Charging Area Extensible Wireless Power Transfer System with an Orthogonal Structure

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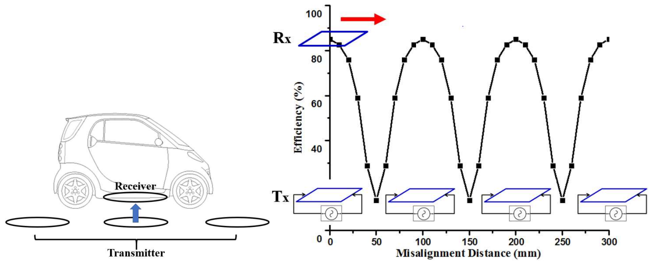
***Abstract*— This paper presents a wireless power transfer (WPT) system with an extensible charging area. The proposed system uses a vertical receiver with an 8-shape transmitter. Conventionally, circular coil structures suffer from coupling condition variation when used for dynamic wireless charging applications. . In this paper, an 8-shape feeding loop is proposed to construct a directional magnetic field for an orthogonal receiver to receive the power efficiently. Furthermore, the transmitter can be extended easily by cascading the transmitter modules. Experimental results have demonstrated a power transfer efficiency of 59% - 70 % when a receiver is moving along a 3-module transmitter array. The proposed structure can be a very good candidate for dynamic WPT applications, especially the charging of moving electric vehicles.**

***Index Terms*—Multi-antiparallel loops, mutual inductance, wireless power transfer.**

I. Introduction

Wireless power transfer (WPT) technology has enabled a wide variety of portable consumer electrical, medical, and industrial devices. This technique has attracted considerable interests and already been proposed to electric vehicles (EVs) charging [1]. Dynamic Wireless Charging (DWC) technology can be used to charge EVs while they are moving. Such technology has a number of advantages as it can mitigate range anxiety, reduce battery size and decrease battery cost [2]. DWC requires magnetic coupling between track coils installed under the road surface and a pick-up coil fitted in the EV [3]. When the track coil and the pick-up coil are fully aligned, the WPT system can achieve its maximum efficiency. However, when the pick-up coil moves to another track coil at intermediate positions, the efficiency decrease rapidly. In order to solve this problem, there have been many researches on the DWC. In [4], an effective bipolar coil topology with the double-D (DD) shape and a quadrature coil (Q-coil) were used as the pick-up coil to receive more power in the intermediate positions. However, the transfer efficiency was still very limited. In [5], a dual-loop primary controller was used to regulate primary-side power and current against lateral misalignment. However, only 40% efficiency was achieved in the null power point position. In this paper, a novel WPT system with an orthogonal structure is proposed. The charging module consists of an extensible modularized array to increase the capacity of maintaining high efficiency while the receiver is moving.



(a) (b)

Fig.1. (a) EVs charging structure. (b) Power transfer efficiency of the conventional MRC-WPT system with a moving receiver.

II. Theoretical Analysis

A. Proposed Orthogonal Extensible WPT Structure

A conventional DWC system for EV charging is shown in Fig.1 (a). The magnetic resonance coupling wireless power transfer (MRC-WPT) system transfers power via magnetic coupling between the transmitter (Tx) and the receiver (Rx). Usually, the maximum efficiency can be achieved only at the optimal position. The power transfer efficiency will fluctuate when the vehicle is moving along the transmitters as shown in Fig.1 (b). In this case, the average power transfer efficiency for the dynamic charging will be relatively low which is not desirable for industrial applications.

A conventional DWC circuit and its magnetic field distribution are shown in Fig.2 (a) and (b), respectively. Three coils are used in the transmitter. It can be seen that the magnetic field lines are distributed vertically in the center of each coil. The receiver should be placed coaxially to the transmitter to realize strong coupling, achieving the maximum power transfer efficiency. However, since the transmitter coils are placed along a straight line, the magnetic field of each transmitter coil will be attenuated by the adjacent coils in intermediate areas as illustrated in Fig. 2 (b). Hence, when the receiver is moving along the path, the magnetic coupling condition will not be maintained at the optimal level, leading to a fluctuation of the power transfer efficiency.

In order to manipulate the magnetic field into a directional distribution manner. A novel 8-shape feeding loop structure is proposed and a receiver is placed orthogonally to the transmitter as shown in Fig. 2 (c). The feed loop is designed with an 8-shape to make sure that the magnetic field generated by the feed loop has the same direction on all transmitting coils in the Tx as shown in Fig. 2 (d). The feeding loops for the three modules

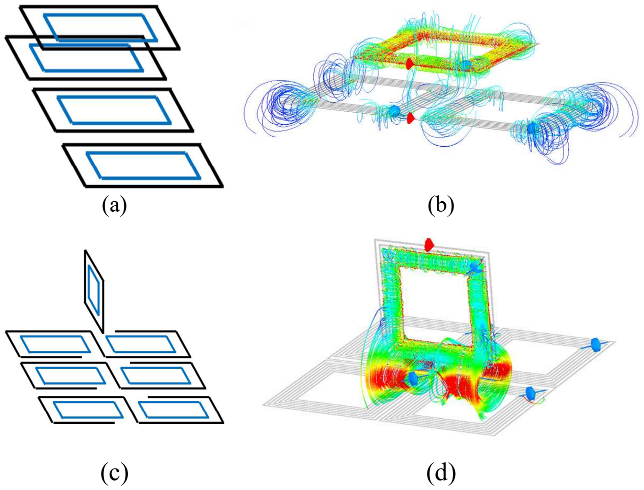


Fig. 2. (a) A conventional WPT system, (b) magnetic field distribution of the conventional WPT system. (c) The proposed WPT system and (d) magnetic field distribution of the proposed WPT system.

