Loss analysis of superconducting wireless charging for electric vehicles

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Abstract. Wireless power transfer (WPT) is an emerging technology with widespread applications. It can be used for charging in multiple 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 an interesting ac loss characteristic which will be studied. This study investigates the transport current and magnetisation loss of HTS coils in the frequency relevant to WPT for EVs. In addition, a comparison between the full anisotropic dependency of the critical current and only considering perpendicular field components is conducted. A homogenous 2D axisymmetric coil model is used to examine three of the most employed coil configurations and their loss characteristics depending on turn numbers.

1. Introduction

The transport sector is one of the biggest contributors towards global climate change and produces large amounts of CO₂. In 2017, 60% of the global oil consumption occurred within the transport sector [1]. One approach to tackle the need for a sustainable solution is a widespread adoption of electric vehicles (EVs). However, large-scale deployment of EVs is held back and only 0.5% of global light duty vehicles (LDV) were EVs with additional two million newly sold EVs in 2018 [2], [3]. Main drawbacks of EVs are the on-board battery technology and its respective charging infrastructure. These result in longer charging times, fewer charging stations and the lower driving capacity, termed ‘range anxiety’ [4]. To address those drawbacks, more charging stations and faster charging cycles need to be employed. Currently, conventional conductive charging cannot exploit the full potential due to long waiting times and limited numbers of dedicated charging stations. Wireless charging can be advantageous and use for charging of EVs has been proven [5], [6].

In general, WPT for EVs is categorised into stationary (SWPT), semi/quasi-dynamic (QWPT) and dynamic charging (DWPT). Stationary charging is similar to conventional charging but with the advantages of WPT. Semi/quasi-dynamic are formed by stationary systems installed in a dynamic environment such as taxi and bus stops and on traffic lights to provide short term charging while waiting, accelerating or decelerating. Dynamic charging provides charging to vehicles on the move i.e. on urban roads or highways. DWPT creates a unique opportunity to overcome range anxiety.
Main components of a WPT system are shown in Figure 1. It consists of two main sub-modules, the ground assembly (GA), located underneath the road surface and the vehicle assembly (VA) built into the underbody 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 air gap length between modules depends on vehicle and its ground clearance as well as road conditions.

Conventionally, copper is used in WPT systems as it provides high conductivity, high availability and low cost. However, new materials emerge such as high temperature superconductors (HTS). Initial tests with HTS coils substituted for copper coils were conducted in [8]. It was demonstrated that HTS coils improve system efficiency. This is mainly due to the higher quality factor Q, compared to copper coils as derived in chapter 2. HTS coils provide virtually zero DC resistance. Furthermore, HTS can carry a large current resulting in high power density compared to copper coils.

With the introduction of standard SAE J2954-2016, the operating frequency of WPT systems is set to be between 81.39 and 90kHz with a nominal operating frequency of 85kHz [9]. AC losses in HTS tapes and coils have been researched extensively, however, limited only to low frequencies up to several kHz [10], [11], [12]. One important aspect for the use of HTS coils in WPT systems is the AC loss characteristics at high frequencies and how they are simulated.

In this article, a 2D axisymmetric model for pancake coils is derived using H-formulation in COMSOL. Separate HTS coil turns are approximated by a homogenous turn. The AC transport current and magnetisation losses in coils with different turn numbers and frequencies are calculated. A comparison of the anisotropic field dependency is made using just the perpendicular field and combining perpendicular and parallel field.
2. Circuit analysis of a WPT system

Figure 2 shows a circuit diagram of an SS compensation. $L_1$ and $L_2$ are the primary and secondary coils, respectively. The resistances of each coil are denoted $R_1$ and $R_2$, while $C_1$ and $C_2$ are the primary and secondary compensation capacitors, respectively. $R_L$ is the load resistance. The primary and load current, $I_1$ and $I_L$, as well as power transfer efficiency are derived. Using Kirchhoff’s Law, by defining the loop-currents for the circuit can be solved using equation (1).

$$\begin{bmatrix} V_{ac} \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j(L_1 * \omega - \frac{1}{C_1*\omega}) & -j\omega M \\ -j\omega M & R_2 + R_L + j(L_2 * \omega - \frac{1}{C_2*\omega}) \end{bmatrix} * \begin{bmatrix} I_1 \\ I_L \end{bmatrix}$$ (1)

