Simulation of AC losses in racetrack coils wound with striated HTS tapes

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Abstract. The T-A formulation has proved a fast and reliable method for the evaluation of AC losses in superconducting tapes, and has been successfully applied to complex geometries such as racetrack coils, CORC® cables, and twisted stacked tapes conductors in either applied magnetic field or self-field. In particular the T-A formulation was used for the evaluation of AC losses in CORC® cables made of striated superconducting tapes in an external applied field, with a null transport current. In this paper, the T-A formulation is adopted to evaluate the AC losses of stacked striated HTS tapes, representative of the straight section of a racetrack coil, with a sinusoidal transport current.

1. Introduction

The second generation of high temperature superconducting (2G-HTS) tapes have a high current density in self and applied field that make such conductors suitable candidates for implementations of superconducting devices such as generators, motors [1], and high field magnets [2],[3]. Their high critical temperature allows the design of devices operating at temperatures higher than 4.2 K, taking advantage of a higher thermal stability of the tapes and more efficient cryocoolers.

An accurate prediction of AC losses is required for the design of superconducting devices. The AC losses will influence the final working temperature of a device and the overall efficiency of the system, in fact removal of a single watt of dissipation at low temperatures requires an expenditure of tens of watt of power at room temperature [4].

The high aspect ratio of 2G-HTS tapes makes them prone to a high level of AC losses when exposed to a varying magnetic field applied perpendicularly to its wide face. This characteristic is relevant not only for situations in which an AC field is applied to the superconductor, but also for situations in which a field steadily ramps up to reach a target value, such as in research or magnetic resonance magnets [5].

In their work, Brandt [6] and Zeldov [7] obtained that the losses per unit length are proportional to the square of the width of the tape. Therefore an easy way to reduce the losses of a superconducting tape is to striate the tape into N filaments, reducing in this way the losses by a factor N. This is true, however, if the applied field fully penetrates the tape, and if the filaments are electrically decoupled [5].
In devices such as motors, or high field magnets, a superconducting tape is simultaneously subjected to changing currents as well as magnetic fields. Analytical equations are often restricted to simplified geometries such as disks, flat tapes, or infinite arrays of tapes, and cannot address complex geometries found in real devices. Therefore the use of numerical methods is necessary to evaluate losses in such complex geometries.

In this work, a finite element method (FEM) based on the \( T-A \) formulation for a single tape modelled as a zero-thickness conductor (sheet model in the following) will be presented and validated against an integral formulation for the same geometry. The main contribution of this work is the extension of the \( T-A \) formulation to a striated tape first, and then to a stack of striated tapes in self-field, representative of the straight section of a racetrack coil. Three different methods that model the normal (i.e. non superconducting) stripes of a striated tape will be presented, and validation against the homogenized \( H \)-formulation will be presented. In all the cases, the modelled tapes are assumed to be infinitely long in the \( z \)-direction; see figure 1 for an example of such a tape.

2. \( T-A \) formulation

The highly nonlinear resistivity of superconducting tapes, and the complexity of the winding geometries require the use of numerical methods to evaluate the current density distribution and the losses of the tapes, and fast and reliable methods are sought after. The \( H \)-formulation can be used to model the actual geometry of the conductor, and often a 2D approach is suitable for obtaining reliable results. However, the high aspect ratio of the superconducting layer requires a very fine mesh and this extends computation time. In the homogenized \( H \)-formulation, the thickness of the SC layer is artificially augmented achieving a shorter computation time without being detrimental to the accuracy of the results [8]. In [9] the \( T-A \) formulation has been shown to have a shorter calculation time than the \( H \)-formulation for the same mesh density along the width of a superconducting tape and for the same calculation error of the AC losses.

The high aspect ratio (\( 10^4 \) to \( 10^5 \) or more) of the SC layer, see figure 1(a), makes it natural to model a tape as a SC sheet, see figure 1(b). When this model is adopted, the current component perpendicular to the tape is neglected, and the current density, \( J \), is tangential to the sheet. This model also neglects the losses due to penetration of magnetic field and current from the flat faces towards the center of the superconducting tape; this is acceptable, however, given that the losses of a superconducting slab in parallel field are proportional to its width [10].

