

# An Efficient Reconfigurable Transmitter with Anti-Offset Performance and High Compatibility for Vehicle-to-Vehicle (V2V) Wireless Charging Systems

Ronghuan Xie<sup>1</sup>, Wenbin Pan<sup>1</sup>, Yuanchao Wu<sup>1</sup>, Zhiwei Shen<sup>1</sup>, Zhongqi Li<sup>2</sup>, and Yiming Zhang<sup>1\*</sup>

<sup>1</sup> College of Electrical Engineering and Automation, Fuzhou University, Fuzhou, Fujian, China

<sup>2</sup> Hunan University of Technology, Zhuzhou, Hunan, China

**Abstract.** To solve the interoperability and anti-offset problems in vehicle-to-vehicle (V2V) wireless charging systems, a reconfigurable transmitter is proposed to adapt to unipolar and bipolar coils. By changing the circuit configuration, power transmits efficiently from one EV to the other. The proposed reconfigurable transmitter works in two modes. Moreover, the anti-offset performance of the proposed coil is improved by adding the anti-series windings. The system is verified by simulation to maintain stable output under different offsets, proving its effectiveness in solving the interoperability and offset problems for V2V wireless charging systems.

## 1 Introduction

To reduce carbon emissions and pollution, electric vehicles (EVs) are becoming a greener way of transportation [1]. Conventional EV charging is wired charging, requiring a physical connection. However, wired charging limits the free movement of EVs and may reduce charging efficiency due to wear and tear on the connectors [2]. To solve these problems, the wireless power transfer (WPT) technology has been developed [3]. The WPT system transfers energy through electromagnetic fields without the physical connection. The utilization of the WPT technology makes the charging process of EVs more convenient and is conducive to the further promotion of EVs [4].

However, there are some challenges in the WPT technology [5]. One of the issues is the offset. It may influence the charging efficiency and even lead to charging interruptions, affecting the user experience.

There are usually three ways to achieve anti-offset performance [6]. The first method is using the closed-loop control [7]. To achieve this, stable and timely communication between the primary and secondary sides is required. Control strategies can also be complex and costly. The second method employs different magnetic couplers [8]. Commonly used coils include unipolar and bipolar coils, as shown in Fig. 1. These coils have good anti-offset performance and only the mutual inductance variation needs to be considered. With the development of the WPT technology, more complex magnetic couplers are proposed such as DDQ and BP [9]. The third approach is to utilize different compensation topologies [10]. The four basic topologies are series-series (S-S), parallel-parallel (P-P), S-P, and P-S. Normally these topologies exhibit monotonic

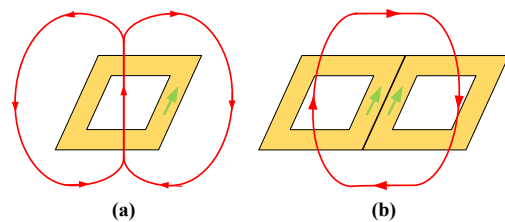


Fig. 1. Commonly used coil. (a) Unipolar coil. (b) Bipolar coil.

change against offset. In addition, high-order topologies such as LCC-S and LCC-LCC are proposed, which are capable of providing stable current or voltage output while exhibiting better performance characteristics.

As the EV market grows rapidly, it leads to a wide variety of EV makes and models available [11]. Each brand may utilize different types of coils for their WPT systems [12]. If a unipolar coil is perfectly aligned with a bipolar coil, it becomes decoupled and cannot transmit power effectively [13]. This poses an interoperability issue. The interoperability issue may result in low charging efficiency, significant energy waste, and even charging failure [14]. For wireless charging systems, interoperability is critical [15].

With the popularity of EVs, one EV can serve as an energy supplier to charge another EV, especially in emergencies without charging stations around [16]. A strongly coupled vehicle-to-vehicle (V2V) wireless charging system was proposed [17]. Two power relay coils are put under the transmitting and receiving coils. This scheme requires two additional relay coils, which should align with the transmitting and receiving coils [18]. However, the above studies did not address the interoperability and offset issues for V2V charging systems.

