Loss characteristics of superconducting pancake, solenoid and spiral coils for wireless power transfer

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Received 4 February 2020, revised 1 May 2020
Accepted for publication 14 May 2020
Published 4 June 2020

Abstract
Wireless power transfer (WPT) is an emerging technology with widespread applications, such as wireless charging for electric vehicles (EVs), which has become a major point of interest. Conventionally, it is used for stationary charging, but also dynamic systems emerge. Key drawbacks of standard WPT systems are the limited transfer distance between the copper coils and the transfer efficiency. By employing high-temperature superconductors (HTS) as coil material these limitations can be alleviated. However, HTS coils have highly nonlinear ac loss characteristics, which will be studied. This paper investigates the transport current loss and the magnetisation loss of HTS coils individually and when combined in the high frequency range relevant to WPT for EVs. A multilayer 2D axisymmetric coil model based on $H$-formulation is proposed and validated by experimental results as the HTS film layer is inapplicable at such frequencies. Three of the most commonly employed coil configurations, namely: double pancake, solenoid and circular spiral are examined. While spiral coils experience the highest transport current loss, solenoid coils are subject to the highest magnetisation loss due to the overall distribution of the turns. Furthermore, a transition frequency is defined for each coil when losses in the copper layer exceed the HTS losses. It is much lower for coils due to the interactions between the different turns compared to single HTS tapes. At higher frequencies, the range of magnetic field densities, causing a shift where the highest losses occur, decreases until losses in the copper stabilisers always dominate. In addition, case studies investigating the suitability of HTS-WPT are proposed.

Keywords: AC loss, electric vehicles (EVs), HTS coils, wireless power transfer (WPT)

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

1. Introduction
With the recent attention in electric vehicles (EVs), one key concern holding back the large scale deployment i.e. charging infrastructure, needs to be addressed. While conventionally, EVs are charged via conductive charging stations employing cables, new charging methods find their way into the transportation sector. Wireless power transfer (WPT) is already used in a wide range of other applications such as smart phones [1], home appliances such as TVs [2], sensors and robotics [3, 4] as well as medical devices [5, 6]. Research has shown that WPT systems for EVs in the power range to several tens of kW is possible [7, 8].

In general, WPT for EVs is categorised based on the environment it is applied to. Namely, stationary (SWPT), semi/quasi-dynamic (QWPT) and dynamic charging (DWPT). SWPT systems add the advantages of WPT into the conventional charging domain. QWPT systems are formed by stationary systems installed in a dynamic environment such as roads or parking lots.
as taxi and bus stops or traffic lights to provide opportunistic charging while waiting, accelerating or decelerating. DWPT provides charging to vehicles on the move i.e. on urban roads or highways. DWPT systems create a unique opportunity to overcome range anxiety.

Figure 1 illustrates main components of a WPT system. It consists of two main sub-modules separated by an air gap. The ground assembly (GA), located in the road surface and the vehicle assembly (VA) built into the chassis of the vehicle. GA comprises grid connection, rectifier and high frequency converter, primary compensation network and primary/transmitter coil Tx. On the contrary, the VA includes the secondary/receiving coil Rx and the secondary compensation topology feeding into high frequency rectifier, a filter network and the battery system. Both coils form a resonance circuit with their respective compensation networks, while the receiving coil is linked to the primary coil via a magnetic field. In addition, both modules share information via a communication link. The ground clearance and type of vehicle determines the air gap length between the modules.

Current systems use copper as coil materials, as it provides high conductivity and high availability at low cost. However, new materials emerge such as high temperature superconductors (HTS). Sedwick conducted initial tests with HTS coils in 2010 and demonstrated improved system efficiency [10]. This is mainly due to the higher quality factor Q, compared to copper coils. HTS coils provide virtually zero DC resistance, while also being able to carry large amounts of current resulting in a higher power density compared to copper coils, allowing for a higher magnetic flux density. When subjected to a time varying current or magnetic field, HTS coils still experience AC losses [11].

With the introduction of the first standard addressing WPT for EVs, SAE J2954-2016, the operating frequency of such charging systems is set to be between 81.39 and 90 kHz [12]. AC losses in HTS tapes and coils have been investigated extensively, however, limited only to low frequencies up to several kHz [13–17]. One important aspect for the use of HTS coils in WPT systems is the loss characteristic at high frequencies. For low frequencies, the main loss component is the hysteresis loss within the HTS layer. However, at higher frequencies, eddy current losses, particularly in the copper layers and ferromagnetic losses in the substrate become more pronounced and cannot be neglected.

