A Comparative study of transport current loss in HTS coils for superconducting wireless power transfer

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Abstract. This paper focuses on the transport current loss modelling for HTS coated conductor coils under high-frequency AC current, which is essential when applying superconducting technology in wireless power transfer system (WPT). The pancake coil, spiral coil and solenoid coil designs were proposed, whose study were carried out based on the Finite Element Method in 2D using H-formulation. The transport current loss in each layer for each coil when applying high-frequency AC current were simulated in the FEM platform. The variation of the transport current loss distribution from different layers of the HTS coated conductor according to changing current input was simulated and compared for different operating frequencies. Finally, the frequency and current dependence of the transport current loss in different layers was shown and compared. The simulation demonstrates that the transport current loss in copper layer could be much higher than the transport current loss in the HTS layer at high current and frequency level due to the skin effect. The results also present that the pancake coil design and spiral coil design could be applied to relatively lower frequency WPT application while solenoid coil design can achieve lowest total loss in higher frequency application. These results are essential when designing HTS coils for WPT system.

1. Introduction
High Temperature superconducting (HTS) coated conductor can carry significant current density and create strong magnetic field. Based on this characteristic, it is wildly used in different applications such as superconducting transformers, Superconducting Energy Storage System (SMES) and also Superconducting wireless power transmission (WPT). The working principle for WPT could be described as: when two separate coils are working at the same resonance frequency, they form a resonant system that is magnetic coupling and are able to transfer energy wirelessly [1]. In the WPT system, HTS coils help generate higher quality factor comparing to standard material such as copper coil to deliver a more substantial amount of power and increase power transfer efficiency [2]. Previous research has shown that WPT with HTS coil is more efficient than the WPT system that only contains copper coil [3–6]. One key point to maximise the transmission efficiency of the WPT is to working at the resonant frequency. For most HTS applications, the HTS system is working on either a quite low-frequency current (50 Hz) or even DC current [7] [8]. However, the optimal working resonant frequency for WPT is relatively much higher in kHz or MHz level. HTS coils working under high frequency AC current could generate
high transport current loss, thus reducing the overall power transfer efficiency for WPT. The HTS pancake coil has already been applied to WPT system in the recent research [9]. The spiral coil with copper stabilizer has been studied in the low-frequency range [10]. The solenoid coil has been proposed in [11] as an intermediate coil for WPT system. However, there is no detailed simulation study regarding the frequency dependence of the transport current loss for these coil design in WPT application. For this reason, validated AC transport current loss model for the HTS coil when working under high operating frequencies are required.

In this paper, three different coil structure designs that could be used for WPT system were presented: pancake coil, spiral coil and solenoid coil. Each coil model was applied with a sinusoidal current at different frequency level ranging from 50 Hz to 85 kHz as it is within the commonly used frequencies range for WPT EV charging [5]. The transport current loss for each layer of the HTS coated conductor was carried out in COMSOL Multiphysics in the frame of H formulation.

2. Structure design and simulation method

2.1. Model structure design

The HTS coated conductor used in the simulation model is based on the Surround Copper Stabilizer (SCS) Tape as shown in Figure 1. Two copper stabiliser layers are located at the top and the bottom of the coated conductor. The HTS layer is located in the middle of the tape between the silver layer and the non-magnetic substrate layer. The two-dimensional cross-section view of the model is illustrated in Figure 2 (a). In the cylindrical coordinates, each turn of the coil has a symmetric structure around the z-axis and was winded in r-direction or z-direction according to different shape design. Each coil has eight turns in total and is winded in different coil structures, as shown in Figure 2 (b). The pancake coil model has 2*4 structure with four coils in r-direction and two coils in z-direction. The spiral coil has all 8 turns in r-direction and the solenoid coil has all 8 turns parallel in z direction. For the pancake coil and the spiral coil, the difference between the radius of the outer coil and inner coil is ignored. The parameters of the chosen HTS coated conductor and winding shapes for the model are listed in Table 1. For wireless power transmission, high frequency AC current is applied to the HTS coils, thus transport current loss is generated in all layers. In this model, the transport current loss for each layer was calculated in the cross-section of the symmetric model.

![Figure 1: Surround Copper Stabilizer (SCS) Tape model for HTS coated conductor [12].](image)

2.2. Simulation method

In this paper, the H formulation is implemented in the 2D symmetric model to solve Maxwell equations using software package COMSOL Multiphysics [15]. By solving a set of PDEs, dependent variables could be calculated in each domain based on the governing Maxwell’s equation.
Figure 2: (a) Cross-section view for single turn HTS coated conductor in the symmetric axis. (b) Three coil designs in simulation: Pancake coil, Spiral coil and Solenoid coil.

