Loss characteristics of HTS coated conductors in field windings of electric aircraft propulsion motors

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Received 11 February 2020, revised 10 March 2020
Accepted for publication 16 April 2020
Published 7 May 2020

Abstract
High-temperature superconducting (HTS) coated conductors (CCs) are widely regarded as a promising candidate to enable very high power density motors. These machines operate at high rotational speeds, with some designs going up to 12 000 rpm. HTS CCs are applied to the field windings of these motors to increase the magnetic loading and hence the power density. Even though the superconducting field windings operate with a DC current, due to the magnetic field environment, losses are present. This paper examines the dynamic and total loss characteristics of YBCO-coated conductors in the frequency range relevant to high-speed motors for electric aircraft propulsion. A multi-layer model was created using the $H$-formulation and the losses for each layer were highlighted. For the first time, it was shown that the DC transport current region in the HTS layer shrinks as the frequency of the applied field increases due to the increased magnetisation current around the edges of the CC, which reduces the dynamic loss per cycle as the frequency increases. To fully understand the loss distribution in the HTS CC, the total loss in the conductor was investigated. For an applied magnetic field of 100 mT and 800 Hz, more than 30% of the total loss occurs in the copper layer due to the decreased penetration depth of the magnetic field and the skin effect. Results show that to accurately model and understand the losses in superconducting field windings, a multi-layer model should be used, since a significant proportion of loss shifts towards the copper stabilizers. Over all, it was shown that both the dynamic loss as well as magnetisation loss play a crucial role in the estimation of the loss in superconducting field windings.

Keywords: dynamic loss, magnetisation loss, HTS rotating machines, frequency, power density

(Some figures may appear in colour only in the online journal)

1. Introduction
HTS coated conductors are widely being researched in power applications. Especially for superconducting rotating machines, HTS CCs have become a promising candidate as opposed to conventional conductors or permanent magnet technology to significantly increase the power densities [1–4]. Superconducting motors in particular are considered vital to enable all-electric propulsion systems. These motors are high-speed rotational machines, with some designs considering rotational speeds of up to 12 000 rpm. The resulting frequency is directly linked to the rotational speed and the number of pole pairs, hence high RPM machines lead to high frequencies. A summary of some prominent superconducting motor designs for aircraft propulsion are highlighted in table 1.

In [11] the overall frequency range for aircraft propulsion motors is considered to be between 225 Hz and 750 Hz.
HTS CCs are most commonly applied to the field windings of rotating machines since they exhibit virtually no loss while carrying a DC current. However, due to the electromagnetic environment, losses are present [12, 13]. These losses can be summarised as follows. Firstly, the tape exhibits dynamic loss due to the occurrence of dynamic resistance, which is caused by a net flow of flux across the DC current-carrying region [14]. Secondly, the magnetic field induces eddy currents in the outer edges of the tape, which lead to magnetisation loss occurring.

The electromagnetic environment in rotating machines is highly dependent upon the machine design itself such as, the number of poles, magneto-motive force, iron or air-cored topologies and winding configurations [11, 15–17].

Most research so far has focused on lower frequencies (i.e. power frequency range), using thin film approximations or homogenized models to calculate the losses [18–20]. In [21] it was shown that for frequencies above approximately 100 Hz, homogenized models consistently underestimate AC magnetisation loss since they only consider the loss in the HTS layer. In this paper, a 2D multi-layer model, based on the \( \mathbf{H} \)-formulation, is used to quantify the total loss, i.e. dynamic and magnetisation loss, for superconducting tapes up to 800 Hz. The loss in each layer, i.e. copper, silver, HTS and substrate will be calculated. Two methods are used to calculate the dynamic loss. The first method is based on the dynamic region, which is dependent on the load factor to calculate the loss [18]. The second method uses the average electric field over the superconducting tape cross-section to determine the dynamic loss [19]. Both methods have been compared with each other and with experimental results for a frequency of 112.5 Hz.