In this article, a 2D axisymmetric multilayer model for the most commonly used coil configurations in WPT i.e. double pancake, circular spiral and solenoid coils is derived using H-formulation in COMSOL. Separate HTS coil turns are approximated by a multilayer structure including copper stabilisers, silver overlayer, HTS layer and substrate. The multilayer structure allows for considering different loss mechanisms in the layers. Transport current and magnetisation loss in coils at various transport current load factors (LF) \( I / I_{c0} \), external magnetic fields (\( B_{ext} \)) and frequencies are calculated. The load factors (LF) are defined as the ratio of transport current \( I_t \) to self-field critical current \( I_{c0} \) of the tape used. A comparison between the different coil configurations is made. Section 2 presents the 2D axisymmetric multilayer model used to investigate the high frequency AC losses of HTS coils for WPT. In addition, the model is validated with experimental data. The AC loss characteristics are shown and evaluated in section 3. Section 4 proposes case studies to investigate the application of HTS coils in WPT-systems.

2. AC loss in HTS coils

HTS have a fascinating loss characteristic, when operated within their superconducting state i.e. critical temperature, current and magnetic field, as they have virtually zero resistance under DC conditions. However, when supplied with a varying current or subject to changing external magnetic field, losses will occur. Cooling modules cool the coils below the critical temperature enabling operation within superconducting state and to sustain operation while redirecting heat caused by losses. The cooling efficiency is limited by the Carnot cycle and small cryostats can only achieve a small fraction of the Carnot efficiency with a specific power \( k_e \) of around 10 W [18]. Therefore, it requires 10 W extraction power to remove 1 W of heat at 77 K. Hence, it is important to limit the losses generated within the HTS system. Due to the additional cooling components and the limited space, particularly in the VA, research has focussed on using HTS coils in the transmission or primary pad, which also coincides with the biggest improvement to the system if only one coil can be substituted [19, 20].

2.1. H-formulation

To evaluate the losses occurring in the HTS coil when supplied by an AC current or located within a varying external magnetic field, a 2D axisymmetric model has been constructed. A 2D axisymmetric model was chosen as it provides a reasonable approximation for rotationally symmetric coil configurations such as investigated here, while minimising the computational time required for solving a 3D model. In addition, the aspect ratio of the investigated multilayer model is very large, particularly for full scale systems, which makes it difficult to simulate. Furthermore, the applied external magnetic field is centrosymmetric, thus does not have one fixed direction.

The model uses the commonly applied \( H \)-formulation and comprises the following equations [21, 22]: Ampere’s law (1), Faraday’s law combined with constitutive law (2), \( E-J \) power law (3) [23] and Ohm’s law (4).
∇ × \mathbf{H} = \mathbf{J} \tag{1}

∇ × \mathbf{E} = −\mu_0 \mu_r \frac{\partial \mathbf{H}}{\partial t} \tag{2}

\mathbf{E} = \mathbf{E}_0 \left( \frac{\mathbf{J}}{J_c} \right)^n \tag{3}

\mathbf{E} = \rho \mathbf{J} \tag{4}

Where \mathbf{H} is the magnetic field intensity, \mathbf{J} is the current density, \mu_0 is the permeability of free space, \mu_r is the relative permeability, \mathbf{E}_0 is the characteristic electric field, \alpha is the power factor. The simulation was performed in COMSOL and (1)-(4) can be rewritten as general form in (5).

\frac{\partial (\mu_0 \mu_r \mathbf{H})}{\partial t} + \nabla \times (\rho \nabla \times \mathbf{H}) = 0 \tag{5}

To introduce cylindrical coordinates, (5) needs to be modified as shown in (6).

\begin{bmatrix}
-\frac{\partial E_r}{\partial \theta} \\
\frac{1}{r} \frac{\partial (r E_r)}{\partial r}
\end{bmatrix} = −\mu_0 \mu_r \begin{bmatrix}
\frac{\partial H_r}{\partial \theta} \\
\frac{1}{r} \frac{\partial (r H_r)}{\partial r}
\end{bmatrix} \tag{6}

The general model layout can be found in figure 2. Three different coil structures are investigated. A solenoid configuration, i.e. stacking turns along the z-direction, a spiral coil, i.e. stacking turns in r-direction, and finally, a double pancake configuration, commonly used in WPT systems. To apply a time-varying external magnetic field, Dirichlet boundary conditions have been used.

