Efficient magnetic resonant coupling wireless power transfer with a novel conical-helix resonator

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Abstract: To improve the performance of magnetic resonant coupling wireless power transfer (MRC-WPT), a novel conical-helix resonator is designed and optimized for efficient power transfer. Simulation is conducted to investigate characteristics of the proposed resonator and compare with the traditional helix-helix coils. It has been observed that the performance of the MRC-WPT system with conical-helix resonator is superior to that with the helix-helix resonator. Experimental prototype is set up for validation. The results indicate that the voltage transferred to the receiving coil is largely improved for the MRC-WPT system with the proposed resonator when distance between transmitter and receiver varies.

Keywords: MRC-WPT, conical-helix resonator, frequency splitting

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

- [1] S. Hekal, *et al.*: “Asymmetric wireless power transfer systems using coupled DGS resonators,” *IEICE Electron. Express* **13** (2016) 20160591 (DOI: 10.1587/elex.13.20160591).
- [2] H. Hoang, *et al.*: “An adaptive technique to improve wireless power transfer for consumer electronics,” *IEEE Trans. Consum. Electron.* **58** (2012) 327 (DOI: 10.1109/TCE.2012.6227430).
- [3] K. Na, *et al.*: “Tracking optimal efficiency of magnetic resonance wireless power transfer system for biomedical capsule endoscopy,” *IEEE Trans. Microw. Theory Techn.* **63** (2015) 295 (DOI: 10.1109/TMTT.2014.2365475).
- [4] C. Mi, *et al.*: “Modern advances in wireless power transfer systems for roadway powered electric vehicles,” *IEEE Trans. Ind. Electron.* **63** (2016) 6533 (DOI: 10.1109/TIE.2016.2574993).
- [5] A. P. Sample, *et al.*: “Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer,” *IEEE Trans. Ind. Electron.* **58** (2011) 544 (DOI: 10.1109/TIE.2010.2046002).
- [6] J. Zhang, *et al.*: “Comparative analysis of two-coil and three-coil structures for wireless power transfer,” *IEEE Trans. Power Electron.* **32** (2017) 341 (DOI: 10.1109/TPEL.2016.2526780).
- [7] S. Y. R. Hui, *et al.*: “A critical review of recent progress in mid-range wireless

- power transfer,” IEEE Trans. Power Electron. **29** (2014) 4500 (DOI: [10.1109/TPEL.2013.2249670](https://doi.org/10.1109/TPEL.2013.2249670)).
- [8] R. H. Huang, *et al.*: “Frequency splitting phenomena of magnetic resonant coupling wireless power transfer,” IEEE Trans. Magn. **50** (2014) 8600204 (DOI: [10.1109/TMAG.2014.2331143](https://doi.org/10.1109/TMAG.2014.2331143)).
- [9] Y. Zhang and Z. Zhao: “Frequency splitting analysis of two-coil resonant wireless power transfer,” IEEE Antennas Wireless Propag. Lett. **13** (2014) 400 (DOI: [10.1109/LAWP.2014.2307924](https://doi.org/10.1109/LAWP.2014.2307924)).
- [10] H. C. Li, *et al.*: “A maximum efficiency point tracking control scheme for wireless power transfer systems using magnetic resonant coupling,” IEEE Trans. Power Electron. **30** (2015) 3998 (DOI: [10.1109/TPEL.2014.2349534](https://doi.org/10.1109/TPEL.2014.2349534)).
- [11] J. Bito, *et al.*: “A real-time electrically controlled active matching circuit utilizing genetic algorithms for wireless power transfer to biomedical implants,” IEEE Trans. Microw. Theory Techn. **64** (2016) 365 (DOI: [10.1109/TMTT.2015.2513765](https://doi.org/10.1109/TMTT.2015.2513765)).
- [12] Y. M. Zhang, *et al.*: “Frequency-splitting analysis of four-coil resonant wireless power transfer,” IEEE Trans. Ind. Appl. **50** (2014) 2436 (DOI: [10.1109/TIA.2013.2295007](https://doi.org/10.1109/TIA.2013.2295007)).

