cross-section, the centres of the tapes in all layers are stacked on top of each other (Figure 7). Then, the following is proposed:
\[
Q_{2D} = \frac{Q_{tot} + Q_{tog}}{2}
\]

where \(Q_{2D}\) — total power loss in the 2D model, \(Q_{tot}\) — power loss in the tape-on-tape cross-section, \(Q_{tog}\) — power loss in the tape-on-gap cross-section.

3.2. Handling the critical current density’s dependence of the magnetic field in twisted tapes

When the anisotropic dependence of the critical current density on the magnetic field is calculated in models where the twist of the tape with respect to the coordinate system is not taken into account, problems may arise.

In standard Cartesian 2D, the correction is fairly easy. There are two magnetic field components, \(H_x\) and \(H_y\). A relationship between the field components and the tape’s unit vectors is achieved mathematically via the method widely known as rotation of base vectors. An illustration can be seen in Figure 3. The representation is made via the following trigonometric formulas:

\[
H_{m-x} = H_x \cos \phi_r - H_y \sin \phi_r
\]

\[
H_{m-y} = H_x \sin \phi_r + H_y \cos \phi_r
\]

\[
\phi_r = \tan^{-1}\left(\frac{x}{y}\right)
\]

where \(H_{m-x}\) is the component of the magnetic field parallel to the wide face of the tape and \(H_{m-y}\) — the component perpendicular to the wide face of the tape. \(\phi_r\) is the angle of rotation of the tape (clockwise). \(x\) and \(y\) are the Cartesian coordinates of point at which the effective magnetic field is calculated, assuming that the cable is centered on \(x = 0, y = 0\).

In 3D, it has been shown that the longitudinal field \(H_z\) has a slightly smaller contribution to the critical current dependence than the field parallel to the wide face of the tape [26]. For simplicity, it has been assumed it bears the same contribution. In such case, \(H_z\) is added as-is to the calculation of the total magnitude of \(H_{m-x}\):

\[
H_{m-x} = \sqrt{(H_x \cos \phi_r - H_y \sin \phi_r)^2 + H_z^2}
\]

\[
H_{m-y} = H_x \sin \phi_r + H_y \cos \phi_r
\]
4. Method verification

The proposed method is tested in three sample 2-layer cables, modelled in 2D and 3D, and one real 4-layer cable, modelled in 2D and compared with the losses from literature.

4.1. Construction of sample 3D cables

Three cables with two layers each are built, their details are shown in Table 1. (+) and (-) signify the direction of the twist of each layer, which does not have any effect on the proposed method, provided that the design of the cable is such that equal current flows in each layer due to balanced inductance value. The tape used in these cables is a 1G Bi-2223 tape characterized in [18]. Each of the three cables has been simulated in 3D by taking a length of 3.5 cm. Longer lengths were shown to produce negligibly different results.

Firstly, the 2D geometry is built by drawing each layer separately using its radius and twist angle, and putting it together with the other layers, according to Equation 13.

To build the geometry for the 3D models, each already-made 2D layer is sweep-extruded along a parametric curve, described mathematically by the pitch length and radius of each layer. The transport current is forced to be equally spread between the layers via pointwise constraint integration, applied on the contact surface of each layer; no restrictions are enforced on the individual tapes.

The AC loss is taken from a small central section of the entire simulated where end effects do not appear:

\[
Q = 2 \int_{0.5/f}^{1/f} \iiint_{V_i} Q dt
\]  

\[Q = 2 \int_{0.5/f}^{1/f} \iiint_{V_i} Q dt\]  

Table 1. Specifications of the 3D cables used in verifying the 2D approximation method. The (+) and (-) signify twist direction.

