Multi-band Coil Design for Wireless Power Transfer at 85 kHz and 6.78 MHz Using High Order Resonant Frequency of Short End Coil

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***Abstract* - Wireless power transfer is a popular research topic in recent years. Allowed frequencies for wireless power transfer (WPT) are limited by the industrial, scientific, and medical (ISM) radio bands and each country's law. Different applications of wireless power transfer need to use different frequency bands. A single transmitter coil which can adapt to multiple frequency bands is needed to reduce the number of transmitter coils. In this paper, transmitter coil design for two frequencies using high order resonant frequency of short end coil is proposed. First resonant frequency is allocated at 85 kHz for Electric Vehicles by using capacitor. Second resonant frequency is allocated at 6.78 MHz (ISM band) by designing the coil shape. Characteristics of a prototype coil is described and the feasibility is confirmed by experiment.**

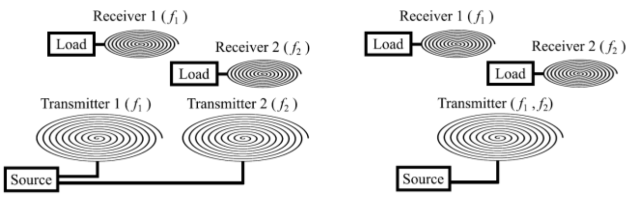
***Index Terms* — Wireless power transfer, Magnetic resonant coupling, Short end coil, Multi-frequency, High order Frequency.**

1. Introduction

Magnetic Resonant Coupling (MRC) for Wireless Power Transfer (WPT) is a popular research topic in recent years[1]. MRC is superior to other WPT methods (e.g. magnetic induction, electric field coupling, microwave) in terms of transfer distance, efficiency and transferred power[2],[3].

This paper focuses on solving the problems of frequency compatibility. Some applications have specific resonant frequency due to law limitation or industrial, scientific, and medical (ISM) bands in MHz band. The frequency allocation for WPT are 85 kHz, 6.78 MHz and so on. Therefore, multiple high frequency bands are required when WPT technology is used at home, office and companies. Each application needs a resonant system in trasmitter side and receiver side respectively. In order to use multiple frequencies, many resonant coils and capacitors are needed, the transmitter side may become costly and space consuming. Hence, a multi-band coil with multiple resonant frequencies is proposed in this paper. The multi-band coil design can reduce the number of transmitter coils needed in WPT system because the multi-band coil can adapt to different frequencies.

This paper presents a design method for a multi-band coil who has two resonant frequencies allocated at 85 kHz and 6.78 MHz.



(a) Conventional system (b) Proposed system

Fig. 1. Multiple frequency band WPT system.

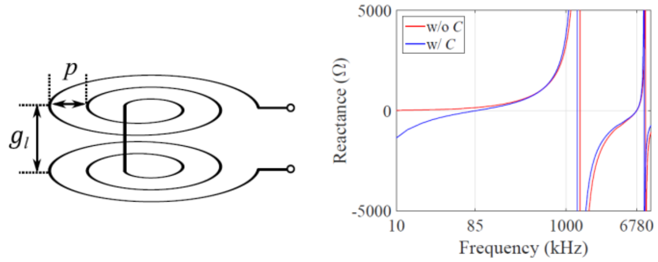
2. Design method of multi-band short end coil

Fig. 1(a) and Fig. 1(b) show the conventional two frequency system and proposed system, respectively. Conventional system has two transmitter coils, but proposed system needs only one transmitter coil [4],[5].

The target of proposed coil design is to achieve self-resonant frequency (second resonant frequency) at 6.78 MHz due to availability of ISM band. And first resonant frequency is produced by external capacitor. Transmission coils are generally divided into two types: the short end coil and the open end coil [6],[7],[8]. Fig. 2(a) shows the concept of the proposed short end coil. Two layer coil structure increase both the strength of magnetic field around center of the coil, and the stray capacitance. Lossless transmission line theory is used for fundamental consideration. The input impedance of short end coil, $Z_{\text{in-short}}$ is derived as