1 Introduction

Recently, more and more attention has been paid to wireless power transfer technology [1]. Compared with the traditional wired power supply, the electric power in wireless power transfer is transmitted without direct wire connection. Due to the advantages of convenience and safety, wireless power transfer has great potential in a wide range of applications, including consumer electronics, biomedical implants and electric vehicles [2, 3, 4]. In the early research on wireless power transfer technique, inductive power transfer (IPT) is investigated, in which the power is transmitted by electromagnetic induction [5]. Magnetic resonant coupling is another alternative for wireless power transfer, in which the energy is transmitted via magnetic coupling. The transfer distance of the magnetic resonant coupling wireless power transfer (MRC-WPT) is much longer and is robust to the coil misalignments than the IPT [6, 7]. MRC-WPT is considered to be the most effective and attractive technique for mid-range power transfer. Extensive research has revealed that the transfer power decreases when the distance between resonant loops drops below a certain value due to frequency splitting [8, 9]. To suppress frequency splitting, frequency tracking control and impedance matching technique has commonly been used, which requires a series of complex circuits and complicates the system [10, 11]. In addition, the frequency splitting can be eliminated by tuning the angle of the resonant loops or changing the coil structure without additional complex circuits [12]. In this paper, a novel conical-helix coil configuration is proposed to suppress frequency splitting in MRC-WPT. Simulations and experiments have been conducted to investigate and validate the performance of the MRC-WPT system with the conical-helix resonant coils.

2 Modeling of the proposed MRC-WPT system

The novel conical-helix coil configuration is illustrated in Fig. 1(a). A conical coil

is applied as the transmitter and a helix coil is used as the receiver. Fig. 1(b) shows the equivalent circuit of MRC-WPT system with conical-helix coil structure, where the subscripts t and r denote the transmitting coil and receiving coil respectively, L and R are the self-inductance and resistance of the coil, C is the resonant capacitance; V_s and R_s are the voltage and internal resistance of the source; R_L is the load resistance; M is the mutual inductance between the resonant coils; I is the current flowing in the coil.

Fig. 1. (a) Schematic of the conical-helix resonator. (b) Equivalent circuit of the MRC-WPT systems with conical-helix resonator.

The relationship among the resonant frequency f_0 , the inductance L and the compensated capacitance C satisfies:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{\omega_0}{2\pi} \quad (1)$$

The MRC-WPT system can be regarded as a two-port network and its power transfer ability can be described by the transmission coefficient S_{21} as

$$S_{21} = \frac{2j\omega M\sqrt{R_s R_L}}{(\omega M)^2 + \left(R_s + j\omega L_t + \frac{1}{j\omega C_t}\right)\left(R_L + j\omega L_r + \frac{1}{j\omega C_r}\right)} \quad (2)$$

At magnetic resonant state, S_{21} is simplified as:

$$S_{21} = \frac{2j\omega_0 M\sqrt{R_s R_L}}{(\omega_0 M)^2 + R_s R_L} \quad (3)$$

The mutual inductance between the proposed conical-helix coils with multiple turns can be calculated as

$$M = \sum_{i=1}^{n_t} \sum_{j=1}^{n_r} M(r_t, r_r, D) \quad (4)$$

where

$$\begin{cases} M(r_t, r_r, D) = 2\mu_0\sqrt{r_t r_r}/k[(1 - k^2/2)K(k) - E(k)] \\ k(r_t, r_r, D) = \sqrt{4r_t r_r / [(r_t + r_r)^2 + D^2]} \end{cases} \quad (5)$$

and where n_t and n_r are the number of turns of transmitter coil and receiver coil respectively, r_t and r_r are the coil radius of transmitter coil and receiver coil respectively, D is the distance between coils, and $K(k)$ and $E(k)$ are the complete elliptic integrals of the first and second kind respectively.

3 Simulation results

It has been revealed that the dramatic variation of the mutual inductance causes frequency splitting. Therefore, a relatively uniform mutual inductance is preferred to suppress the frequency splitting. To study performance of MRC-WPT system with conical-helix coil, simulation analysis is conducted and compared with that using traditional helix-helix coil. The resonant frequency is set to be 8 MHz.