Table 1. HTS tape parameters [24, 25].

| Parameter                                | Value                        |
|------------------------------------------|------------------------------|
| YBCO tape width                         | 4 mm                         |
| YBCO film thickness                     | 2 \mu m                      |
| Copper thickness                        | 20 \mu m                     |
| Silver thickness                        | 2 \mu m                      |
| Substrate thickness                     | 75 \mu m                     |
| Copper resistivity at 77 K              | $1.97 \times 10^{-9}$ Ω m$^{-1}$ |
| Silver resistivity at 77 K              | $2.7 \times 10^{-9}$ Ω m$^{-1}$ |
| Substrate resistivity at 77 K           | $1.25 \times 10^{-6}$ Ω m$^{-1}$ |
| Free space permeability                 | $4\pi \times 10^{-7}$ H m$^{-1}$ |
| Power-law exponent                      | 25                           |
| $k$                                      | 0.67                         |
| $\alpha$                                 | 0.6                          |
| Critical current in self field          | 245 A                        |
| Characteristic E-field                  | $10^{-4}$ V m$^{-1}$         |
| Magnetic field constant                 | 0.2 T                        |
| Coil radius                             | 0.0625 m                     |
| Turn number                             | 8                            |

2.2. AC loss calculation

The model uses real geometric data from Fujikura FYSC SCH04 outlined in table 1. A cross-sectional view of the HTS coated conductor (CC) is depicted in figure 3. The GdBCO superconducting layer thickness is 2 \mu m, copper stabiliser thickness is 20 \mu m (located on top and bottom of the tape), silver layer thickness is 2 \mu m and the non-magnetic substrate (Hastelloy®) thickness is 75 \mu m. Each coil investigated has an inner radius of 0.0625 m and is comprised of 8 turns with an intra-turn spacing of 200 \mu m due to the Kapton tape insulation.

To incorporate the magnetic field dependency on the critical current density $J_c(B)$, an anisotropic Kim-like model shown in equation (7) was adopted [26]. It uses both, the perpendicular and the parallel component of the magnetic field to adjust the critical current density.

$$J_c(B) = \frac{J_{c0}}{\left(1 + \sqrt{\frac{B_{\perp}}{B_{\parallel}}} + \frac{B_{\parallel}}{B_{\perp}} \right)^{\alpha}} \tag{7}$$

A multilayer approach is used as shown in figure 3. Each layer of the HTS tape is included in the model and treated as
an individual domain. The different layers are connected in parallel and carry the transport current \( I_t \), see (8). For a sinusoidal input signal, the AC loss \( Q_n \) within each layer can be calculated by integrating the power density of the layer over the domain \( \Omega \) and the second half of the steady state period \( T \) as described by equation (9) [27]. Finally, the total AC loss of the HTS coil can be calculated from (10). All parameters used for the coil simulation are summarised in table 1.

\[
I_t = I_p \sin(2\omega t) = \int_{\Omega} J(t) \, d\Omega \\
Q_n = \frac{2}{T} \int_{T/2}^{T}\int_{\Omega} E \cdot J \, d\Omega \, dt \\
Q_{total} = \sum_{n=1}^{5} Q_n
\] (9) (10)

A 2D multilayer tape model [28] was built and the comparison to experimental data from [13] is shown in figure 4. It should be pointed out that, the substrate used in figure 4 and [13] is magnetic. The tape model was extended to include geometrical features of a coil and obtained results were compared with experimental measurements and simulations from [29]. The comparison for transport current loss is shown in figure 5 and the results for magnetisation loss are depicted in figure 6. As displayed, the simulated results are in good agreement in the case of single tapes at higher frequencies as well as for coils, subject to AC transport current and time varying external magnetic field. Furthermore, the losses in each of the layers of the HTS tape are shown. As the frequency increases, the losses in the copper layers cannot be ignored.

3. Results and discussion

Based on the validated multilayer model, the transport current loss and magnetisation loss for different HTS coils over a wide frequency range have been calculated and compared.

3.1. AC transport current loss

Initially, the transport current loss for the three coil configurations is investigated. Key loss characteristics involve the hysteresis loss in the HTS layer, which is the main loss
mechanism at lower frequencies, coupling and eddy current losses. The tape under investigation uses Hastelloy\textsuperscript{0}, a non-magnetic substrate and there are no superconducting filaments involved. Hence, ferromagnetic losses and coupling losses are neglected. To evaluate the transport loss, a sinusoidal AC current with different frequencies, between 50 Hz and 85 kHz, is applied to the coil and there is no external magnetic field. The transport current is quantified by LF and ranges from 0.1 to 0.8, equivalent to up to 80% of the critical current of the coil.