### 2. Numerical model

To model the superconductor behaviour, the \( \mathbf{E} \cdot \mathbf{J} \) power law is used for the HTS layer [22, 23]

\[
E = E_0 \left( \frac{J}{J_c(\mathbf{B})} \right)^n, \tag{1}
\]

where \( E_0 \) is the critical electric field, defined as \( 10^{-4} \, \text{V m}^{-1} \), \( n \) is the power index and \( J_c(\mathbf{B}) \) is the field dependence of the critical current density, which follows equation (2). Since perpendicular fields cause the majority of the loss [24] and only perpendicular fields are applied in this paper, the parallel field component and anisotropic field dependency can be ignored.

\[
J_c(\mathbf{B}) = \frac{J_{c0}}{1 + \frac{B_0}{B^c}}, \tag{2}
\]

where \( J_{c0} \) is the critical current density in self-field, \( B_0 \) is the perpendicular component of the self-field and the applied magnetic field with respect to the surface of the HTS tape and \( B^c \) is the characteristic field of the superconductor.

To evaluate the losses in the model, the commonly used \( \mathbf{H} \)-formulation [21, 25, 26] is used, which comprises of the following equations, Faraday’s law combined with constitutive law (3) and Ampere’s law (5)

\[
\nabla \times \mathbf{E} = -\mu_0 \partial \mathbf{H} \frac{\partial}{\partial t}, \tag{3}
\]

with

\[
\mathbf{H} = \mathbf{H}_s + \mathbf{H}_{\text{ext}}, \tag{4}
\]

where \( \mathbf{H}_s \) is the self-magnetic field of the transport current and \( \mathbf{H}_{\text{ext}} \) is the external AC field. A Dirichlet boundary condition is applied to the surrounding boundary of the tape to apply a magnetic field of the desired magnitude, frequency and angle.

\[
\mathbf{J} = \nabla \times \mathbf{H}. \tag{5}
\]

YBCO-coated conductors consist of 5 layers, hence the current for each layer can be defined as

\[
I_n = \int_{S_n} \mathbf{J} \, d\mathbf{S} = I_n(t), \tag{6}
\]

where \( n \) ranges from 1 to 5, \( S_n \) is defined as the cross-sectional area of the \( n \)-th layer of the coated conductor and \( i(t) \) is a ramp function to ramp up the DC transport current to the required load ratio. A point wise constraint for the current is applied to the tape, which forces the applied current to flow within the tape geometry.

The tape parameters used in the model are shown in table 2. All the simulations were performed in COMSOL, with the simulations running for two cycles and taking the resultant loss over the last cycle only, to avoid transients caused by the ramping of the transport current.

| Parameter Variable | Value |
|--------------------|-------|
| Critical current (77 K) | \( J_{c0} \) 2.63 \times 10^{10} \, \text{A m}^{-2} |
| \( n \)-Value | 22.5 |
| Magnetic field constant | \( B_0 \) 0.135 T |
| Tape width | 2a 4 mm |
| YBCO layer thickness | \( h_{\text{YBCO}} \) 1 \, \mu \text{m} |
| Total copper thickness | \( h_{\text{Cu}} \) 40 \, \mu \text{m} |
| Silver thickness | \( h_{\text{Ag}} \) 2 \, \mu \text{m} |
| Substrate thickness | \( h_{\text{Subs}} \) 50 \, \mu \text{m} |
| Copper resistivity (77 K) | \( \rho_{\text{Cu}} \) 1.97 \times 10^{-9} \, \text{Ωm} |
| Silver resistivity (77 K) | \( \rho_{\text{Ag}} \) 2.7 \times 10^{-9} \, \text{Ωm} |
| Substrate resistivity (77 K) | \( \rho_{\text{Subs}} \) 1.25 \times 10^{-6} \, \text{Ωm} |

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Table 1. HTS motor designs.

| Ref | Power rating | RPM | Poles | Field frequency |
|-----|--------------|-----|-------|-----------------|
| [5] | 150 kW       | 2700 | 8     | 720 Hz          |
| [6] | 450 kW       | 3000 | 6     | 600 Hz          |
| [7] | 1 MW         | 12000 | 4       | 1600 Hz         |
| [8] | 5 MW         | 5000 | 2     | 333 Hz          |
| [9] | 2 MW         | 3000 | 2     | 200 Hz          |
| [10] | 200 kW       | 4000 | 6     | 800 Hz          |