The use of a sheet model has led to different formulations for the problem of calculating the current distribution and the AC losses in superconducting tapes. In [11] a FEM simulation employing a 1D integral approach was used to evaluate the current density distribution and the AC losses in a 2D model of a superconducting tape extending indefinitely in the \( z \)-direction.

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**Figure 1.** Schematic representation of a SC layer, \( w/h \approx 10^4-10^5 \) (a). Sheet model representation of a SC layer (b). A cartesian coordinate system used in the text is added for reference.
The \( T-A \) formulation for a sheet conductor has been successfully implemented in [12] to evaluate the current density distribution and the AC losses of a single turn of a twisted stacked conductors (TSTC) made of multiple unstriated superconducting tapes, exposed to a spatially homogeneous, time varying magnetic field. In the same work, the \( T-A \) formulation was also used to evaluate transport losses of a full racetrack coil consisting of five turns of unstriated tape.

In [9], the \( T-A \) formulation was implemented to obtain the current density distribution and the AC losses of a stack of straight unstriated tapes extending in the \( z \)-direction, representative of a racetrack coil, in the case of an applied transport current and in the case of an applied magnetic field.

In [13], a multi scale and an homogeneous models based on the \( T-A \) formulation were presented and used to model a racetrack coil made of ten stacked pancakes, each one containing 200 turns of unstriated superconducting tape carrying a sinusoidal transport current.

In [14], the current flow and AC losses for a CORC® cable in applied field were calculated using the \( T-A \) formulation. In the same work, a CORC® cable made of striated conductors was modeled and the AC current distribution and losses in applied field were obtained.

In the following, we will introduce the mathematical \( T-A \) formulation, then the \( T-A \) formulation in the sheet approximation for an unstriated and a striated tape, and finally for a stack of striated tapes afterwards.

### 2.1. \( T-A \) mathematical formulation

In the \( T-A \) formulation two state variable are defined and solved for: the current density vector potential, \( \mathbf{T} \), defined as

\[
\mathbf{J} = \nabla \times \mathbf{T},
\]  

(1)

where \( \mathbf{J} \) is the current density, and the magnetic vector potential, \( \mathbf{A} \), defined as

\[
\mathbf{B} = \nabla \times \mathbf{A}.
\]  

(2)

The conducting material involved in the study is described by the constitutive relation

\[
\mathbf{E} = \rho \mathbf{J},
\]  

(3)

where \( \rho \) is the resistivity of the material considered.

The governing equation for the \( \mathbf{T} \) potential in a conducting material is Faraday’s equation

\[
\nabla \times (\rho \nabla \times \mathbf{T}) = -\frac{dB}{dt},
\]  

(4)

while the governing equation of the \( \mathbf{A} \) potential is

\[
\nabla \nabla \mathbf{A} = -\mu_0 \mathbf{J},
\]  

(5)

where \( \mu_0 \) is the magnetic permeability of free space, and it is assumed that in air \( \mathbf{J} = 0 \). The magnetic vector potential \( \mathbf{A} \) is used to obtain the magnetic field \( \mathbf{B} \) which is then incorporated in equation (4) [12].

For a normal material \( \rho \) is chosen to be constant, however, for a superconductor \( \rho \) is described by a highly nonlinear function of \( |\mathbf{J}| \)

\[
\rho = E_C \frac{|\mathbf{J}|^{n-1}}{J_C^n},
\]  

(6)
where $E_C = 1 \ \mu V/cm$, is the critical electric field value, and in this work $n = 20$.

