Coil Design for 100 KHz and 6.78 MHz WPT system :Litz and Solid Wires and Winding Methods

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***Abstract*—Coil design is one of the critical part to get high power transfer efficiency for wireless power transfer (WPT) system. There exists coil figure of merit (FOM), which is used to evaluate coil design in the aspect of WPT system efficiency. WPT coil FOM is function of coil quality factor (Q-factor) and coupling coefficient, k and higher Q and k guarantees higher coil-to-coil efficiency. Coil DC loss, skin effect, proximity effect, and displacement current between turns are key factors to determine Q-factor and its effects changes depending on wire-type, winding method, and target frequency. In this paper, we focus on transmitter coil design to maximize Q-factor in both 100 MHz and 6.78 MHz. Coil Q-factor equations are provided to explain and analyze the physics and measurement was done for the validation of the equation. Finally optimal coil winding methods are proposed to maximize coil Q-factor**

Keywords—WPT coil; coil equation; coil winding; solid wire; stranded wire; litz wire; 6.78 MHz; 100 kHz

I. Introduction

Wireless power transfer (WPT) system market is continuously growing and lots of products are now applying WPT technology. Mobile phone charging is the most popular application, which can be easily found in our surroundings. There are several requirements for that application including charging distance, charging area, transferred power, EM-shielding to reduce radiation, and temperature. However power transfer efficiency is one of the key factors to evaluate WPT system and very important factor.

Typical mobile phone charging WPT system is constructed as shown in Fig. 1. Power amplifier (PA), Tx and Rx coil with series matching capacitor, rectifier, and buck-converter. Each of this block experiences some losses during power transfer and these should be minimized to maximize the power transfer efficiency. Among these blocks, PA, rectifier, and buck is the active devices and there's some given guides for the design with acceptable good efficiency within target operation range. By applying these given guides or purchasing some module-level components, active devices can be determined to have acceptable performance. More important portion is the coil design itself. Even WPT standard provides some reference coil structure [1-2], there's much more kinds of coil design depending on applications and designer decision. Tx- and Rx-coil size, coil separation, coil turn number, coil shapes and all thing can be changed. To increase the coil-to-coil link efficiency, power loss caused by coil resistance should be minimized. However, coil-to-coil efficiency is also the function of mutual inductance between coils because it changes the current flowing through the coil. To simply consider all of this factor, coil figure of merit (FOM) was proposed for 2-coil WPT system as shown in Fig. 1 [3].

$$FOM = k \cdot \sqrt{Q_{Tx} \cdot Q_{Rx}} \quad (1)$$

The above FOM equation is derived from the circuit model with an assumption that equivalent Rx load resistance is much larger than Rx coil resistance and it is true for most cases. As the result, coil-to-coil efficiency becomes maximum when FOM becomes maximum. Mostly k is determined by the geometry of Tx- and Rx- coils and usually simulations are required to get the k value. Focused on a single coil, FOM is function of Q-factor and not direct function of coil resistance. Large turn number or large size coil has higher resistance, but could have larger Q-factor because of increased inductance. Single coil design can be optimized to have the maximum Q-factor.

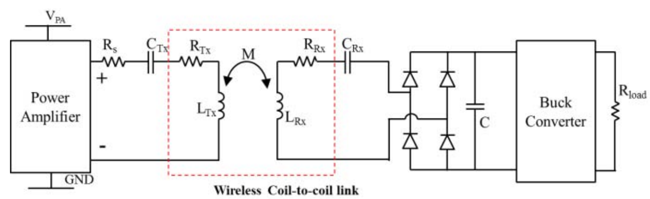


Fig. 1. Typcial wireless power transfer system with series-series matching network. Our paper focuses on the coil-to-coil link

In this paper, Tx-coil winding method is proposed to maximize Q_{Tx} for 100 kHz and 6.78 MHz, which is the standard operating frequency of Qi and Air Fuel Alliance [1-2]. Litz wire and solid wire are considered and compared at each operating frequency. For the optimization of Q_{Tx} at different operating frequency and different wire-type, EM-software like Ansys Maxwell [4] can be used. However it takes lots of time for stranded wire and it is almost impossible to run the simulation for litz wire because of its complexity. Especially resistance simulation is very challenging work at simulation. To prevent simulation to get the resistance, coil resistance model is provided and validated by measurement. Based on the coil resistance model, optimal coil wires and winding methods are provided