Table 2. SuperPower YBCO-coated conductor.
2.1. Dynamic loss calculation methods

In this paper, two different methods are used to calculate the dynamic loss. The first method considers the dynamic region to quantify the loss. For a coated conductor carrying a DC transport current $I_{DC}$ under an AC magnetic field $B$, the transport current occupies the superconducting layer with width $2ia$ in the center, leaving the rest of the width $(1-i)2a$ free on both sides, where $a$ is defined has half the width of the HTS tape and $i$ is the load factor. This region is defined as the dynamic region, the concept is illustrated in figure 2. A more detailed discussion on the dynamic region and the current density distribution in the superconducting layer can be found in [18].

Hence, the average dynamic loss in the dynamic region can be calculated as

$$Q_{dyn} = \frac{1}{T} \int_0^T E \cdot J dS_{dyn}dt,$$

(7)

where $T$ is the period of the applied magnetic field and $S_{dyn}$ is the dynamic region for the YBCO layer as defined in figure 1.

The second method calculates the dynamic loss within YBCO coated conductors by using the average electric field as stated in [20]. The average electric field across the cross-section of the HTS tape can be defined as

$$E_{ave}(t) = \frac{\int S E(t) dS}{S},$$

(8)

where $S$ is the total cross-sectional area of the tape, hence the instantaneous loss can be calculated with

$$P_{dyn} = E_{ave} \cdot I_{HTS},$$

(9)

where $I_t$ is the DC transport current for the HTS layer. The average dynamic loss over one cycle can hence be given as

$$Q_{dyn} = \frac{I_t}{T} \int_0^T E_{ave}(t) dt.$$

(10)

The two methods are used together to calculate the dynamic loss and are compared to experimental results.

2.2. Total loss calculation method

To calculate the total loss for each layer, i.e. dynamic loss and magnetisation loss, equation (11) is used.

$$Q_{total} - n = \frac{1}{T} \int_0^T E \cdot J dS_n dt,$$

(11)

where $T$ is the period of the applied magnetic field, $S_n$ is defined as the cross-sectional area of the $n^{th}$ layer of the coated conductor, with $n$ ranging from 1 to 5.

The total loss in the conductor can hence be written as

$$Q_{total} = \sum_{n=1}^{5} Q_{total-n}.$$

(12)

3. Loss results

3.1. Experimental validation

In this section the dynamic loss modelling results will be highlighted and the two methods for calculating the dynamic loss are validated with experiments. Details on the experimental setup can be found in [14]. Further dynamic loss results for a frequency of 26.62 Hz can be found in [17].

The investigated frequency is 112.5 Hz and the applied magnetic field ranges from 0 mT to 100 mT in 10 mT steps. The investigated load factors (LF) are 0.3, 0.5, 0.7 and 0.9. From figure 3 it can be seen that the two methods are in good agreement.
agreement with each other and the experimental results. As expected the loss is in positive correlation with the applied field as well as with the load factor. There is no loss when the applied field is below the threshold field. For a load factor up to 0.7 and an applied field up to 100 mT the dynamic loss remains in linear correlation with applied field. Only for a load factor of 0.9 and applied fields beyond 60 mT does the loss enter the non-linear region. The rapid increase in loss in the non-linear region occurs due to the field dependence of the critical current, which leads to the critical current $I_c(B)$ dropping below the transport current $I_{DC}$ for short periods of time each cycle [17, 18].

### 3.2. Dynamic loss

While the two calculation methods were in good agreement for a frequency of 112.5 Hz, a difference in calculated dynamic loss starts to occur for higher frequencies. This is highlighted in figure 4, which shows the calculated dynamic loss for a frequency range of 112.5 Hz to 800 Hz, for a load factor of 0.5 and an applied AC field of 50 mT.

For a low frequency the two methods agree well with each other, but as the frequency increases, the dynamic loss results calculated from either method start to deviate. For a load factor of 0.3, the calculated loss from either method stays in relatively good agreement. The difference in the calculated results from the two methods can be explained through investigating the current density and magnetic field distributions in the tape.