\* Corresponding author: [zym@fzu.edu.cn](mailto:zym@fzu.edu.cn)

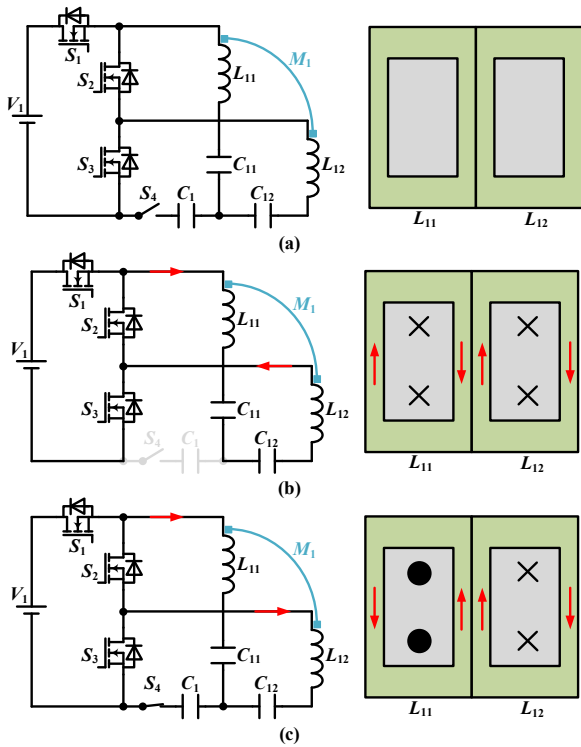


Fig. 2. Proposed transmitter. (a) Structure. (b) UCM. (c) BCM.

To solve the interoperability and offset issues in V2V wireless charging system, a novel reconfigurable transmitter is proposed in this paper. By changing the circuit configuration, the proposed transmitter adapts to both unipolar and bipolar coils. In addition, the anti-parallel coil is added to the proposed transmitter to improve the anti-offset performance. A simulated prototype is constructed. In practical applications, it is not always possible to ensure that the magnetic couplers are perfectly aligned. Consequently, it is important to assess the anti-offset performance. Both interoperability and anti-offset capabilities are evaluated.

## 2 Proposed transmitter

The proposed reconfigurable transmitter is shown in Fig. 2.  $V_1$  is the dc voltage of the inverter.  $C_1$ ,  $C_{11}$ , and  $C_{12}$  are the capacitors.  $L_{11}$  and  $L_{12}$  are the self-inductances.  $S_1$ ,  $S_2$ , and  $S_3$  are power MOSFETs.  $S_4$  is the relay switch.

### 2.1 Circuit configuration

The transmitter has two operating modes, unipolar coil mode (UCM) and bipolar coil mode (BCM), as shown in Fig. 2(a)-(b). The control signal of the power MOSFETs and relay switch are shown in Fig. 3.

In the UCM, the relay switch is on, and the two unipolar coils are in series, and the current flows from the synonymous end of the coil, creating the same magnetic field, which can be equivalent to a unipolar coil.

In the BCM, the relay switch is closed, the two unipolar coils are in parallel, and the current flows from

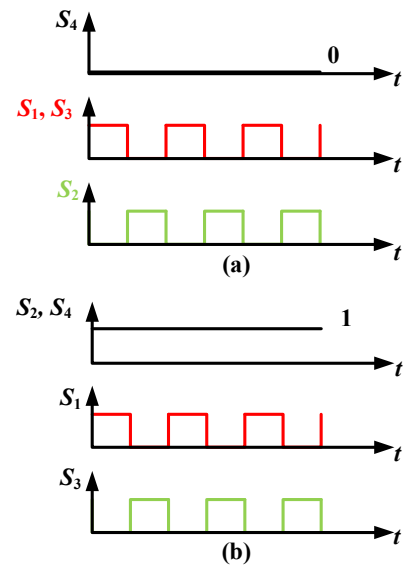


Fig. 3. Key waveforms. (a) UCM. (b) BCM.

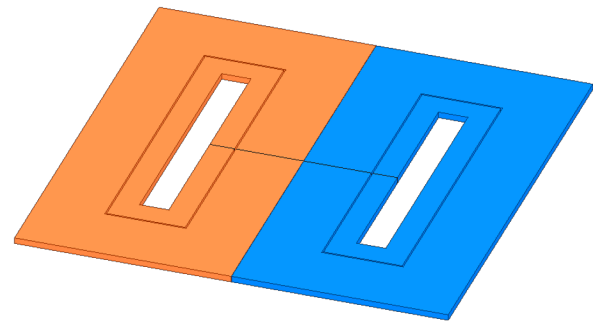


Fig. 4. Transmitting Coil.