Equivalent total impedance of the circuit with SS-compensation is the sum of primary circuit impedance and secondary reflected impedance derived in equation (2). The secondary reflected impedance is the ratio of reflected voltage and primary current.

$$Z_{tot} = Z_1 + Z_r = \left( R_1 + j\left(L_1 * \omega - \frac{1}{C_1*\omega}\right) + \frac{(\omega*M)^2}{R_2+R_L+j(L_2*\omega-\frac{1}{C_2*\omega})} \right)$$ (2)

The current drawn from the power supply can be evaluated with equation (3).

$$I_1 = \frac{V_{ac}}{Z_{tot}} = \frac{V_{ac} + j(R_2+R_L+j(L_2*\omega - \frac{1}{C_2*\omega}))}{\left(R_1+j(L_1*\omega-\frac{1}{C_1*\omega})\right)\left(R_2+R_L+j(L_2*\omega-\frac{1}{C_2*\omega})\right)+(\omega*M)^2}$$ (3)

According to equations (1) and (3), the current that supplies the load is:

$$I_L = \frac{-V_{ac} * j\omega M}{\left(R_1+j(L_1*\omega-\frac{1}{C_1*\omega})\right)\left(R_2+R_L+j(L_2*\omega-\frac{1}{C_2*\omega})\right)+(\omega*M)^2}.$$

Input power, output power and efficiency of the power transfer are calculated using equations (5)-(7). It is assumed that power is supplied with unity power factor into the primary compensation network.

$$P_{in} = V_{ac} * I_1 = \frac{V_{ac}^2 \left(R_2+R_L+j(L_2*\omega-\frac{1}{C_2*\omega})\right)}{\left(R_1+j(L_1*\omega-\frac{1}{C_1*\omega})\right)\left(R_2+R_L+j(L_2*\omega-\frac{1}{C_2*\omega})\right)+(\omega*M)^2}$$ (5)
\[ P_{\text{out}} = R_L \cdot |I_L|^2 = R_L \cdot \left| \frac{-V_{\text{ac}} \cdot j\omega M}{R_1 + j\left( L_1 \cdot \omega - \frac{1}{j\omega L_1}\right)} + \frac{R_2 + R_{L1} + j\left( L_2 \cdot \omega - \frac{1}{j\omega L_2}\right)}{R_2 + j\left( L_2 \cdot \omega - \frac{1}{j\omega L_2}\right)} \right|^2 \]  

(6)

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{R_L}{\left( R_2 + R_{L1} + j\left( L_2 \cdot \omega - \frac{1}{j\omega L_2}\right)\right)^2} \]  

(7)

At zero-phase-angle frequency, the reactive power flow is zero. To form a resonance circuit with maximum power transfer capability, this frequency must be equal to the resonance frequency \( \omega_0 \), where the reactive parts in equations (3)-(7) cancel out. Assuming identical coils in the primary and secondary circuit, the resonance frequency can be calculated using equation (8).

\[ \omega_0 = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}} = \sqrt{\frac{1}{LC}} \]  

(8)

The efficiency at resonance frequency is expressed by equation (9) with the quality factors Q for each coil in equation (10). It can be seen that a high quality factor is advantageous for system efficiency.

\[ \eta(\omega_0) = \frac{R_L}{(R_2 + R_{L1})^2} = \frac{R_L k^2 Q_2}{(R_2 + R_{L1})^2 + (R_2 + R_{L1}) k^2 Q_2} \]  

(9)

\[ Q_{1/2} = \frac{2\pi f \cdot \text{Energy stored}}{\text{Energy dissipated}} = \frac{\omega_0^* L_{1/2}}{R_{1/2}} \]  

(10)