Figure 5 highlights the current density and magnetic field profiles for a frequency of 112.5 Hz, 400 Hz and 800 Hz, at a load factor of 50% and an external AC field of 50 mT. For a frequency of approximately 100 Hz and below, the dynamic region can be clearly defined as a function of the load factor. However, as the frequency increases, a higher magnetisation current is induced around the edges of the tape, which pushes the transport current further into the centre reducing the transport current area, and hence the size of the dynamic region. Due to the reduced area, the transport current density in the dynamic region increases. For 112.5 Hz, the peak current density in the transport current region is approximately $2.5 \times 10^{10} \text{Am}^{-2}$, for 800 Hz the peak current density increases to $3 \times 10^{10} \text{Am}^{-2}$. However, over all the area under the curve decreases as the frequency increases. Since for a load factor of 0.3 the transport current already only occupies a small area of the tape, the increased magnetisation current has little effect on the dynamic region and hence, the calculated loss for either method stays in relatively good agreement.

From the results it can be seen that the dynamic loss ($W\text{m}^{-1}$) increases with frequency, however, as the frequency increases the dynamic loss per cycle ($J \text{cycle}^{-1} \text{m}^{-1}$) decreases. This is partly due to the reduced transport current region, but another phenomenon takes place. As the frequency increases, the penetration depth of the magnetic field decreases and the magnetic field becomes weaker the further it travels into the HTS tape according to the Beer–Lambert law. This results in a lower net flow of flux across the DC current carrying region, reducing the dynamic loss per cycle.

Figure 3. Total dynamic loss results with experiments for load factors of 0.3, 0.5, 0.7 and 0.9 with an AC applied field of 0–100 mT in 10 mT steps.

Since the penetration depth of the magnetic field decreases, this poses the question of how the current density distribution in the copper stabilizers, which is located above the HTS
Figure 4. Dynamic loss over a frequency range of 112.5–800 Hz for a load factor of 0.3, 0.5, 0.7 and 0.9 and an applied field of 50 mT. The dash–dot line uses the dynamic region method and the simple line uses the average electric field to calculate the dynamic loss.

Figure 5. Current density and magnetic field profiles for the HTS layer for a load factor of 0.5 and an applied field of 50 mT and frequencies of 112.5 Hz, 400 Hz and 800 Hz.

Figure 6. Current density profiles in the copper layer for no current, 0.3 load factor and 0.9 load factor with an applied field of 50 mT and a frequency of (a) 112.5 Hz and (b) 800 Hz.

layer as highlighted in figure 1, changes with frequency. Figure 6 shows the current density distribution within the copper stabilizers for load factors of 0%, 30% and 90% for an applied field of 50 mT with a frequency of 112.5 Hz and 800 Hz.

For the cases where solely an AC field is applied, the current density distribution is symmetrical. It increases by a factor of 10 from 112.5 Hz to 800 Hz. When the HTS tape is also carrying a DC current, the current distribution in the copper is shifted upwards into the positive direction, indicating that a portion of the DC current is now flowing in the copper layers. This phenomenon can be explained through figure 4. The increased current density in the transport current region leads to a lower conductivity of the HTS layer due to its dependence on the critical current and transport current densities. The reduced conductivity causes a small proportion of the transport current to flow in the copper layer, since the HTS and copper layers form a parallel electric circuit. A higher load factor leads to a further shift of the copper current distribution and further increases the current density in the copper.

Since the current density distribution in the copper and HTS layer significantly change with frequency and load factor, it becomes essential to consider the total loss in the HTS tape to accurately study and understand the loss characteristics of field windings in very high RPM machines.

3.3. Total loss

This section will discuss the total loss in the HTS tape in regards to dynamic loss and magnetisation loss as well as the loss in the various layers for the investigated frequency range.
3.3.1. Dynamic loss to total loss ratio. In this section the ratio of the dynamic loss to the total loss is compared. The total loss is defined as the magnetisation loss as well as the dynamic loss. To compare the effect of the DC transport current on the total loss, the loss in a HTS-coated conductor carrying a DC transport current is also compared to a HTS tape, which is only subject to an applied magnetic field (i.e. 0% LF), hence exhibiting solely magnetisation loss. It was shown in [21] that the \( H \)-formulation based numerical model can reliably be used to determine the magnetisation loss over a wide frequency range. Figure 7 shows the total loss, the dynamic loss, the difference between the two losses and the magnetisation loss of a tape subject to solely an AC field as a reference.