Figure 7 shows the total transport current loss of eight-turn coils wound as double pancake, spiral and solenoid, respectively. In general, the loss increases with rising frequency and higher LF. The impact of LF increases with frequency, as more skin is pushed into a smaller conducting area, confined by the skin effect [28]. To achieve the required overall system efficiency of 85% for WPT-systems [12], the losses in the coils must be reduced. The losses generated by the HTS coils are extremely high for LF and frequencies targeted by such systems, particularly taking into account that the operating temperature is 77 K. To minimise the impact of the skin effect, other materials such as MgB\textsubscript{2} are used in superconducting applications, which allows reduced AC losses due to its multifilament structure [30–33]. However, there is no literature on the use of MgB\textsubscript{2} in the frequency range used in WPT, which makes it difficult to gauge feasibility. Disadvantageous are the lower critical temperature and therefore higher cooling penalty. Additionally, non-insulated tapes, different stabilisers (e.g. Ag) and stabiliser free tape are potentially viable to reduce the losses [34].

Comparing the different loss characteristics of the presented coil configurations, it is evident that the spiral coil experiences the highest total transport current loss, closely followed by the double pancake configuration. Resulting from the multilayer nature within the double pancake coil, each tape only faces high magnetic fields on the outer edges of the turn, this is paired with a similar occurrence of high current densities, leading to high transport current losses. However, the current penetrates deeper into the tape with increasing load factor offsetting the benefits of the multilayer structure. On the other hand, within the solenoid structure, magnetic field hotspots are localised in the gaps between each turn and on the outer edges of the first and last turn. Here, the highest magnetic fields occur at the top and bottom of the coil and decreases towards the gaps in the centre of the coil until the fields cancel each other in the centre of the winding (along z-direction). Furthermore, only one side of the turn experiences a high magnetic field, while the magnetic field on the other side gets cancelled by the previous turn. In the spiral configuration, there is no field cancellation, resulting in high magnetic fields on each side of the tape. Nevertheless, there is a slight shielding effect, limiting the magnetic and electric fields in tapes in the middle of the winding.

Each HTS tape comprises several different layers and figure 8 shows the contribution of each of the layers on the total loss with changes in frequency for a LF of 0.5. As shown, the HTS layer itself has the highest contribution towards the losses of the HTS tape, followed by the copper. Losses within the silver and the substrate layer are several magnitudes smaller than other losses. The substrate considered here is non-magnetic and even though it has the highest volume fraction, its limited electric conductivity results in the lowest loss contribution. With increasing frequency, the contribution of the HTS layer decreases and the share of the copper layer increases. This is due to the skin effect pushing the current into the outer layers of the tape i.e. the copper layers [28]. An additional factor that influence the losses is the critical current of the coil. When transitioning from single tapes towards stacks and coils, the interaction between individual turns and tapes cannot be neglected as the self-field lowers the critical current compared to single tapes. A self-consistent model was used to determine the influence of subsequent turns onto the critical current of each individual turn [35]. It uses the voltage drop per unit length as criterion in each tape to determine the new critical current of the coil. Results obtained are displayed in figure 9. As shown, the configuration has great influence on the critical current of a coil. The two extremes considered are the solenoid and spiral configuration. In a solenoid configuration, the critical current is widely stable and only reduces by a small fraction compared to an individual tape. However, in a spiral coil, the effect of subsequent turns is much higher, resulting in a much lower critical current. Additionally, the double pancake configuration, ranks between the two previous structures as it combines features of spiral and solenoid configuration.