In a superconducting tape, the critical current density $J_C$ is strongly dependent on the applied magnetic field and on its direction with respect to the surface of the tape. The Kim model is used to describe the dependency of $J_C$ on the magnetic field. The equation for the Kim model is given by:

$$
J_C(B) = \frac{J_{C0}}{I + \left(\frac{k^2 B_{||}^2 + B_{\perp}^2}{B_0}\right)^{\alpha}},
$$

where $J_{C0}$ is the critical current in zero field, $B_{||}$ and $B_{\perp}$ are the parallel and perpendicular components of $B$ with respect to the tape surface. Here, $\alpha = 0.5$, $k = 3$ and $B_0 = 0.1$ T, and are typical values obtained from measurement of SC tapes in applied field [15]. Although the sheet approximation of a SC tape neglects the AC losses of a field parallel to the tape, the Kim model introduce a dependency of $J_C$ on the field parallel to the tape [13].

3. Unstriated tape

The situation depicted in figure 1, showing a SC tape extending indefinitely in the $z$-direction and lying on the $xz$-plane, with the $y$-direction perpendicular to the wide face of the tape, is considered first. This geometry is invariant in the $z$-direction, and the current density $J$ is directed in the $z$-direction only. In this case, the $J = \nabla \times T$ relation on the conductor domain reduces to

$$
J_z = \frac{dT_y}{dx},
$$

where $T_y$ is the component of $T$ perpendicular to the wide face of the tape, and Faraday’s law becomes

$$
\frac{d}{dx}\left(\rho \frac{dT_y}{dx}\right) = \frac{dB_y}{dt},
$$

where $B_y$ is the component of the magnetic field perpendicular to the tape [9]. In the following the index $y$ is dropped from $T_y$ to simplify the notation.

A boundary condition relating the current density in the conductor to the magnetic field intensity is imposed according to the equation

$$
(H_{2z} - H_{1z}) = J_z,
$$

where $H_{1z}$ and $H_{2z}$ are the $x$–components of the magnetic field intensity $H$ in the air region just above and below the tape, and $J_z$ is the $z$-component of the current density $J$.

Since $T$ is defined up to an additive constant, its value at a point can be set arbitrarily, and in this work the value of $T$ on the left edge of the tape is set to zero, i.e. $T_1 = 0$, see figure 1. Therefore, the value of $T$ on the right-hand side of the tape is the applied current $I_{ap}$ flowing in the tape, i.e. $T_2 = I_{ap}$; this property is used to impose a transport current in the tape, see figure 1.

In this work, the commercial package COMSOL® has been used to obtain the magnetic field $B$, the current density distribution $J_z$, and the losses in the sheet. The characteristics of the tape and the value of some parameters used in COMSOL are resumed in Table 1.

The spatial and temporal evolution of the $T$ potential, and the current density $J_z$ for the unstriated tape geometry are shown in figure 2. At the coordinate $x = -2$ mm, i.e. at the left edge of the tape, the value of $T$ is zero during the entire simulated period (0.02 s), as imposed. At the coordinate $x = 2$ mm,
i.e. at the right edge of the tape, the value of $T$ follows a sinusoidal shape, as imposed by the transport current $I_{ap} = 120 \sin(2\pi f t)$ A, where $f = 50$ Hz.

The current density is obtained by taking the spatial derivative of $T$, i.e. $J_x = dT/dx$, and is shown in figure 2(b) for the first period (0.02 s). As expected, the current density distribution over the width of the tape changes from the edges towards the center of the tape as the transport current increases from its null value at time 0.

The results obtained with the $T$-$A$ formulation were validated using an integral model devised for a sheet conductor [16]. The spatial and temporal evolution of the current density $J_x$ for the integral model is shown in figure 2(c).

A direct comparison of the instantaneous power losses is shown in figure 2(d), and a very good agreement between the two formulations is found, with a maximum absolute difference between the two curves of 1.2 mW/m (1.0% relative difference).

Table 1. Values of parameters used during the simulations.

| Parameter                                | Value          |
|------------------------------------------|----------------|
| Tape width                               | 4 mm           |
| Tape critical current                    | 120 A          |
| Tape critical current density $J_{C0}$   | 30 kA/m        |
| Striation width                          | 50 $\mu$m      |
| Gap between stacked tapes                | 200 $\mu$m     |
| Number of time steps per period          | 64             |
| Mesh Density density on Conductor-conductor | 20 mm$^{-1}$ |
| Absolute tolerance                       | 1e-6           |

4. Single striated tape

A simulation of striated tapes using the $T$-$A$ formulation in applied field is given in [14], where a CORC® cable is assembled with striated SC tapes and AC losses in applied field are evaluated. In that particular case, given the absence of a transport current, the current potential $T$ is assigned the same value on the left and right edges of each superconducting stripe to impose a null net current flow.