II. Tx-Coil Modeling and Validation

Coil resistance modeling starts from the coil DC resistance modeling. At DC, current flows uniformly through the surface of wire and current is uniform for all strands inside litz wire. DC resistance is simply calculated as the function of metal conductivity, total length, and cross-sectional area. For the coil winding shown in Fig. 2, DC resistance can be calculated using the below equation.

$$R_{DC} = \frac{1}{\sigma} N_t \cdot \frac{4}{ID + OD} \tag{2}$$

There are two kinds of physics that determine coil AC resistance: skin effect and proximity effect. As frequency increases, current starts to flow through the boundary of the wire due to skin effect. Also current flow is affected each other by the current from the nearby strands. As the result, current distribution of straight solid wire and litz wire are illustrated in Fig. 3[5]. In the real case, litz wires are made with internal twist, which makes each strands to occupy the whole cross-sectional area of litz wire and current distribution is somewhat different.

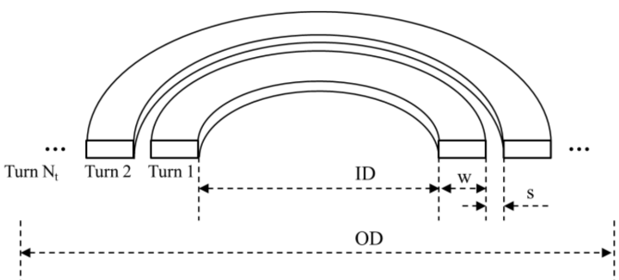


Fig. 2. Target Tx-coil structre with N-turn winding.

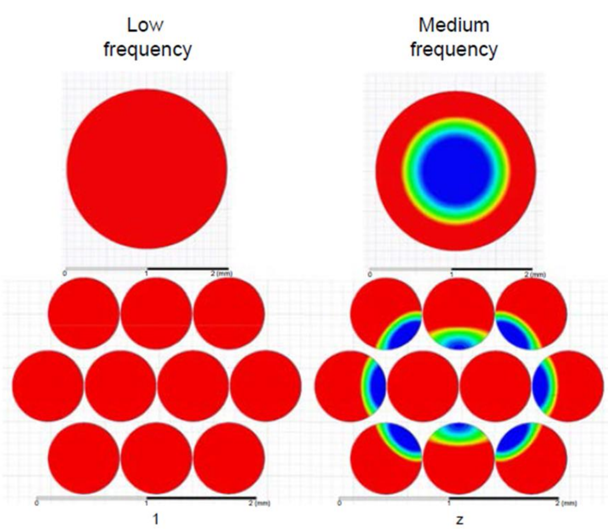


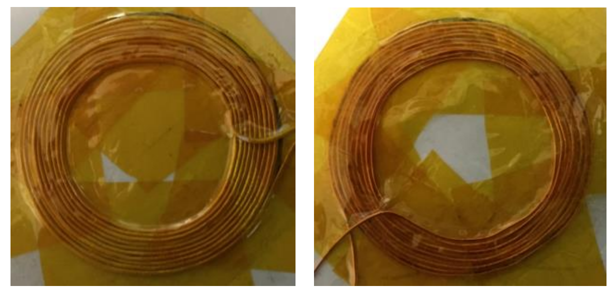
Fig. 3. Eddy current effect in straight single solid wire and in straight single litz wire at low and medium frequencies [5]

For the litz wire, there exists a paper that models coil resistance based on some physics with some fitting to include coils shapes [6]. Based on that reference paper, litz-wire coil resistance can be calculated using the following equations.

$$R_{Tx\_AC} = R_{Tx\_DC} \cdot \left(1 + \frac{f^2}{f_h^2}\right) \tag{2}$$

$$f_h = \frac{2\sqrt{2}}{\pi r_s^2 \mu_0 \sigma \sqrt{N_t N_s \eta \beta}} \tag{3}$$

For the validation of that equations for our WPT Tx-coil design, we made coil using litz wire and solid wire as shown in Fig. 4. For both cases, outer diameter (OD) is 50 mm and direction is coil spacing is 0. For litz wire coil, turn number is 5 while number of strands are 105 and 40 AWG. For solid Tx-coil, 0.69mm thickness wire is used.