| Common values for all cables | # of conductor layers | # of shield layers | # tapes in layer 1 | # tapes in layer 2 | Extrusion length | AC frequency | Total \(I_c\) | Tape |
|-----------------------------|----------------------|-------------------|-------------------|-------------------|------------------|--------------|-------------|------|
|                             | 2                    | 0                 | 12                | 12                | 35 mm            | 50 Hz        | 1872 A      | Choi [18] |
| Cable 1                     | Pitch length, layer 1| 300 mm (+)        |                   |                   |                  |              |             |      |
|                             | Pitch length, layer 2| 300 mm (-)        |                   |                   |                  |              |             |      |
|                             | Layer 1 inner radius | 5.8289 mm         |                   |                   |                  |              |             |      |
|                             | Layer 2 inner radius | 6.3389 mm         |                   |                   |                  |              |             |      |
| Cable 2                     | Pitch length, layer 1| 300 mm (+)        |                   |                   |                  |              |             |      |
|                             | Pitch length, layer 2| 100 mm (-)        |                   |                   |                  |              |             |      |
|                             | Layer 1 inner radius | 5.8289 mm         |                   |                   |                  |              |             |      |
|                             | Layer 2 inner radius | 6.3389 mm         |                   |                   |                  |              |             |      |
| Cable 3                     | Pitch length, layer 1| 100 mm (+)        |                   |                   |                  |              |             |      |
|                             | Pitch length, layer 2| 100 mm (-)        |                   |                   |                  |              |             |      |
|                             | Layer 1 inner radius | 6.2224 mm         |                   |                   |                  |              |             |      |
|                             | Layer 2 inner radius | 6.8174 mm         |                   |                   |                  |              |             |      |
where $V_t$ is the volume of interest, $Q = JE$ is the AC loss.

Swept meshing is used in all domains as a compromise between a sufficiently fine mesh within the superconducting domain and a reasonable amount of degrees of freedom (Figure 4 and Figure 5). However, with the twisting of each layer being different, the two swept meshes would not be able to join. Then, adding buffer domain(s) where the mesh is free tetrahedral becomes necessary.

To be able to achieve convergence, the Jacobian was set to be updated once per timestep, up from the default "minimal" setting. This improves the Newton Method’s ability to calculate in the presence of very large non-linearities, but it is more computationally expensive.

4.2. Construction of a 2D model based on a real cable

A cable, installed and tested in semi-laboratory environment [27] has been selected to be modelled in 2D due to the existence of sufficient detail of its specifications and AC loss data. It is a 66 kV, 100-metre long cable in a 3-cores-in-1-cryostat configuration. The details relevant to the AC loss simulations are provided in Table 2.

The 2D geometry is built by drawing each layer, including the shield layers, separately using

![Figure 4. Illustration of the twist and meshing of the two layers in Cable 2 from above.](image)

![Figure 5. Illustration of the twist and meshing of the two layers in Cable 2 along the tapes.](image)

| Table 2. Specification of the real 2D cable used in verifying the 2D approximation method. |
|-----------------------------------------------|
| # of conductor layers | 4 |
| # of shield layers | 2 |
| # tapes per conductor layer | 13 |
| # tapes per shield layer | 26/27 |
| Conductor outer radius | 10 mm |
| Shield outer radius | 18.5 mm |
| Conductor pitch lengths, mm | 130(+), 305(+), 400(-), 115(-) |
| Shield pitch lengths, mm | 350(-), 530(+), 115(-) |
| Total $I_c$ (Ph 1, Ph 2, Ph 3) | 2730 A, 2760 A, 2780 A |
| Tape dimensions | 0.24 mm $\times$ 3.8 mm |
| Tape $I_c$ and $n$ | 52-53 A, 10.5* |
its radius and twist angle, and putting it together with the other layers. Each tape of a particular layer has its width $w_t$ modified by the cosine of the twist angle $\alpha$ of that layer, as in Equation 13.

The layers were placed evenly within the inner and outer radii of the conductor and shield.

Only half the tapes of each phase are simulated, due to symmetry, using an appropriate symmetry boundary condition — in this case for symmetry along the $y$-axis — $H_y = 0$.

Due to lack of data about the $J_c(B)$ dependence in [27], it is assumed the tapes exhibit the field dependence and silver to HTS ratio from [18] — another tape from the beginning of the 21st century.

5. Results analysis

5.1. Three two-layer cables, simulated in 3D and 2D

Results from the simulations of the three custom cables are available in Figures 8-10. The highest difference between the losses in the 2D and 3D (from the central volume) models in Cable 1 being 8%, in Cable 2 — 19%, and in Cable 3 — 20%.

It was observed the shorter the pitch length of a layer, i.e. the sharper the twist, the denser the swept mesh has to be in order to capture the smoothness of the twist realistically. Coincidentally, it was also observed that with increasing the density of the swept mesh, the 3D calculated loss
The simulated AC losses from all models for Cable 3 are shown in Figure 10. A graph illustrating these losses is presented, where the x-axis represents the ratio of transport to critical current ($I_t/I_c$), and the y-axis shows the AC losses in joules per cycle per meter ($J/cycle/m$). The graph includes data points for both the central section volume loss and the loss obtained from the proposed 2D model.

Figure 11. The average value of the magnetic field magnitude within the HTS material of all tapes of Cable 3, for three values of the transport current.