Here, three different methods (namely Resistive, Constant Potential, and Isolated Stripes) to model the normal stripes while imposing a transport current on a striated conductor in the $T$-$A$ formulation framework are presented. The geometry of a striated tape can be defined as an alternating sequence of superconducting and normal stripes, or as a sequence of superconducting strips intercalated by air regions, see figure 3.

4.1. Resistive method

For the first method, the normal stripe is assigned a very high surface resistivity value, $\rho_s = 1 \Omega$ in this example, to prevent a significant current flow in this region, see figure 3. Given the continuity of the domain over which $T$ is solved, only the values on the left edge ($T_1 = 0$) and on the right edge ($T_4 = I_{ap}$) have to be imposed, while the values of $T_2$ and $T_3$ are not assigned in the solution node.

4.2. Constant Potential method

For the second method, the potential $T$ is assigned a spatially uniform, time varying, value on the normal stripe, see figure 3; this condition will force a zero current density on this region, since $J = \frac{dT}{dx} = 0$. The value of $T$ in the normal region will be determined during the solving of the problem, and will ensure the continuity of the potential across the entire domain. The total transport current is then imposed, as before, by setting $T_1 = 0$ and $T_4 = I_{ap}$.

In both cases above, the $T$ potential is solved in the superconducting and regions of constant $\rho$. 
4.3. Isolated Stripes method

For the third method, the superconducting regions are isolated, and no normal region is present. This is obtained by solving Faraday’s equation on the superconducting stripes only, while the geometric lines connecting the superconducting stripes are maintained to provide the three formulations with the same mesh. However, $T$ values on consecutives edges of adjacent stripes are set to the same value determined during the solution of the problem, in this example $T_2 = T_3$, see figure 3. As before, $T_1 = 0$ and $T_4 = I_{ap}$.

![Figure 2](image1.png)

**Figure 2.** Spatial distribution and time evolution of the current density potential $T$ for an unstriated tape (a); spatial distribution and time evolution of the current density $J_z$ obtained with the $T$-$A$ formulation (b); spatial distribution and time evolution of the current density $J_z$ obtained with an integral formulation (c); comparison of the power losses obtained with the $T$-$A$ formulation and the integral formulation (d).
For the three methods mentioned above, the losses of a striated 4 mm wide tape, with four equally spaced normal regions 50 μm wide, are presented. A sinusoidal current with an amplitude equal to the critical current of the striated tape, i.e. \(I_{ap}=118.5 \sin(2\pi ft)\) A, where \(f=50\) Hz, is applied to the conductor. In figure 4 the spatial and temporal evolution of the \(T\) potential and of the current density \(J\) for the first period are shown.

In figure 4 (a), (c), and (d) the spatial and temporal distribution of the \(T\) potential is presented for the three formulations. For the Resistive and Constant Potential method (figure 4 (a) and (c)), a stripe centered at coordinate \(x=0\) and 50 μm wide can be identified. This is a region of negligible spatial derivative \((dT/dx=0, \text{figure 4(a)})\) or null spatial derivative \((dT/dx=0, \text{figure 4(c)})\), and therefore of negligible or null current density respectively (figure 4 (b) and (d)), corresponding to the normal stripe at the center of the superconducting tape.

For the Isolated Stripes method (figure 4 (e)), there are two surfaces separated by a gap centered at coordinate \(x=0\) and 50 μm wide, corresponding to the gap between the two superconducting stripes. Such a gap is also visible in figure 4 (f), separating the two SC regions with a current flow.

In figure 5 a direct comparison of the instantaneous power losses during the first cycle is shown, and a very good agreement between the three formulations is found, with a maximum absolute difference between the three curves of 31 μW/m (5.3% relative difference).