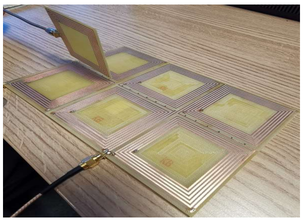


Fig. 3. Experimental setup of the proposed WPT sytem.

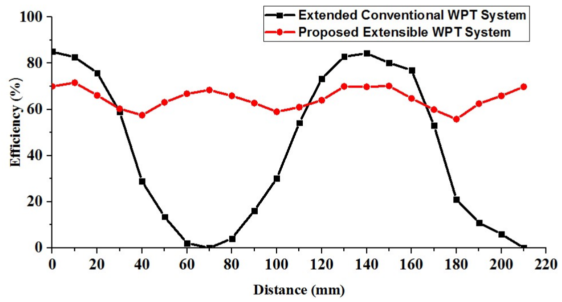


Fig. 4. Comparison of the transfer efficiency of the proposed extensible WPT system with the conventional WPT system when the receiver is moving.

can be connected in series to form a planar 1×3 transmitter array. It can be seen that the magnetic field of the proposed extensible transmitter is almost uniform along the receiver's moving direction. Also, with the receiver placed orthogonally to the transmitter, the majority of the magnetic flux can be captured, leading to a high transfer efficiency. This will also reduce less eddy current loss on metal parts of EVs due to the astray magnetic field. Therefore, the proposed WPT system is very suitable for the dynamic charging of EVs.

III. Experimental Verification

The proposed WPT system with a single receiver was fabricated as shown in Fig. 3. The feed loop and transmitting coils were fabricated on a single FR4 substrate with a length of 137 mm and a width of 69 mm. The S-parameters of the WPT system were measured using an Agilent N9917A vector network analyser (VNA).The receiver part was fabricated in a similar way. The maximum efficiency was achieved at 13.56 MHz in the aligned position, which is 87.1% with S_{11} = -26.8 dB and S_{21} = -0.6 dB. The performance of the fabricated WPT system was measured when the misalignment was from 0 to 21 cm with a step of 1 cm. At each distance, the S-parameters were measured to calculate the efficiency. Fig. 4 shows the efficiency as a function of the misalignment distance Δd. Also, the extended conventional WPT system has been measured for comparison. The conventional structure can achieve an efficiency of 90% when the Rx and Tx are aligned while the maximum efficiency of the proposed WPT system is 70%. However, the conventional WPT system can achieve its maximum efficiency only when Tx and Rx are fully aligned, When the Rx moves to another Tx at intermediate position, the efficiency decreases rapidly. The proposed extensible WPT system can achieve a very smooth efficiency response of 59% - 70% with a Rx moving range of 21 cm.

IV. Conclusion

In conclusion, an extensible dynamic charging WPT system with an 8-shape feed loop and an orthogonal structure has been proposed in this paper. With the proposed multi-coil 8-shape structure, the magnetic field of the transmitter is regulated to a directional distribution manner. This feature enables the proposed WPT system to have good extensibility. As demonstrated by experiment, the proposed extensible WPT system can achieve a smooth efficiency response of 59% - 70% when an Rx is moving in a range of 21 cm (three times the Rx side length) using a three modules transmitter. The proposed system is particularly useful for charging a moving vehicle or for charging vehicles with different sizes.

References

[1] S. Li and C. C. Mi, "Wireless power transfer for electric vehicle applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 3, (1), pp. 4-17, 2015.

[2] A. Ahmad, M. S. Alam and R. Chabaan, "A comprehensive review of wireless charging technologies for electric vehicles," *IEEE Transactions on Transportation Electrification,* vol. 4, (1), pp. 38-63, 2018.

[3] S. Lukic and Z. Pantic, "Cutting the cord: Static and dynamic inductive-wireless charging of electric vehicles," *IEEE Electrific. Mag.,* vol. 1,no. 1, pp. 57–64, Sep. 2013.

[4] C. C. Mi et al, "Modern advances in wireless power transfer systems for roadway powered electric vehicles," *IEEE Trans. Ind. Electron.,* vol. 63, (10), pp. 6533-6545, 2016.

[5] R. Tavakoli and Z. Pantic, "Analysis, Design, and Demonstration of a 25-kW Dynamic Wireless Charging System for Roadway Electric Vehicles," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 6, (3), pp. 1378-1393, 2018.