(a) (b)

Fig. 4. Tx-coil for measurement. (a) square-shape Tx-coil with litz wire and (b) round-shape Tx-coil with solid wire

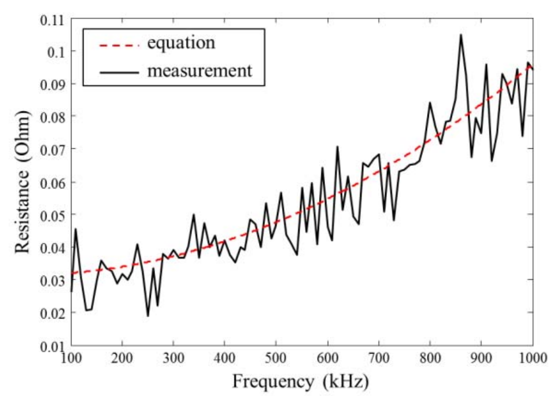


Fig. 5. Correlation between resistance equation and measurement for litz wire Tx-coil

Figure 5 shows that resistance equation for litz wire agrees well with the measurement at low frequency range. However as frequency increases, this equation would be inaccurate because it does not consider the capacitance between each turns of wire. Especially as coil size increases and number of turns increase, turn-to-turn capacitance cannot be neglected. This capacitance makes self-resonance of coil and resistance further increases as frequency goes close to the self-resonance frequency. To consider the effect of self-capacitance, following equations was also proposed for litz wire [6].

$$C_{self} = \frac{C_b(l-1)}{N_t^2} \tag{4}$$

$$C_b = \varepsilon_0 \varepsilon_r \int_0^{\pi/4} \frac{\pi D_i r_0}{\zeta + \varepsilon_r r_0 (1-\cos\theta)} d\theta \tag{5}$$

Tx coil can be simplified as R, L, and self C as shown in Fig. 6. Using this simplified circuit model, Tx equivalent resistance can be derived as Equation 6. It shows the effect of further increased resistance related to the self-capacitance. At self-resonance frequency, resistance becomes very high based on this equation and cannot be used for WPT coil. For 100 kHz application, equation 2 can be used to get the resistance equation, but equation 6 should be considered for the 6.78 MHz application. This becomes more issues as Tx coil size increases and turns increase, which increase self-capacitance and inductance, therefore decrease the self-resonance frequency.

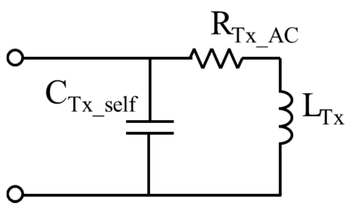


Fig. 6. Simplified circuit model for Tx-coil considering Tx self capacitance. Coil can be modeled as simple R, L, C ciruict.

$$R = \frac{R_{Tx\_AC}}{(1-\omega^2 L_{Tx} C_{Tx\_self})^2 + \omega^2 R_{Tx\_AC}{}^2 C_{Tx\_self}{}^2} \tag{6}$$

Also, there's big difference for the self capacitance between the litz wire and solid wire. As the result, litz wire is very effective to reduce the coil resistance at 100 kHz system while it is not a good solution for 6.78 MHz. Fig. 7 illustrates the Tx resistance of 10-turn winding coil using solid and litz wire. At low frequency, litz wire resistance is smaller than solid wire while it becomes larger at high frequency due to proximity effect and self-capacitance effect. These becomes dominant loss mechanism at higher frequency while skin effect is dominant loss mechanism at low frequency.

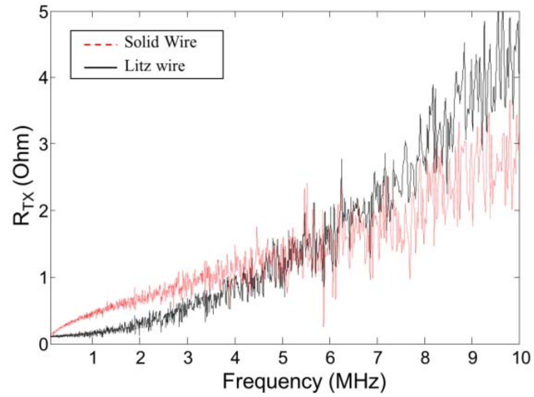


Fig. 7. Comparison between measured solid wire and litz wire

For the coil inductance, there' also some equations [6-7]. Inductance of each turn along with the mutual among turns should be considered as shown in the below equation.