Table 1: Parameters for HTS coated conductor model [13] [14]

| Parameters                        | Value               |
|-----------------------------------|---------------------|
| Width of HTS coated conductor \( w_{\text{tape}} \) (mm) | 4                   |
| Thickness of one copper layer \( h_c \) (µm)             | 20                  |
| Thickness of the silver layer \( h_{\text{ag}} \) (µm)   | 2                   |
| Thickness of the substrate layer \( h_s \) (µm)          | 50                  |
| Thickness of the HTS layer \( h_{\text{sc}} \) (µm)      | 1                   |
| Coil Inner Radius \( r \) (mm)                        | 62.5                |
| Inter-winding distance in \( r \) direction \( d_r \) (mm) | 0.2                 |
| Inter-winding distance in \( z \) direction \( d_z \) (mm) | 5                   |
| \( n \)-value \( n \)                                 | 38                  |
| Total number of windings \( N \)                         | 8                   |
| Critical current \( I_c \) (A)                          | 99.23               |
| Reference electric field \( E_c \) (V/m)                | \( 1 \times 10^{-4} \) |
| Critical current density \( J_c \) (A/m²)               | \( 2.481 \times 10^{10} \) |

\[
\nabla \times (\rho \nabla \times H) = -\mu \frac{dH}{dt},
\]

\[
\nabla \times H = J,
\]

where \( \mu \) is the permeability, \( \rho \) is the resistivity, \( H \) is the magnetic field strength and \( J \) is the current density.

The resistivity for each layer is illustrated in Table 2. For copper, substrate and silver layer, the resistivity is constant. For the HTS layer, the resistivity is given by the \( \mathbf{E} - J \) power law at
\[ \rho_{\text{HTS}} = \frac{E_c}{J_c} \left( \frac{|J|}{J_c} \right)^{n-1}, \]  
\( n \) is the approximation exponent. Each turn of the three coil designs is applied with equal AC current input as the integral constraint
\[ I_{\text{total}} = \int JdS \]  
where \( S \) is the cross-section area of the HTS coated conductor.

For periodical current input, the average loss is calculated by the integration of the power density over the chosen domain in a certain period
\[ Q = \frac{1}{T} \int_T^T dt \int_S \mathbf{E} \cdot \mathbf{J} dz, \]
where \( T \) is the period of the AC current cycle [16]. This equation gives a loss with units of W/m.

The input current to the model is increasing from 10\% \( I_c \) to 90\% \( I_c \), no external field is applied to the coil. According to Kim’s model, a like equation is used to define the dependency of the critical current density to the magnetic field
\[ J_c B = J_c \left( 1 + \frac{\sqrt{k^2 B_z^2 + B_r^2}}{B_0} \right)^\alpha, \]
where \( B_0 = 0.04265 \)T, \( k = 0.29515 \), \( \alpha = 0.7 \) and \( B_z \) and \( B_r \) are the magnetic field components in \( z \) and \( r \) direction, respectively.

| Layer                  | Resistivity (Ω · m) |
|------------------------|---------------------|
| Copper Layer           | 1.97 \times 10^{-9} |
| Silver Layer           | 2.7 \times 10^{-9}  |
| Substrate Layer        | 1.25 \times 10^{-6} |
| Superconductor Layer   | \( \rho_{\text{HTS}} \) |

3. Simulation results and discussion
In this chapter, the frequency dependence and the current dependence of AC transport current loss for three coil designs has been investigated. The input current for three coil designs vary from 0.1 \( I_c \) to 0.9 \( I_c \). The frequency of the input current varies from 50Hz to 85kHz.