To take into account the different critical currents of the coils, the applied transport current, resulting from LF of the HTS tape, was adjusted to fit the actual LF of the coil. Figure 10 shows the adjusted total transport current of the three coil layouts. The overall losses are for double pancake and spiral coils smaller as the applied current is lower. In addition, the
As verified, the main driver for transport current losses at higher frequencies is the skin effect [28]. This phenomenon occurs in all three coil configurations. Therefore, a transition frequency is defined where \( Q_{\text{HTS}} = Q_{\text{Cu}} \). It changes depending on the configuration and applied transport current as illustrated in figure 11. For a single HTS coated conductor, the losses in the HTS are prevalent up to 100 kHz [28]. Generally, due to the interaction between the different tapes within a coil, the transition frequency for coils is much lower. When comparing the different transition frequencies, it is noteworthy that for LF below 0.3 the difference in coil configurations is small. At high LF, the transition frequency for double pancake and spiral coils are similar, while it is much higher for the solenoid coil. A higher transition frequency represents a later shift from the HTS layer towards the copper stabilisers as main contributor of the transport current losses. The higher transition frequency of the solenoid configuration can be explained by the field cancellation, reducing the impact of the magnetic field on \( J_c \) of the HTS layer and the reduced local current density in the conducting area.
When designing the cooling system used for HTS coils, it is of interest where local temperature hot spots occur. Therefore, figures 12–14 depict the share of each turn on the total transport loss for a LF of 0.5 and frequencies between 50 Hz and 85 kHz. L1-L8 denote the turn from left to right or top to bottom for the spiral and solenoid configuration, respectively. While T1-T4 are the top turns and B1-B4 are the bottom turns from left to right in the double pancake coil. As one can see, the double pancake and spiral coils have comparable distributions, while the solenoid coil has vastly different characteristics. At low frequencies e.g. 50 Hz and 1 kHz, the loss distribution amongst the turns is mostly even for pancake and spiral coils. As the frequency increases to 10 kHz and later 85 kHz, innermost turns are subject to the highest losses. This is due to the increased magnetic field in the centre of the coil. The increase is compensated by a reduction in the share of the outer turns, while the second last turn for the pancake and the second and third last turns of the spiral coils experience the lowest loss. Subsequent coil turns are shielded from the magnetic field and the transport current penetration depth is lower, resulting in an overall decrease of the combined electric and magnetic field and therefore loss.

The loss distribution within the solenoid coil is vastly different to the previous two configurations. All turns are subject to the same local magnetic field, while each turn contributes to the field cancellation between the turns. The outermost turns do not experience this cancellation and therefore experience the highest loss. With increasing frequency, this trend weakens, and the loss contribution of the innermost turns increases. As the frequency increases the losses in the copper layer increase and dominate at frequencies above the transition frequency. The solenoid layout is clearly advantageous when considering transport current loss characteristics for WPT systems. Particularly, when considering the magnetic field distribution above the centre of the coil as shown in figure 15, which is an important parameter for a WPT-system and its performance.

3.2. AC magnetisation loss

In this chapter the magnetisation loss is investigated. All external fields are alternating at frequencies up to 85 kHz and perpendicular to the wide tape surface, demonstrating the worst case for a WPT-system. Applied AC magnetic field densities range from 10 mT to 200 mT and there is no additional current applied to the coils.

Figure 16 illustrates the magnetisation loss for the previously introduced coil configurations. In general, the magnetisation loss per unit length increases with stronger external magnetic fields. Lower external magnetic fields are not strong enough to penetrate the HTS layer due to the shielding current produced, repelling the external field. The effect of the magnetic field increases rapidly with frequency. Contrary to the results obtained for the transport current loss, the solenoid configuration experiences the highest loss, while the spiral coil has the lowest losses. This is due to the shielding effect. In a spiral coil, the outermost turns shield...
Figure 15. Magnetic field distribution above the centre of the coil at adjusted LF = 0.5.

Figure 16. Total magnetisation loss of eight-turn coils (double pancake: full line, spiral: dashed line, solenoid: dotted line) at different magnetic field densities and frequencies up to 85 kHz.

Figure 17. Total magnetisation loss contribution of pancake (black), spiral (red), solenoid (blue) at $B_{\text{ext}} = 100$ mT and frequencies up to 85 kHz.

When looking at the contribution of the different layers depicted in figure 17, a similar tendency as for the transport loss is shown. HTS and copper layers largely dominate the magnetisation losses in the HTS coil, while silver and substrate layer have only minor contribution.

The loss in the HTS layer increases with frequency up to 50 kHz and stagnates at higher frequencies. On the other hand, the losses in the copper layers rapidly increase. This is a direct result of the skin effect, causing the current to be pushed into the copper layers as well as to the outer edges of the HTS tape. Similarly, the magnetic field is greatly increased at the outer edges of the tape. Figures 18–20 show the interaction between the HTS layer and the copper stabilisers of the different coils. The overall trend is similar for all three coils, but the curves are shifted towards higher $B_{\text{ext}}$ when comparing solenoid, double pancake and spiral. The shift is caused by the shielding effect in the spiral and double pancake coil whereas it is absent in the solenoid coil. There exists a maximum and minimum for the loss share in the HTS layer and the copper stabilisers, respectively. At a frequency of 50 Hz, almost all losses occur in the HTS layer for double pancake and solenoid coils, independently of the external magnetic flux density. However, as the frequency increases, the penetration depth of the magnetic field decreases and the magnetic field becomes weaker the farther it penetrates into the HTS tape according to the Beer–Lambert Law. Yet, the magnetic field penetrates the copper layer, generating the majority of the losses. As soon as a stronger magnetic field penetrates the HTS layer, most of the losses will occur there, until the skin effect pushes the magnetic field and current into the copper layer and the outer edges of the turn. Before reaching the maximum/minimum, frequency and $B_{\text{ext}}$ have the same relationship and higher frequencies result in higher external magnetic fields to transition from higher copper to HTS losses.