$$L_{Tx} = \sum_{turn} L_{self\_turn} + \sum_{i,j} M_{i,j} \tag{7}$$

Inductance also increases as the operating frequency goes close to the resonance frequency and Tx inductance equation becomes like equation 8.

$$L = \frac{L_{Tx}(1-\omega^2 L_{Tx} C_{Tx\_self}) - \omega R_{Tx\_AC}{}^2 C_{Tx\_self}}{(1-\omega^2 L_{Tx} C_{Tx\_self})^2 + \omega^2 R_{Tx\_AC}{}^2 C_{Tx\_self}{}^2} \tag{8}$$

III. Proposal of Coil Winding for Maximum Q-factor

At the previous chapter, Tx coil resistance and inductance were modeled and equation was given. Because we could get the both resistance and inductance equation, Q-factor of Tx-coil can be calculated based on the equation. However, inductance equation needs integral to consider mutual among turns and not easy to get simple closed form equation.

In practice, inductance can be easily obtained using commercial software like Maxwell. Fig. 8 shows the way to simulate circular coil inductance in a short time. Instead of considering each strands of wire, circular disc is simulated with the current excitation at the side of the disc. The inner and outer diameter of disc is same as coil inner and outer diameter. After get the inductance value of this disc, L_i, square of coil turn number is multiplied to get the real coil inductance as shown in equation 9.

$$L_{Tx} = N_t^2 \cdot L_i \tag{9}$$

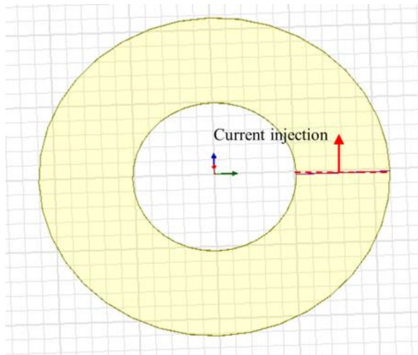


Fig. 8. Maxwell simulation set-up for Tx-coil. To increase simulation speed, strands of wire are merged and current is excited through whole disc

This simulation does not give accurate resistance value, but inductance result is very accurate. A coil simulation with 10-turn strands takes more than several hours while this simulation takes less than 10 minutes for the coil with outer diameter of 50 mm. However, accurate resistance cannot be obtained using this simulation and equation 6 will be used to get the resistance. For the optimization of coil winding to maximize coil FOM, coil Q-factor should be maximized. If coil outer and inner diameter is fixed, coil turn number, width and space can be optimized to maximize coil Q-factor using previous equations.

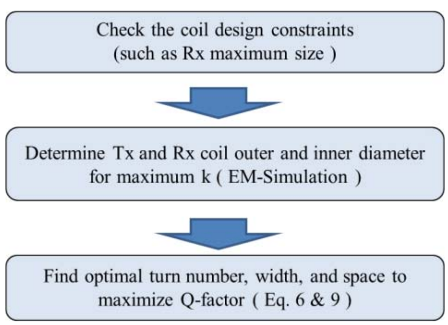


Fig. 9. WPT coil design procedure

For the WPT system design, the above procedure of Fig. 9 can be used. First coil design constraints needs to be checked such as maximum Rx-coil outer diameter and coil thickness, which is related to the application. Then, Tx and Rx coil outer and inner diameter will be optimized to maximize k. This simulation can be quickly done using EM-simulation using a single-turn disc simulation similar to Fig. 8. If Rx coil outer diameter is fixed, then design variable is Rx inner diameter, Tx outer diameter and Tx inner diameter. Within reasonable range, optimal value can be found using EM-simulation. Then, each coil Q-factor should be maximized. Because outer diameter and inner diameter is determined, L_i was obtained by EM-simulation and we have again 3 variables: coil turn number, width of each turn, and spacing between turn. Using equation 6 and 9, optimal value can be quickly found in a given range. For the case with ferrite, EM-simulation needs to be done with ferrite and ferrite loss needs to be additionally modeled to get accurate total coil resistance.

IV. Conclusion

Optimal WPT coil design is very different depending on the applications and suitable coil design is very important factor to maximize the WPT system efficiency. Coil FOM is the key factor to determine the coil-to-coil efficiency and finally determines the WPT system efficiency. For single coil design, optimizing Q-factor is the key to increase the efficiency. Coil AC resistance model including self-capacitance is used to estimate frequency-dependent coil resistance and optimal coil winding method is proposed.

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