3.1. Frequency dependence of AC transport current loss
Figure 3 (a) (b) (c) presents the AC transport current loss generated in separate layers for three coil designs. Figure 3 (d) illustrates the frequency dependence of total loss in three HTS coil designs. Figure 4 shows the cross section view of the current distribution of the two copper stabilizers in the HTS pancake coils based on the simulation results in COMSOL Multiphysics, with chosen frequency at 100Hz, 10kHz, 50kHz and 85kHz. Only the 4 upper coils are shown here because of the symmetric structure of the Pancake coil.
It is obvious that for three coil designs, the distribution of the loss in each layer varies as input frequency change, and the loss in the copper layers increases to higher than the loss in the HTS layer in high frequency level. For example in the pancake coil simulation results shown in Figure 3 (a), the loss generated in the HTS layer contributes most to the total loss when the input frequency is lower than 40kHz. As the input frequency increase to higher than 40kHz, the transport current loss in the copper layer dominates the total loss. For low frequency bands, the current in the HTS layer dominates the electromagnetic property of each layer in HTS tape, resulting in a majority loss contribution from the HTS layer. At the same time, the loss in the copper layer can be ignored. However, Figure 4 shows that as the frequency increase, the current distribution in the copper layer moves towards the two sides of the layer due to the skin effect, causing an increase of both transport current and resistance in the copper layer.

It should be noted that the loss in the substrate layer and the silver layer are negligible in all frequency level compared with the loss in the HTS layer and the copper layer. For different coil design, the frequency dependency of the loss in the copper layer is slightly different. The frequency level for $Q_{\text{Cu}}$ to exceed $Q_{\text{HTS}}$ is 40kHz, 30kHz and 85kHz for pancake coil, spiral coil...
Figure 4: Current density distribution of the copper layer of HTS pancake coil carrying AC current from 100Hz, 10kHz, 50kHz and 85kHz. The current level is set at 0.5 $I_c$. The results are simulated in COMSOL Multiphysics based on the H-formulation.

and solenoid coil respectively. From Figure 3 (d) we can conclude that the solenoid coil design has the smallest AC transport current loss among all three designs. We can conclude that, the solenoid coil has better loss performance as well as wider frequency band compared to pancake coil and spiral coil.

3.2. Current dependence of AC transport current loss
Figure 5 (a) (b) (c) shows the correlation between the transport current loss for each layer and input current in different coil designs. Figure 5 (d) presents the current dependence of the total transport current loss in three coil designs. It can be observed that, in spiral coil, when current is lower than 0.6 $I_c$, the majority of the loss has been concentrated on the HTS layer. At current level higher than 0.6 $I_c$, the loss in the copper layer is larger than the loss in the HTS layer. This phenomenon also applies to pancake coils with current level around 0.8 $I_c$. However, in solenoid coil, the loss in the HTS layer dominates in all current level. It should be pointed out that, compared to the frequency dependence of the transport current loss in the copper and the HTS layer discussed in section 3.1, the effect from increasing current to the loss in the copper layer is much smaller. With the set frequency level at 20kHz, the solenoid coil shows the lowest total transport current loss among all three designs.

4. Conclusion
This paper has discussed the transport current loss distribution from different layers of three HTS coils designs regarding changing input current and operating frequencies. The transport current loss model has been analysed using a 2D finite element method with H-formulation in
Figure 5: The current dependence of the transport current loss in each layer of HTS coated conductor for (a) pancake coil, (b) Spiral coil, (c) Solenoid coil. (d) Total transport current loss for three coil designs. The input current is vary from 0.1 \( I_c \) to 0.9 \( I_c \), the input frequency is set at 20kHz.

COMSOL Multiphysics. The input current to the HTS coils has been set to increase from 0.1 \( I_c \) to 0.9 \( I_c \), and the operating frequency has been designed to rise from 50 Hz to 85 kHz.

The simulation results show that at the chosen current level, the transport current loss in two copper layer increases dramatically as the frequency increase. At high frequency level, the loss in the copper layer dominates the total loss. This is because of the skin effect in the copper layer, which results in most of the current flow through the limited area at two ends of the copper layer. Compared with the frequency dependence, the input current level shows relative small impact on the loss distribution in each layer. At chosen 20kHz, the copper loss exceeds the HTS loss in a relatively high current level in pancake and spiral coil, while the copper loss level remains similar in the solenoid coil. The loss in Substrate and Silver layer shows a small impact on the total loss in all simulations.

From the simulation results we can conclude that it is important to consider the loss in the copper layer when designing HTS coils for high frequency application such as wireless charging. Among three coil designs, the solenoid coil generates the smallest total loss at all frequency and current level. At frequency lower than 85kHz, the copper loss is still remains at
a low level for solenoid coil, which makes this design suitable for WPT EV charging. Pancake coil and spiral coil are still applicable in WPT application, but the operating current and frequency level needs carefully design. For future study, the HTS coated conductor with no copper stabilizers could be considered in high frequency application to reduce the transport current loss in the copper layer.

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