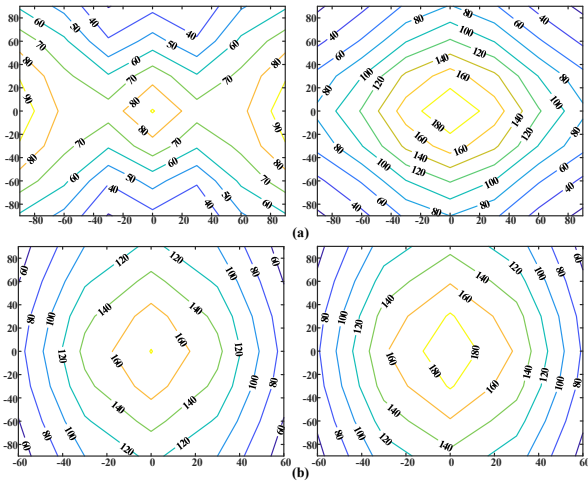
the homonymous end of the coil, generating the opposite magnetic field, so it is equivalent to the bipolar coil.

### 2.2 Coil configuration

The proposed coil is innovative and based on a bipolar coil. As shown in Fig. 4, the reverse winding coils are introduced in the center of the coils to reduce the magnetic flux in the center area, achieving a uniform distribution of the magnetic flux in the whole plane, thus significantly improving the anti-offset performance of the coil.

In addition, by adjusting the circuit configuration and controlling the direction of the current flowing, the proposed coils can obtain the same magnetic field as the unipolar or bipolar coils, achieving compatibility with the unipolar and bipolar coils. Such an innovative design significantly enhances the adaptability and flexibility of the proposed system in diverse charging environments.

In the UCM, the mutual inductance of the proposed coil and the traditional unipolar coil varies against the offset, as shown in Fig. 5(a). It is evident that the magnetic flux of the central region is effectively reduced. In comparison to the conventional unipolar coil, the mutual inductance of the proposed coil demonstrates greater stability in response to the offset, indicating it more suitable for V2V wireless charging systems. A



**Fig. 5.** The variation of mutual inductance with offset. (a)Proposed coil in UCM and traditional unipolar coil. (b)Proposed coil in BCM and traditional and bipolar coil.

similar conclusion is obtained in the BCM. The mutual inductance varies with the offset, as shown in Fig. 5(b).

### 3 V2V system

The topology of the V2V wireless charging is depicted in Fig. 6(a).  $C_2$  is the compensation capacitor.  $L_2$  is the self-inductance.  $R_L$  is the load resistance. The resonant angular frequency  $\omega$  can be expressed as

$$\omega = \frac{1}{\sqrt{C_{11}(L_{11} - M_1)}} = \frac{1}{\sqrt{C_{12}(L_{12} - M_1)}} \quad (1)$$

$$= \frac{1}{\sqrt{C_1 M_1}} = \frac{1}{\sqrt{C_2 L_2}}$$

#### 3.1 UCM

The equivalent topology of UCM is shown in Fig. 6(b).  $U_1$  is the ac output voltage of the inverter.  $R_{EQ}$  is the ac load resistance.  $I_1$  and  $I_2$  are the corresponding currents.  $R_{11}$ ,  $R_{12}$ , and  $R_2$  are the equivalent series resistances (ESRs).  $U_1$ ,  $R_{EQ}$  can be expressed as

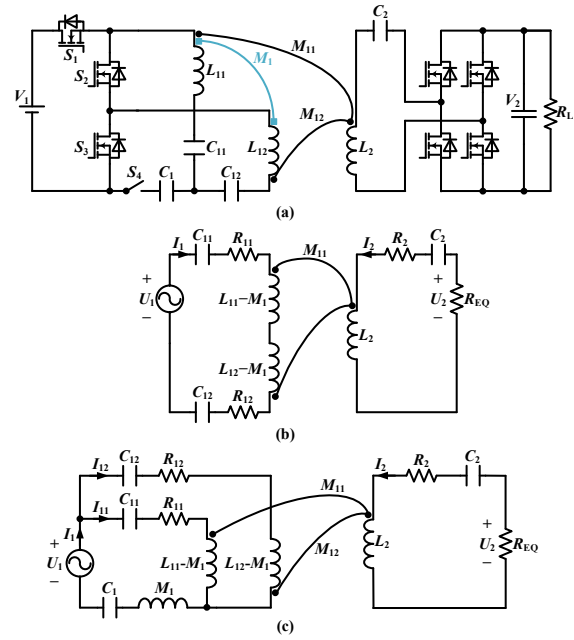
$$U_1 = \frac{\sqrt{2}}{\pi} V_1, \quad R_{EQ} = \frac{8}{\pi^2} R_L \quad (2)$$

When the  $S_4$  is deactivated, the two unipolar coils are in series, resulting in the generation of identical magnetic fields, which subsequently form a larger unipolar coil.