subsequent turns, resulting in higher than per-turn-average losses for the first and last turn, while other turns experience lower than average losses. A similar mechanism causes reduced loss in the double pancake coil. However, in a less pronounced fashion. In contrast, all turns in a solenoid layout are subject to the same field, without any shielding. It is therefore possible to use the shielding effect and change the layout of the windings to shield as many turns as possible, hence reducing the overall influence of external magnetic fields. Additionally, stabiliser-free tapes can be used to eliminate one of the loss sources.
After the maximum is reached there is an inverse relationship between frequency and $B_{\text{ext}}$ dictating the transition from HTS layer losses towards copper layer losses. Higher frequencies push the cross over point towards lower magnetic field densities. At a frequency of 85 kHz, neither spiral nor solenoid configuration, go through the described trend as the copper losses are always higher than the losses in the HTS layer.

The cross over point i.e. transition frequency when $Q_{\text{Cu}} = Q_{\text{HTS}}$ is depicted in figure 21. As shown, all three coil configurations exhibit similar trends in their transition frequency. It is characterised by a sharp parabolic trend, however, the maximum is shifted depending on the coil structure. The solenoid coil reaches its maximum transition frequency of circa 83 kHz at a magnetic field of approximately 7.5 mT, just shortly after reaching the threshold field. As each turn is subjected to the same external magnetic field, the solenoid configuration is extremely prone to magnetic fields above its threshold field, which affects the critical current density and has great impact on the loss distributions. Similarly, to the maximum transition frequency of the solenoid coil, the spiral coil reaches its peak at a magnetic field of 45 mT. Its transition frequency is attained at greater external fields, as inner turns are shielded. The double pancake coil has the highest transition frequency with almost 90 kHz, which it reaches at a magnetic field of 20 mT. It achieves the highest transition frequency as it combines shielding and cancelling effects.

When looking at the magnetisation loss contribution of each turn for an external magnetic field of 100 mT, as shown in figures 22–24, the results are generally not skewed towards the innermost turns of the coil. While the turns in the middle of the coils are still shielded in the case of spiral and double pancake coil, the difference between inner and outermost turns is smaller. Nevertheless, the difference still increases with frequency providing further evidence of the skin effect. The opposite is true for the solenoid structure. While at frequencies below 10 kHz, the loss contribution amongst the different turns is stable, the discrepancy between the innermost and outermost turns is smaller. Nevertheless, the difference still increases with frequency providing further evidence of the skin effect. The opposite is true for the solenoid structure. While at frequencies below 10 kHz, the loss contribution amongst the different turns is stable, the discrepancy between the innermost and outermost turns increases with frequency and the outermost turns contribute less to the total loss than the innermost turns. This is due to a channelling effect enhancing the external magnetic field in the gaps between turns and the local magnetic field in the turns themselves. While the innermost turns are subject to this effect on either side, the outermost turns only face it on one side, reducing the overall loss in the turn compared to the
Figure 21. Transition frequency for different coil configurations over a range of external magnetic field densities.

Figure 22. Turn loss contribution in an eight-turn double pancake coil for different frequencies with an external magnetic field of 100 mT.

Figure 23. Turn loss contribution in an eight-turn spiral coil for different frequencies with an external magnetic field of 100 mT.

Figure 24. Turn loss contribution in an eight-turn solenoid coil for different frequencies with an external magnetic field of 100 mT.

3.3. Combined loss

This chapter discusses the effect of applying a time varying transport current while also being subject to an external AC magnetic field, posing as real scenarios encountered by HTS WPT-systems. Transport current and external magnetic field have the same frequency and there is no phase shift between the two. Transition frequencies for different load factors between LF = 0.1–0.8 of the coil geometries investigated are displayed in figures 25–27. As shown, the initial parabolic trend is flattened with increasing load factor irrespective of the coil structure. For smaller external fields, the transport current loss in the HTS layer dominates the transition frequency. This results in an increase in transition frequency for low external magnetic field densities.

For load factors smaller than LF = 0.4, an overall peak in transition frequency exists, similar to the LF = 0 case. However, the transition frequency is much lower. As the load factor increases to ultimately LF = 0.8, the transition frequencies widely remain constant, particularly for external fields up to circa 50 mT, as the loss share for the HTS and copper layers stay constant. The transport current dictates the transition frequencies for small and medium external magnetic field densities. While at large external fields, the transition frequency is reduced further due to the skin effect and the increased magnetic flux that penetrates the HTS layer and therefore lowering the critical current density.
Figure 25. Transition frequency for eight-turn double pancake coil over a range of external magnetic field densities and various load factors.