3. AC loss in HTS coils

HTS have an interesting loss characteristic, when operated within 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. Conventionally, HTS systems require cooling modules to cool the coils below the critical temperature enabling operation within superconducting state. Additionally, these modules redirect the heat caused by the losses. The low operating temperature has an additional effect on the system, as the maximum possible efficiency that can be achieved when removing heat is dictated by the Carnot cycle. At the boiling temperature of liquid nitrogen (77K), the Carnot efficiency is \( \eta_{\text{carnot}} = \frac{T_C}{T_H - T_C} \) e.g. at 300K, the Carnot efficiency is 34.5%. Cryostats can only achieve a small fraction of the Carnot efficiency, with smaller cryostats performing worse than large systems [13]. Assuming an efficiency of 30% of the Carnot efficiency, the total efficiency is 10.4%, indicating a specific power of around 10W. Therefore, it requires 10W extraction power to remove 1W of heat at 77K. Hence it is important to limit the losses generated within the HTS system. For WPT systems, space requirements must be taken into consideration. Available space is limited particularly in the VA, which makes it difficult to accommodate an additional component such as the cooling system. Consequently, 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 [14], [15].
3.1. $H$ formulation

To evaluate the losses occurring in the HTS coil when supplied by an AC current or located within an external magnetic field a 2D axisymmetric model has been constructed. It uses the commonly applied $H$ formulation and comprises the following equations: Ampere’s Law (equation 11), Faraday’s law combined with constitutive law (equation 12) and E-J power law (equation 14).

$$ \nabla \times \mathbf{H} = \mathbf{J} \quad (11) $$

$$ \nabla \times \mathbf{E} = -\mu_0 \mu_r \frac{\partial \mathbf{H}}{\partial t} \quad (12) $$

$$ E = E_0 \left( \frac{J}{J_c} \right)^n \quad (13) $$

Where $\mathbf{H}$ is the magnetic field intensity, $\mathbf{J}$ is the current density, $\mathbf{E}$ is the electric field, $\mu_0$ is the permeability of free space, $\mu_r$ is the relative permeability, $E_0$ is the characteristic electric field, $J_c$ is the critical current density and $n$ is the power factor. The simulation was performed in COMSOL and equations (11)-(13) can be rewritten as

$$ \left[ -\frac{\partial E_\phi}{\partial z} \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r E_\phi}{\partial r} \right) \right] = -\mu_0 \mu_r \left[ \frac{\partial H_r}{\partial t} \frac{\partial H_z}{\partial t} \right] \quad (14) $$

The general model layout can be found in Figure 3. Dirichlet boundary conditions have been used to apply an external field.

![Figure 3. Coil model layout.](image)

3.2. AC loss calculation

The model uses real geometric data from Fujikura FYSC. The superconducting layer thickness is 2µm, copper stabiliser thickness is 20µm (located on top and bottom of the tape), silver layer thickness is 2µm and the substrate thickness is 75µm.
For coils and stacks of tapes the interaction between different turns and tapes cannot be neglected as it results in lower 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. It uses the voltage drop per unit length as criterion in each tape to determine the new critical current of the coil [16]. Results obtained are displayed in Figure 4. As shown, the configuration has great influence on the critical current of a coil. The two extremes considered are a solenoid and spiral configuration. In a solenoid configuration, i.e. stacking turns along the z-direction, the critical current is widely stable and only reduces by a small fraction compared to an individual tape. However, in a spiral coil, i.e. stacking turns in r-direction, the effect of subsequent turns is much higher, resulting in a much lower critical current. Additionally, a double pancake configuration, commonly used in WPT systems was investigated. Due to its nature of combining features of spiral and solenoid configuration, its critical current diminishes more than for the solenoid, but not as much as it is the case in a spiral configuration.

To incorporate the magnetic field dependency on the critical current density \( J_c(B) \), anisotropic Kim like model shown in equation (15) was adopted [17]. It used both, the perpendicular and the parallel component of the magnetic field to adjust the critical current density. Commonly equation (15) can be simplified for tapes as the effect of the perpendicular magnetic field component onto the critical current density is greater than that of the parallel field, see equation (16). However, for coils, particularly those used in WPT systems, displacement between the coils frequently occurs as EVs traverse over the transmitting pad. Furthermore, so far only multilayer coils are used for WPT systems, causing additional parallel cross-turn effects. Therefore, it suggests that the influence of the parallel field cannot be neglected and should be included.

\[
J_c(B) = \frac{J_{c0}}{\left(1 + \frac{k^2 B_{para}^2 + B_{perp}^2}{B_0^2}\right)^\alpha} \tag{15}
\]

\[
J_c(B) = \frac{J_{c0}}{\left(1 + \frac{B_{perp}}{B_0}\right)} \tag{16}
\]

![Figure 4](image-url)