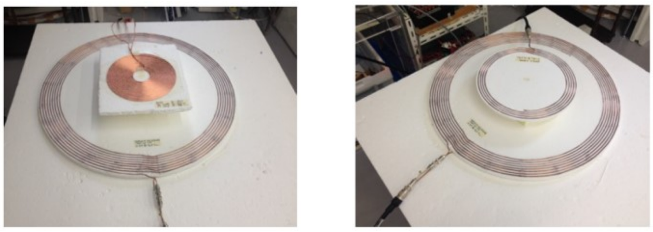
$$Z_{\text{in-short}} = jZ_0 \tan\beta l. \quad (1)$$

where Z_0 is the characteristic impedance, β is the phase constant ($\beta=\omega/c$, ω : angular frequency, c : light speed), l is transmission line length From (1), in order to create many resonant points in available frequency band, l should be longer to achieve larger βl. If βl goes larger, two resonant frequencies become closer. The proposed design method is to modify βl since βl can be raised by expanding the coil radius and increasing number of turns. Then, the second resonant frequency is adjusted to target frequency by changing the layer gap g_l or wire pitch p. Coil design was performed to achieve that first resonant frequency is set at 85 kHz and second self-resonant frequency set at 6.78 MHz. As for the design conditions, number of turns is 8.5, radius is 300 mm, wire diameter is 2 mm. The optimal values of shape parameter are chosen by comparing the shape vs. resonant frequency characteristics. g_l and p were decided to be 10 mm



(a) Concept of short end coil (b) Reactance frequency plots

Fig. 2. Characteristics of short end coil.



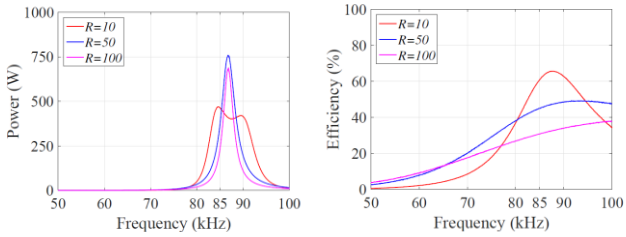
(a) 85 kHz case (b) 6.78 MHz case

Fig. 3. Experimental setup.

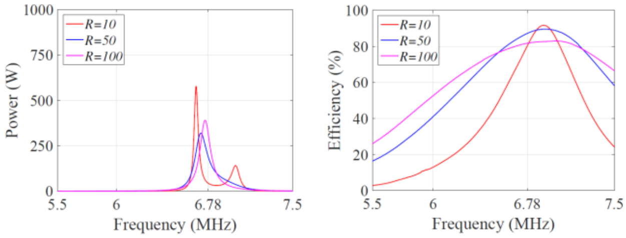
and 5 mm respectively. Fig. 2(b) shows the experimental result, reactance frequency plots of designed multi-band coil. First resonant frequency is successfully set at around 85 kHz by adding a capacitor, and second resonant frequency is successfully set at around 6.78 MHz by coil design. Adding capacitor has no influence of second resonant frequency. In brief, the first resonant frequencies can be attained by attaching a capacitor (with specific value), and the second resonant frequency can be adjusted by tuning the gap g_l and pitch p.

3. Experimental Verification

By using the designed multi-band coil, wireless power transfer characteristics are discussed. Two receiving coil were used for experiment, one operates at 85 kHz, the other at 6.78 MHz. In this experiment, the fact that one transmitter can transfer power to receiving coils at different frequencies is confirmed. Characteristics of wireless power transfer was measured by using network analyzer E5061B (Agilent Technologies). The gap between coils is 50 mm, and load resistance R is changed (R = 10, 50, 100 Ω). Assuming that input voltage is 100 V, received power is calculated by measuring S-parameter. Frequency range is 50 kHz to 7.5 MHz. Fig. 3 shows the experimental setup. Fig. 4 shows the experimental result of receiving power and efficiency. From the results, it is confirmed that power can be transmitted around the designed multiple resonant frequencies. The designed multiband coil can resonate at more than one resonant frequencies and transfer power to multiple receivers resonating at different frequencies. Effectiveness of proposed multi-band coil design was confirmed.



(a) Power (85 kHz) (b) Efficiency (85 kHz)



(c) Power (6.78 MHz) (d) Efficiency (6.78 MHz)

Fig. 4. Power transmission characteristics of the multi-band coil.

4. Conclusion

The multi-band short end coil using high order resonant frequency is proposed in this paper. Target frequency was set at 85 kHz (for EVs) and 6.78 MHz (ISM band) in coil design. First resonant frequency is generated by capacitor, and second resonant coil is designed by changing shape of coil. Experimental results shows that only one designed multiband coil can transmit power at 85 kHz and 6.78 MHz. Therefore, effectiveness of proposed multi-band coil design was confirmed.

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