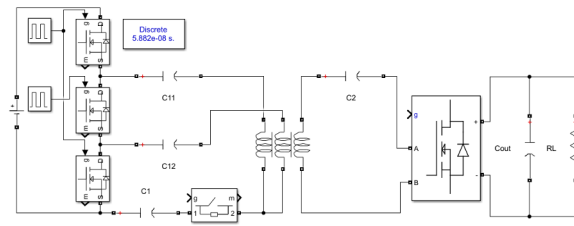
Using Kirchhoff's Voltage Law (KVL) and ignoring  $R_1$  and  $R_2$  yield

$$I_2 = \frac{U_1}{\omega(M_{11} + M_{12})} \quad (3)$$

$$I_1 = \frac{R_{EQ} U_1}{\omega^2 (M_{11} + M_{12})^2} \quad (4)$$



**Fig. 6.** V2V system. (a) Topology. (b) UCM. (c) BCM.



**Fig. 7.** Simulated prototype.

#### 3.2 BCM

The equivalent circuit of BCM is depicted in Fig. 6(c).  $I_{11}$  and  $I_{12}$  are the currents. When the  $S_4$  is activated, the two unipolar coils are in parallel, resulting in the generation of opposing magnetic fields, which is equivalent to that of a bipolar coil.

Using KVL yields

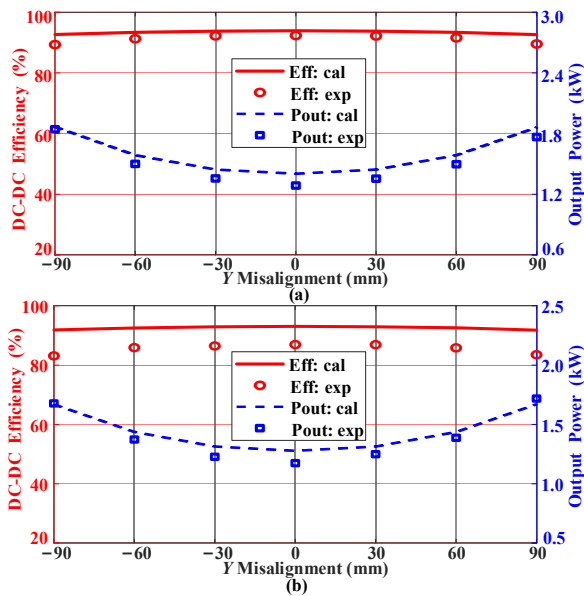
$$I_2 = \frac{U_1 (\omega M_{12} R_{11} + \omega M_{11} R_{12})}{R_{11} R_{12} R_{EQ} + (\omega M_{12})^2 R_{11} + (\omega M_{11})^2 R_{12}} \quad (5)$$

$$I_1 = \frac{U_1 [(R_{11} + R_{12}) R_{EQ} - \omega^2 (M_{11} - M_{12})]}{R_{11} R_{12} R_{EQ} - \omega^2 (R_{11} M_{12}^2 + R_{12} M_{11}^2)} \quad (6)$$

### 4 Simulated verification

To validate the effectiveness of the proposed scheme, a simulated prototype is constructed, as shown in Fig. 7. The results of the simulation, including both the dc-dc efficiency and the output power, are presented in Fig. 8. There is a close alignment between the calculated and the simulated results.

In UCM, the operating efficiency is stabilized at more than 90% with a minimum power of about 1.2 kW. While in BCM, the efficiency is lower with a minimum



**Fig. 8.** The calculated and simulated results. (a) UCM. (b) BCM.

efficiency of 83.5%. This is due to the parasitic parameters in the transmitting coils resulting in uneven current distribution and high losses in the transmitter. In this mode, the minimum power is about 1.2 kW and the maximum power is up to 1.7 kW.

The obtained results support the stability of both efficiency and power in the proposed system. This indicates that the system exhibits excellent anti-offset performance, which is crucial for V2V wireless charging system. By comparing the simulated and calculated data, it can be concluded that the proposed scheme achieves high efficiency and stable output power.

## 5 Conclusions

This paper proposes a method for solving the interoperability and offset issues in the V2V charging system. A reconfigurable transmitter comprising two adjacent unipolar coils can be reconfigured as a unipolar coil or a bipolar coil. Both two working modes can realize stable power transfer. To improve the anti-offset performance, the anti-series coils are added to achieve a uniform magnetic field. A simulated prototype has been constructed. The calculated and simulated results validate the effectiveness of this proposal. The proposed scheme is effective in solving the interoperability and offset issues in the V2V charging system.