Figure 26. Transition frequency for eight-turn spiral coil over a range of external magnetic field densities and various load factors.

Figure 27. Transition frequency for eight-turn solenoid coil over a range of external magnetic field densities and various load factors.

4. Case study

Recent literature on superconducting wireless power transfer systems focuses on low input power and operating frequencies in the range of several kHz to tens of kHz [20, 19, 36, 37], 370 kHz [38–40] or 13.56 MHz [41, 42]. To estimate the impact of the AC losses and cooling power requirements of HTS WPT systems, two case studies have been investigated. Namely, a low-power scenario with a LF of 0.1 and a high-power case with a LF of 0.8. Both cases look at three different transmission distances i.e. 0.01 m, 0.05 m and 0.125 m, which are equivalent to an air gap to coil diameter ratio of 8%, 40% and 100%. The WPT systems use the double pancake coil introduced in chapter 2, with the same dimensions and an operating frequency of 85 kHz. The LF in the transmitting coil (Tx) determines the primary current $I_p$ which is used in combination with an FEA model to calculate the magnetic field present at the Tx, while the induced current $I_s$ in the receiving coil (Rx) is calculated and used as a base for the magnetic field in the Rx. With the aid of the current in the respective coils and their magnetic field, the AC losses are calculated and converted into an equivalent resistance $R_{eqTx/Rx}$. Input power $P_{in}$ and output power $P_{out}$ are calculated using (11) and (12) and the cooling power required for each coil is calculated using (13) where $k_c$ is the specific power introduced in chapter 2, $\omega$ is the angular frequency, $M$ is the mutual inductance between Tx and Rx and $R_L$ is the optimal load resistance.

$$P_{in} = |I_p|^2 \left( R_{eqTx} + \frac{(\omega M)^2 * (R_{eqTx} + R_L)}{(R_{eqRx} + R_L)^2} \right)$$  \hspace{1cm} (11)

$$P_{out} = |I_p|^2 \left( R_{eqTx} + \frac{(\omega M)^2 * R_L}{(R_{eqRx} + R_L)^2} \right)$$  \hspace{1cm} (12)

$$P_{coolTx/Rx} = k_c |I_p|^2 R_{eqTx/Rx}$$  \hspace{1cm} (13)

Table 2 summarises the system performance parameters for the different case studies investigated. As shown, the transfer efficiency is high for the low power scenario due to the low air gap length, but also due to the low equivalent resistance of the HTS coils used. On the contrary, for the high-power scenario, the transmission efficiency decreases rapidly with distance as the equivalent resistance of the HTS coils has a great impact.
Naturally, the transfer efficiency decreases with increasing air gap length. Nevertheless, if the cooling power is taken into account and an overall system efficiency is derived, the performance of the HTS system is greatly affected. In general, the system efficiency decreases rapidly due to the low operating temperature and the cooling penalty, defined by $k_c$. According to SAE J2954 [12], the WPT-efficiency should be at least 85%, which is difficult to achieve as demonstrated, particularly for high-power, high frequency applications such as EV charging.

5. Conclusions

For the first time, an investigation of the transport current loss, magnetisation loss and combined loss of HTS coils in the frequency relevant to WPT (up to 85 kHz) for EVs has been carried out. The study used a 2D axisymmetric multilayer coil model, resolving the overall loss distribution in the turns and showed that, the loss in the copper layer surpasses the loss generated by the HTS layer at higher frequencies. Three different coil configurations were used, including spiral, solenoid and double pancake. Key findings include:

1) Investigation of transport current losses in various HTS coil structures in the frequency range from 50 Hz to 85 kHz with the aid of a multilayer model taking skin effect into account. In general, the frequency has a great impact on the transport current loss and its effect increases at higher load factors. Solenoid coils have the lowest transport current loss, while spiral coils have the highest.

2) The magnetisation loss increases with increasing magnetic field densities and frequency. Contrary to the results obtained from the transport current loss calculations, the spiral configuration has the lower magnetisation loss, while the solenoid layout has the highest. Depending on the frequency, the main contributor towards the magnetisation loss shifts between the copper and the HTS layer. At higher frequencies, the penetration depth of the external magnetic field changes and the field cannot penetrate the HTS layer, subjecting the copper stabilisers to high losses. For medium external magnetic fields, the HTS layer generates the main share of losses before it shifts back into the copper stabilisers depending on a high enough magnetic field. The range of magnetic field densities, causing the highest loss to occur in the HTS layer, decreases with increasing frequency until the losses in the copper stabilisers are always higher than the HTS layer losses.