The values were approaching those calculated by the 2D model; finally plateauing at the values presented in Figures 8-10.

To confirm that the model does exhibit a symmetrical 3D cable, the following criteria are examined in post-processing: 1) consistency of current densities on points along a path, parallel to the length of the same tape; 2) symmetry of magnetic fields at the same points of every tape within a layer; 3) direction of the current density magnitudes inside each tape.

The values of current density on three points along the central section of two tapes are presented in Figure 14 and Figure 15 for the negative half-cycle, where a strong consistency can be seen. Figure 14 and Figure 15 also compare the current densities at the points from the 3D model with the value of the current density for the same point, in the corresponding 2D, averaged between the tape-on-tape and tape-on-gap methods. There is an excellent match at the peak values of current density, and the "delay" between the 2D waveforms perfectly matches the "delay" between the 3D waveforms.

Similarly for the current densities on the same point of a tape, taken from each of the 12 tapes in a layer, a near perfect symmetry can be seen (Figure 16 and Figure 17). For the cable at $I_t/I_c = 1.2$, there is a sharp edge, which is a numerical effect that may be attributable to the mesh quality.

The average magnetic field density of Cable 3 for three values of the transport current can be...
seen in Figure 11. As expected, the magnetic fields from each model are very similar for the same transport current, and the average magnetic field in the 'tape-on-tape' cross-section model is the highest.

Lastly, the direction of the current is observed in Figure 12. It can be seen to follow the tape as expected, and that behaviour is the same throughout all tapes. All of this shows the 3D model indeed represents a 3D cable.

5.2. A real four-layer cable simulated in 2D
The reported AC power loss in [27] is 3-phase, which means leakage fields may affect neighbouring phases. In the model of a single phase, a change of less than 0.1% of the critical current density was observed further than 2 mm away from the shield layer, at peak $I_t$. However, in [27] it is reported that only 93% of the transport current is in the shield, in contrast with 99% in the present model, which implies in reality there is a larger field leakage. When the shield current is constrained to 93% of the transport current in order to observe the higher leakage magnetic

Figure 14. Current density along a current flow line. Cable 3, $I_t/I_c = 0.8$.

Figure 15. Current density along a current flow line. Cable 3, $I_t/I_c = 1.2$.

Figure 16. Current density on the same point within a tape, around all tapes of a layer. Cable 3, $I_t/I_c = 0.8$.

Figure 17. Current density on the same point within a tape, around all tapes of a layer. Cable 3, $I_t/I_c = 1.2$. 

10
field, $J_c(B)$ outside the cable would be 99% of $J_c(0)$ or higher, increasing with distance. Such a small effect corresponds to a few mT and would have negligible effect on the neighbouring phases. Therefore, each phase may be simulated separately from the rest, thus decreasing model complexity. Change in losses due to lower shield current is in the range of $3\%-4\%$, which is too small to justify an artificial constraint on the shielding effect.

The cable was simulated for eight values of the peak transport current. These values were extracted from Figure 5 (measurements dataset) in [27] using a graph data extractor. Figure 8 in [27] shows that each phase has a different critical current. Therefore, they are not identical and each phase must be simulated. Then, the resulting AC power losses from each phase can be summed together.

The results from the simulations are summarised in Figure 18, and compared against the measurements reported in [27] in Figure 19. The ‘tape-on-tape’ cross-section simulation produces power loss with increasing current at a larger rate than the ‘tape-on-gap’ cross-section. This is because stacking current carriers (tapes — Figure 6 and Figure 7) above each other produces a stronger local magnetic field and thus a lower critical current density.

Averaging the AC loss values of the ‘tape-on-tape’ and ‘tape-on-gap’ cross-section models produces a difference with the values measured in [27] of no more than 5% when approaching critical current. This demonstrates that the proposed technique, as per Equation 14, is reasonable — according to [12], a 10% to 50% accuracy variation is satisfactory.

6. Conclusion
A method for approximating the total AC power loss of first generation twisted-layer cables under transport current conditions in 2D has been successfully implemented. It has been verified against 3D models of three sample 2-layer cables with different pitch lengths, with the results achieving a match with differences within the range of $5\%-10\%$, and no more than $20\%$. Furthermore, the good match (within $1\%$ to $5\%$ at $I_t/I_c > 0.5$) of the results for the real cable is promising.

Despite these results, there is a need for more complete experimental data, including tape properties, to be made available in order to facilitate a validation of the proposed modelling technique that is free from modelling assumptions.
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