## References

1. Z. Shen, et al., "A strong offset-resistant electric vehicle wireless charging system based on dual decoupled receiving coils," *IEEE Trans. Ind. Electron.*, 2024 in press. DOI: 10.1109/TIE.2024.3371002.
2. K. Zhao, et al., "An unsymmetrical driving scheme for inductive power transfer systems using

- decoupled transmitter coils," *IEEE J. Emerg. Sel. Top. Ind. Electron.*, vol. 2, no. 4, pp. 614-624, Apr. 2023.
3. C. Liu, M. Zhou, R. Xie, Y. Zhuang, and Y. Zhang, "A novel bipolar coil structure with high interoperability performance for electric vehicle wireless charging systems," *Int. J. Circuit Theory Appl.*, 2024 in press. DOI:10.1002/CTA.4080.
4. Y. Zhang, et al., "Passive paralleling of multi-phase diode rectifier for wireless power transfer systems," *IEEE Trans. Circuits Syst. II-Express Briefs*, vol. 2, no. 70, pp. 646-649, Feb. 2023.
5. J. Feng, G. Wei, J. Zhang, and C. Zhu, "An LCCC-LCC compensated dual-coupled WPT system with MI enhancement and high misalignment tolerance," *IEEE Trans. Power Electron.*, vol. 12, no. 38, pp. 15162-15167, Dec. 2023.
6. Y. Zhang, H. Tang, Z. Shen, Y. Zhuang, and Z. Li, "An LC squared-compensated inductive power transfer system with misalignment tolerance and constant-current output," *IEEE Trans. Power Electron.*, vol. 4, no. 39, pp. 4850-4857, Apr. 2024.
7. Y. Chen, R. Mai, Y. Zhang, M. Li, and Z. He, "Improving misalignment tolerance for IPT system using a third-coil," *IEEE Trans. Power Electron.*, vol. 4, no. 34, pp. 3009-3013, Apr. 2019.
8. Y. Wang, Y. Yao, X. Liu, D. Xu, and L. Cai, "An LC/S compensation topology and coil design technique for wireless power transfer," *IEEE Trans. Power Electron.*, vol. 3, no. 33, pp. 2007-2025, Mar. 2018.
9. C. Da, L. Wang, F. Li, C. Tao, and Y. Zhang, "Analysis of undersea simultaneous wireless power and 1 Mb/s data rate transfer system based on DDQ coil," *IEEE Trans. Power Electron.*, vol. 10, no. 38, pp. 11814-11825, Oct. 2023.
10. Y. Zhang, et al., "Interoperability study of electric vehicle wireless charging system based on three decoupled non-overlapping unipolar transmitting coils," *IEEE Trans. Transp. Electrification*, 2024 in press. DOI: 10.1109/TTE.2024.3351077.
11. Y. Zhang, et al., "A quadrupole receiving coil with series-connected diode rectifiers for interoperability of nonpolarized and polarized transmitting coils," *IEEE Trans. Power Electron.*, vol. 7, no. 38, pp. 8000-8004, Jul. 2023.
12. R. Xie, et al., "An interoperable wireless power transmitter for unipolar and bipolar receiving coils based on three-switch dual-output inverter," *IEEE Trans. Power Electron.*, vol. pp. 1-5, Feb. 2024.
13. K. Song, et al., "A review on interoperability of wireless charging systems for electric vehicles," *Energies*, vol. 4, no. 16, pp. 1653, Feb. 2023.
14. Y. Zhang, et al., "A family of self-adaptive interoperable receivers based on multiple decoupled receiving poles for electric vehicle wireless charging systems," *IEEE Trans. Power Electron.*, 2024 in press. DOI: 10.1109/TPEL.2024.3404819.
15. R. Xie, et al., "A magnetic adapter realizing the interoperability of unipolar and bipolar coil," *Proc. IEEE APET*, 2023, pp. 496-500, DOI:

- 10.1109/APET59977.2023.10489598.
16. V. Shah and S. Payami, "Integrated converter with G2V, V2G, and DC/V2V charging capabilities for switched reluctance motor drive-train based EV application," *IEEE Trans. Ind. Appl.*, vol. 3, no. 59, pp. 3837-3850, May./Jun. 2023.
  17. R. Xie, Y. Wu, H. Tang, Y. Zhuang, and Y. Zhang, "A strongly coupled vehicle-to-vehicle wireless charging system for emergency charging purposes with constant-current and constant-voltage charging capabilities," *IEEE Trans. Power Electron.*, vol. 4, no. 39, pp. 3985-3989, April 2024.
  18. L. Shi, S. Wang and K. Wang, "Overview of wireless charging alignment detection technology," *Proc. IEEE AEEGE*, 2023, pp. 64-69, DOI: 10.1109/AEEGE58828.2023.00020.