**Figure 4.** Critical current for different coil configurations and turn numbers.
To increase computational speed, the HTS coil turns are approximated by the homogenisation model presented in [18]. The critical current of the multilayer turn is adjusted by the volume fraction of the superconducting layer $f_{HTS}$ according to $I_{c, Eq}(B) = I_c(B) f_{HTS}$. Finally, for a sinusoidal input signal, the AC loss $Q_{total}$ within the coil can be calculated by equation (17) where $T$ is the period and $\Omega$ is the coil domain. All parameters used for the coil simulation are summarised in Table 1.

$$Q_{total} = \frac{2}{T} \int_{0.5T}^{T} \int_{\Omega} E \cdot Jd\Omega dt$$

(17)

| HTS coil parameters |
|---------------------|
| Tape width          | 4mm |
| Superconducting layer thickness | 2µm |
| Substrate layer thickness | 75µm |
| Copper layer thickness (top and bottom) | 20µm |
| Silver layer thickness | 2µm |
| n-value             | 23  |
| Coil Inner diameter | 0.125m |
| $E_0$               | $10^{-2}$ V/m |
| $B_0$               | 0.2T |
| $k$                 | 0.67 |
| $\alpha$            | 0.6 |

Table 1. Coil simulation parameters.

**Figure 5.** Comparison of simulated and measured [19] AC transport current loss for an HTS tape at frequencies up to 15kHz and a transport current of $I_0 = 45A$.

**Figure 6.** Comparison of simulated and measured AC transport current loss for a 36-turn double pancake coil at 200Hz and different transport currents $I_0$ [20].

Simulation results are compared with experimental measurements and other reference models for single HTS tapes and multilayer coils in Figures 5-6. As shown, the obtained results are in agreement with measured results. In case of an HTS coated conductor with magnetic substrate such as used in [19], the homogenisation model must be adapted to accommodate the substrate and its $\mu_r$. Other layers can still be modelled using the homogenisation approach.
4. Results and discussion

4.1. Transport current loss

Figure 7 depicts the transport current loss of a double pancake coil with different turn numbers at various frequencies. The coil is driven with a load factor of 0.5 at frequencies between 50Hz and 85kHz. As seen, the loss increases with increasing turn number. This is due to the increase in magnetic field, generated by the additional turns, influencing the loss characteristics in a non-linear fashion. The increase is partly offset by the additional coil domain area, limiting the loss per unit length. Furthermore, the loss per cycle decreases with increasing frequency as the current is pushed to the outer regions of the tape and cannot penetrate the tape any further. Results from the analytical solutions of Norris strip and Ellipse are adjusted by the turn number and shown as well. There is good agreement between the analytical model and the 2D axisymmetric model.

For comparison, Figure 8 illustrates the results obtained considering the full anisotropic dependency and the perpendicular field only. For the frequencies, load factors and turn numbers used here, the difference in both approaches is minor. However, it increases with rising turn numbers but is largely independent of frequency. This suggests that the influence of the parallel field component on the transport current loss is insignificant even when (multilayer) coils are considered.

Figure 9 and Figure 10 show the transport current loss of an eight turn double pancake coil and its dependency on frequency and load factor. Evidently, the loss increases with increasing load factor as more current is pushed through the coil, increasing the magnetic and electric fields in and surrounding the coil. As the load factor increases, the effect of frequency becomes more pronounced as a result of the current being pushed towards the tape edges.
Figure 9. Transport current loss for an eight-turn double pancake coil at different frequencies over a wide range of load factors $I_0/I_c$.

A multitude of different coil configurations are used in WPT systems, however, spiral coils are dominant within charging systems for EVs. Figure 11 and Figure 12 demonstrate the influence of the different coil configurations and subsequent turns. The spiral coil configuration generates the highest transport current loss, closely followed by the double pancake arrangement, while the solenoid layout has the lowest. Within the solenoid configuration, magnetic field hotspots are generated in the gaps between the tapes and on the outer edges of the first and last turn. The highest magnetic fields occur on the outer edges of the outermost turns and decrease towards the gaps in the centre until the fields cancel 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.

When using the spiral configuration, there is no field cancellation, resulting in each of the turns experiencing high magnetic fields on each side of the tape. There is a slight shielding effect, preventing the magnetic and electric fields to penetrate tapes in the middle of the winding too much. Additionally, the innermost turn of the coil experiences the strongest magnetic field.