5. Stack of Striated Tapes
Finally, more complex geometries, obtained by increasing the number of layered tapes and the number of stripes have been used in simulations using the three methods described above. In the following, the case of five stacked conductors each one having five superconducting stripes is reported. This model is representative of the straight side of a racetrack coil used in electrical machines.

In figure 6 the geometry for such a case is presented. The value of the potential \(T\) at the edges of a SC region is indicated with a matrix-like notation \(T_{ij}\), where \(i\) represent the position of the tape in the stack, and \(j\) is the boundary node, see figure 6 for an example. In the following \(i=1,\ldots,5\), and \(j=1,\ldots,10\).

Each tape of the stack is carrying a transport current \(I_{ap}\), therefore for the three methods considered, the value \(T_{ij}=0\) is imposed on the left edge of the tapes, while on the right edges the value \(T_{i10}=I_{ap}\) is imposed. The three methods can now be implemented in this geometry according to the value imposed of \(T\) on the nodes between a SC and normal regions in a similar fashion as they have been applied for a SC with a single normal striation only.

The coupling between the filaments via the magnetic field is obtained by imposing the boundary condition (10), relating the current density to the magnetic field intensity, to all the tapes in the stack; similar boundary conditions were also applied in [14] when dealing with a conductor made of multiple tapes.

5.1. Results, validation, and discussion
For the three methods mentioned above, the losses of a striated 4 mm wide tape, with four equally spaced normal regions 50 μm wide, are presented. A sinusoidal current with an amplitude equal to
Figure 4. Spatial and temporal distribution of the $T$ potential and current density $J_z$ for the three methods for a single striated tape. Resistive method (a) and (b), Constant Potential method (c) and (d), and Isolated Stripes method (e) and (f).
70% of the critical current of the striated tape, i.e. \( I_{ap} = 79.8 \sin(2\pi f t) \) A, where \( f = 50 \) Hz, is applied to the conductor.

In figure 7, the \( T \) potential and the current distribution for the top layer of the stack for the resistive formulation only are shown. In figure 7(a) the surface representing the spatial and temporal evolution of the current density potential \( T \) is presented, and four thin stripes can be identified. These stripes correspond to zones of low spatial derivative \( (dT/dx \approx 0) \), and therefore of low current density proper of the normal stripes in the conductor. Figure 7(b) shows the spatial and temporal evolution of the current density. Four zones of negligible current density can be clearly identified, and correspond to the normal regions of the superconducting tape.

Figure 5. Evolution of instantaneous losses for the three methods: Resistive (*), Constant Potential (o), and Isolated Stripes (+).

Figure 6. Geometry of a stack of five striated tapes. The vertical gap between the tapes is 200 \( \mu \)m, see Table 1.

In figure 7(c) the losses for the first period (0.02 s) for the three methods are shown. While the losses for the Resistive and Constant Potential methods have a maximum absolute difference of 2.5 mW/m (1.5% relative difference), the losses evaluated with the Isolated Stripes method are lower.
than the others by a maximum absolute value of about 0.15 W/m (9.0% relative difference). This discrepancy was not present when a single tape was considered and does not decrease when a finer mesh or a higher accuracy are used when solving this particular formulation with COMSOL®.

These results were validated against the $H$-formulation by comparing the losses of a stack of 5 striated tapes, whose geometry was obtained by expanding by 20 $\mu$m in the $y$-direction the sheet model of figure 6 to obtain a 2D representation of a superconducting tape. The domain corresponding to the superconducting tapes was meshed with a structured mesh having in the $x$-direction the same number and distribution of elements as in the sheet geometry, and 2 elements in the $y$-direction. The air domain was meshed using a triangular mesh with the same parameter used in the sheet models. The use of an augmented thicknesses of 10 and 30 $\mu$m for the tape, 2, 4, and 6 mesh elements in the $y$-direction, or a denser mesh in the $x$-direction did not produce significant changes in the results.