3) A transition frequency was introduced, at which copper losses are equal to the losses in the HTS layer. Due to the interaction between the different turns, the transition frequency for coils is much smaller than for single tapes. Below a LF of 0.3 there was no significant difference between the coil structures. At higher LF, the solenoid coil had a much higher transition frequency.

The transition frequency for the magnetisation loss is vastly different than in the case of transport current loss. It is characterised by a sharp maximum, which is shifted depending on the coil arrangement. The spiral coil reaches its transition frequency at the highest external field densities, while the double pancake coil has the marginally highest frequency.

When combining transport current and external magnetic field, the transition frequency is mainly influenced by the transport current and its associated loss. For low external fields, the transition frequency increases when compared with cases where only the external field is applied. On the contrary, at high external fields, the transition frequency is reduced further due to skin effect and the reduced critical current density.

4) Examination of loss contribution of individual turns within the coil. The transport current loss contribution of single turns within the coils showed that losses are heavily generated in the innermost turns. While the trend increases with frequency for the spiral and double pancake configuration, it decreases for the solenoid coil.

The magnetisation loss contribution of individual turns was not skewed towards the innermost turns, particularly for the solenoid structure. Within the solenoid coil, the outermost turns have the lowest contribution as the magnetic field is enhanced in the gaps between subsequent turns.

5) Demonstration of HTS WPT-systems from the perspective of HTS coated conductor properties. It has been shown that coil layout greatly influences the loss properties and the transition frequency. Whereas spiral coils are the most common type used in WPT-systems, double pancake coils offer a good trade-off, due to the multilayer nature of the coil. Previous research has outlined HTS-WPT for EVs as a promising technology, however, the skin effect at high frequencies has widely been neglected. Therefore, such conclusions do not show the full picture. For the first time, the AC losses of the most common coil structures used for WPT are quantified based on the multilayer structure of HTS CCs. Results show that the application of HTS CCs in high power WPT is not practical, because the cooling power required is too large, compromising the overall WPT-system efficiency.

| Cases          | d = 0.01 m | d = 0.05 m | d = 0.125 m |
|----------------|------------|------------|-------------|
| **Input power [W]** |            |            |             |
| LF 0.1 with $B_{ext} = 20$ mT | 2259       | 718        | 174         |
| LF 0.8 with $B_{ext} = 150$ mT | 144737     | 46876      | 13463       |
| **Output power [W]** |            |            |             |
| LF 0.1 with $B_{ext} = 20$ mT | 2137       | 602        | 81.67       |
| LF 0.8 with $B_{ext} = 150$ mT | 129730     | 33553      | 3495        |
| **Transfer efficiency [%]** |            |            |             |
| LF 0.1 with $B_{ext} = 20$ mT | 94.60      | 83.92      | 46.97       |
| LF 0.8 with $B_{ext} = 150$ mT | 89.63      | 71.11      | 25.96       |
| **Cooling power Tx [W]** |            |            |             |
| LF 0.1 with $B_{ext} = 20$ mT | 605.54     | 605.54     | 605.54      |
| LF 0.8 with $B_{ext} = 150$ mT | 76396      | 76396      | 76396       |
| **Cooling power Rx [W]** |            |            |             |
| LF 0.1 with $B_{ext} = 20$ mT | 572.82     | 508.19     | 357.71      |
| LF 0.8 with $B_{ext} = 150$ mT | 68475      | 54327      | 19833       |
| **System efficiency [%]** |            |            |             |
| LF 0.1 with $B_{ext} = 20$ mT | 62.17      | 32.89      | 7.68        |
| LF 0.8 with $B_{ext} = 150$ mT | 44.80      | 62.17      | 3.19        |
MgB₂ or stabiliser-free HTS CCs could be a good alternative to reduce AC losses as shown in the literature. However, there is no literature on the use of MgB₂ in the frequency range investigated here, which makes it difficult to judge the applicability. Nevertheless, high frequency HTS-WPT is still appropriate for low power applications.

Given the findings, this paper can be used as useful guidance for high frequency applications that employ axisymmetric coils. It is important to use a multilayer structure of the HTS CCs in the frequency range investigated here as the influence of the copper stabilisers cannot be neglected for high frequency regimes. Furthermore, it is imperative for effective cooling to avoid thermal hotspots caused by losses.

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