Due to the multilayer nature of the double pancake coil, each tape only faces high magnetic fields on one side, similar to the solenoid layout, reducing its loss. However, the current penetrates deeper into the tape with increasing load factor offsetting the benefits of the multilayer structure. For different turn numbers, the increase in loss is highest for double pancake and spiral arrangements. Solenoid layout is clearly advantageous when considering loss characteristics for WPT systems.
4.2. Magnetisation loss

In this chapter the magnetisation loss is investigated. All external fields are perpendicular to the wide tape surface, unless stated otherwise. Figure 13 illustrates the results obtained by considering the full anisotropic critical current dependency (black) and from using the perpendicular field component only. Similar to the results obtained for the transport current loss, the influence of the parallel field seems to be negligible for different frequencies, turn numbers and magnetic field densities. Furthermore, the magnetisation loss per unit length increases with stronger external magnetic fields and decreases with increasing number of turns.

To fully investigate the effect of the parallel magnetic field component Figure 14 and Figure 15 demonstrate the angular dependency of the magnetisation loss for an eight-turn double pancake coil at different external magnetic field strengths. It can be seen that the results are very similar, particularly...
at higher magnetic field densities above the threshold field, as defined in [21]. At lower magnetic field densities, the results follow comparable trends but slightly differ in magnitude. The losses drop off rapidly with changing angle as it approaches being parallel to the wide tape surface. This drop off is more prevalent at lower magnetic field densities. Also, there is no dependency regarding frequency.

![Figure 14](image1.png) ![Figure 15](image2.png)

**Figure 14.** Angular dependency of magnetisation loss of an eight-turn double pancake coil at different external AC magnetic fields at 50Hz (black) and 85kHz (red) obtained from full anisotropy.

**Figure 15.** Angular dependency of magnetisation loss of an eight-turn double pancake coil at different external AC magnetic fields at 50Hz (black) and 85kHz (red) considering only perpendicular field.

![Figure 16](image3.png) ![Figure 17](image4.png)

**Figure 16.** Magnetisation loss of an eight-turn double pancake coil at different external AC magnetic fields over a wide range of frequencies.

**Figure 17.** Magnetisation loss of an eight-turn double pancake coil at different frequencies with respect to external magnetic field density.

Figure 16 and Figure 17 illustrate the effect of different frequencies and external magnetic field densities on the magnetisation loss of an eight turn double pancake coil. As shown the effect of frequency is small and decreases with increasing magnetic field density. The cut-off point for a noticeable decrease in magnetisation loss with frequency is at a field around the threshold field.

Figure 18 shows the angular dependency of the magnetisation loss for different coil layouts. 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 subsequent turns, resulting in higher than average (per turn) losses for the first and last turn, while other turns experience lower than average losses. In contrast, all turns in a solenoid layout are subject to the same field, without any shielding.
Figure 18. Angular dependency of magnetisation loss for different four-turn coil configurations at 85kHz and 100mT.

5. Conclusion

An investigation of the transport current and magnetisation loss of HTS coils in the frequency relevant to WPT for EVs has been carried out. In addition, a comparison between the full anisotropic dependency of the critical current and only considering perpendicular field components for HTS WPT coils was conducted. The study used a 2D axisymmetric coil model. Furthermore, the tape was approximated by a homogenisation approach. The model was validated with experimental results up to 15kHz. While the results obtained with the model are in good agreement, eddy currents in the copper stabilisers are not considered. Eddy current losses can become prevalent at high frequencies and should be considered. Three different coil configurations were used, including spiral, solenoid and double pancake. The critical current of each coil was evaluated based on the layout and the turn number. Results show that the effect of the parallel field is only minor even in (multilayer) HTS coils. Hence, can be neglected for coils. Transport current losses per unit length increase non-linearly with increasing turn numbers. In general, the frequency only has minor impact on the loss per cycle, however, its effect increases at higher load factors. Solenoid coils have the lowest transport current loss, while spiral coil have the highest. Magnetisation loss increases with increasing magnetic field densities and are generally independent of frequency when the external magnetic field exceeds the threshold field. However, it decreases with increasing turn number, as shielding effects occur, reducing currents penetrating the HTS tape. 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.

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