It can be seen that over all, the total loss for an HTS tape carrying a DC current with an AC applied field is the summation of the magnetisation loss and the dynamic loss. This holds true for a load factor up to 0.7 and a frequency up to approximately 400 Hz. As the frequency increases beyond 400 Hz, the magnetisation loss for the case with a DC transport current becomes greater than the magnetisation loss for solely an AC applied field. This can be explained through the current density profiles in the copper, which were highlighted in figure 6. As the frequency increases, more current is induced in the copper stabilizer, this phenomenon is further reinforced by the transport current, due to the reduced conductivity of the HTS layer. The higher the load factor, the higher the current in the copper, hence additional loss is generated in the copper layer as compared to the 0% load factor magnetisation case. For a load factor of 0.9, almost the whole width of the HTS layer is occupied by the transport current, hence the total loss is dominated by the dynamic loss.

After a frequency of approximately 500 Hz, the magnetisation loss starts to become greater than the dynamic loss due to the reduced penetration depth of the applied field and the reduced dynamic region. Over all, it was shown that for low load factors, the magnetisation loss dominates the contribution towards the total loss. At a load factor of 0.7, which is a common load factor for field windings to ensure safe operation, the dynamic loss and magnetisation loss are comparable up to approximately 300–400 Hz, as the frequency increases further, the magnetisation loss becomes dominant.

While for fully superconducting machines most studies only consider the AC loss in the stator, results show that the induced loss in the rotor field windings can become significant as well depending on the frequency and magnetic field environment within the machine.

Since the loss distribution in each layer is highly dependent on the applied frequency, the next section highlights the contribution to the total loss by each layer under the investigated frequency and magnetic field amplitude ranges.

3.3.2. Loss per layer. In this section the total loss for each layer will be highlighted and its dependence on frequency and applied magnetic field will be investigated. Figure 8 shows the loss ratio, which is the loss in each layer of the tape divided by the total loss in the tape, for the HTS, copper, silver, and substrate layers as the frequency increases from 112.5 Hz to 800 Hz.

It can be seen that virtually no loss occurs in the silver and substrate layers over the investigated frequency range.

Figure 7. Loss components of an HTS tape subject to an AC field of 50 mT for a frequency range of 112.5–800 Hz for load factors of 0.3, 0.5, 0.7 and 0.9.
For a frequency of approximately 100 Hz and below, the vast majority of the loss occurs in the HTS layer. As the frequency increases, the contribution to the overall loss by the copper layer increases significantly. At 800 Hz, approximately 30% of the total loss occurs in the copper layer. From the figure it can also be seen that the loss ratio is dependent on the load factor, a higher load factor leads to more loss occurring in the copper layer, which agrees well with the results highlighted in figure 6.

4. Conclusion

In this paper the loss characteristics for HTS tapes carrying a DC current under an AC applied magnetic field were investigated in the frequency range relevant to high speed rotating machines. Both the dynamic loss and total loss were studied. It was shown for frequencies below 100 Hz, that the DC transport current region in the HTS layer can be clearly defined as a function of the load factor. As the frequency increases, the magnetisation current, which is induced around the edges of the tape, pushes the DC transport current region further into the centre of the tape, reducing the dynamic loss region. Results show that the dynamic loss per cycle decreases with frequency, since the penetration depth of magnetic fields decreases with frequency and because of the reduced transport current region. Due to the decreased penetration depth, the current density in the copper stabilizer was investigated. For high magnetic fields and high frequencies, a significant amount of loss is produced in the HTS tape, with a substantial proportion of the total loss occurring in the copper layer. Over all, it was shown that both the dynamic loss as well as magnetisation loss play a crucial role in the estimation of the loss in field windings. In addition, results highlight that to accurately model and understand the loss in HTS field windings of high rotational speed machines, it becomes essential to use multi-layer models. Single-layer or homogenized models could underestimate losses by more than 30%.

Acknowledgment

This work was supported by the Engineering and Physical Sciences Research Council [Grant number: EPSRC EP/N09644/1].

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