Fig. 2 shows mutual inductance comparisons obtained from ANSYS Maxwell simulation and from Eq. (4)~(5) calculation for various coil structures when $r_t = 5$ cm, where h-h stands for helix-helix coil and c-h is for conical-helix coil. There exists error between simulation and calculation due to the fact that the coil is equivalent to a series of single turn connected in series in the calculation. However, the coils are structured just as the actual coils in simulation. The mutual inductance obtained from the simulation is more accurate than the calculation. With regards to the traditional helix-helix coil structure, the mutual inductance has a dramatic rise when the distance is less than 6 cm, which leads to frequency splitting. To avoid this, the mutual inductance at close distance should be smoothly changed as much as possible. The variation of the mutual inductance between the conical-helix coils change more slowly compared with the helix-helix coil structure. The receiving coil with a larger radius has a more uniform mutual inductance.

Fig. 2. Comparisons of mutual inductance versus distance.

With the simulated mutual inductance, Fig. 3 shows $|S_{21}|^2$ versus distance at the resonant state where S_{21} is computed using Eq. (3). For the helix-helix coil, the $|S_{21}|^2$ drops dramatically when the distance is smaller than 6 cm. However, the $|S_{21}|^2$ largely increases for all conical-helix coil structures when the distance is small. Besides, the $|S_{21}|^2$ keeps at highest value when the radius of receiving coil is 11 cm, which is chosen as the optimal conical-helix coil structure.

With the simulated mutual inductance, Fig. 4 depicts $|S_{21}|^2$ versus frequency where S_{21} is computed using Eq. (2). For traditional helix-helix coil, frequency splitting occurs and $|S_{21}|^2$ at the resonant frequency drops largely with decrease of distance. However, for optimal conical-helix resonator, frequency splitting is completely avoided and $|S_{21}|^2$ maintains at a relatively higher value. It indicates the conical-helix coil is effective to suppress frequency splitting and enhance the power transfer capability of MRC-WPT system.

Fig. 3. $|S_{21}|^2$ versus distance for MRC-WPT system with helix-helix coil and conical-helix coils.

Fig. 4. Comparison of frequency-insensitive characteristics for the MRC-WPT with (a) helix-helix coil; (b) proposed conical-helix coil.

Fig. 5 shows the magnetic field distribution between the helix-helix resonator and the conical-helix resonator. It can be seen that the magnetic field of the conical-helix resonator is comparatively less intensive for shorter distances and the magnetic over-coupling is degraded compared with the helix-helix resonator.

Fig. 5. Magnetic field distribution for the resonators at small distance.

4 Experimental validation

An experimental prototype of MRC-WPT system has been established to estimate performance of the proposed conical-helix resonator, as given in Fig. 6. The transmitting coil is connected in series with a power amplifier whose input signal is provided by a function generator. The receiving coil is connected to a load with

the value of $7.5\ \Omega$. Compensated capacitors are used for magnetic resonance. The coils parameters are the same with that in the simulation.

Fig. 6. Photography of the experimental setup.

Fig. 7 shows the comparisons of transfer voltage measured on the load for two different coil structures when the receiving coil moves close to the transmitting coil. The transfer voltage of the proposed conical-helix resonator is much higher than that of the traditional helix-helix resonator when the distance varies.

Fig. 7. Transfer voltage on the load.

5 Conclusion

In this paper, a conical-helix coil configuration is proposed for effective power transfer in MRC-WPT system. Based on numerical simulation, the characteristic of the proposed coil was investigated and compared with the traditional helix-helix coil. It indicated that the conical-helix resonator was effective in suppressing frequency splitting. Additionally, the conical-helix resonator was optimized where frequency splitting was totally eliminated and the performance of the MRC-WPT system was improved for various distances. Experimental validation was carried out by measuring the transfer voltage at the load when the distance between the transmitter and receiver varied from 0 cm to 20 cm. The MRC-WPT system with the proposed optimal coils shows a much higher transfer voltage compared to the traditional helix-helix coil and can be adopted for efficient power transfer.

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