![Figure 7](image)

**Figure 7.** $T$-distribution and $J_z$-distribution evaluated with the Resistive method for the conductor on top of the stack of figure 6; (a), and (b). Losses of the stack during the first period (0.02 s, 50 Hz) (c). Losses of the stack evaluated for the second period of a sinusoidal transport current at different frequencies and amplitudes. The transport current is indicated as a percentage of the critical current of the striated tape (d).
In the $H$-formulation, the domains corresponding to a superconducting region were assigned a resistivity and a field dependency adapting equations (6) and (7) to the new 2D geometry, however keeping the same values for parameters $n$, $k$, $\alpha$, and $B_0$, while the normal zones were assigned a high resistivity value to hinder the current flow. The current applied to each tap is $I_{ac} = 79.8 \sin(2\pi f) \ A$, where $f = 50 \text{ Hz}$; this is a situation similar to the one for the Resistive methods described above. The losses for the $H$-formulation for the first period are also shown in figure 7(c), and have a maximum discrepancy with the losses obtained with the Resistive method of 0.13 W/m (8% relative difference).

In figure 7(d) the losses of the stack, evaluated for the second period of the sinusoidal current to reduce the effect of the initial current transient, are shown for several frequencies and amplitudes of a sinusoidal transport current. The losses are weakly dependent on the frequency, as it is expected with superconductors whose resistivity has a typical $n=20$ value of the exponent in equation (6).

In table 2, the losses obtained with the Resistive method are compared to the losses obtained with the Constant Potential and the Isolated Stripes methods. The maximum difference between the loss values of the Isolated Stripes and Resistive methods are an order of magnitude higher than the values between the Constant Potential and Resistive methods, and increases with the current amplitude of the transport current. The difference increases with the maximum amplitude of the transport current, however no clear trend with respect to the frequency of the applied current is found.

**Table 2. Maximum and relative difference between losses obtained with the Resistive method, and the losses obtained with the Constant Potential and Isolated Stripes methods.**

| Current amplitude [A] | Constant Potential method | Isolate Stripes method |
|-----------------------|---------------------------|------------------------|
|                       | maximum difference [μJ/cycle-m] | relative difference | maximum difference [μJ/cycle-m] | relative difference |
| 0.5$I_c$             | 1.8 (10Hz)                | 49e-5                  | 18 (10Hz)                  | 5e-3                  |
| 0.7$I_c$             | 5.0 (100Hz)               | 40e-5                  | 0.7e3 (10Hz)               | 44e-3                 |
| 0.9$I_c$             | 27(50Hz)                  | 26e-5                  | 1.5e3 (100 Hz)             | 21e-3                 |

When the losses obtained with the $H$-formulation are compared to the losses obtained with the Resistive method, a maximum difference of 0.21 mJ/cycle-m (6.7% relative difference) is obtained at a transport current of 50% $I_c$, a maximum difference of 0.73 mJ/cycle-m (5.6% relative difference) is obtained at a transport current of 70% $I_c$, and a maximum difference of 52 mJ/cycle-m (12% relative difference) is obtained at a transport current of 90% $I_c$. The difference between the losses increases with the maximum amplitude of the transport current, however no clear trend is found with respect to the frequency of the applied current.

6. Conclusions
In this work, a $T$-$A$ formulation adapted to the case of striated superconducting tapes with transport current has been presented. The tape has been modelled as a zero thickness layer (sheet approximation), and three different methods to model normal stripes of striated tapes have been presented.

Agreement between the results obtained with the three methods has been found for simple geometries, however minor discrepancies in the losses have been found when more complex geometries are considered. When applied to a stack of five striated tape, the three methods presented in this paper predict losses that are within 5% of each other for frequencies of 10, 30, 50, 70, and 100 Hz and sinusoidal currents with a maximum amplitude of 0.5, 0.7 and 0.9 $I_c$.

A maximum difference of 52 mJ/cycle-m (12% relative difference) was observed when comparing the losses of the stack of five tapes obtained with the Resistive method and the $H$-formulation.
Acknowledgments
This research is supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organisation for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs. Project number: 15362

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