Verification of the Effects of Cross-Coupling on Dynamic Wireless Power Transfer for Heavy-Duty Vehicles Using Double-LCC Circuits

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ABSTRACT: Dynamic Wireless Power Transfer (DWPT) is a technology that extends the cruising distance of electric vehicles and contributes to their widespread use. To extend the cruising distance of heavy-duty vehicles with DWPT, increasing the average power received by installing multiple receiver coils is being considered. However, it is known that wireless power transfer using three or more coils causes cross-coupling, which deteriorates the transmission characteristics. In this study, the effects of cross-coupling (CC) are investigated for two types of circuit configurations: Independent Multi-Pad Receiver and Series Multi-Pad Receiver. As a result, it was found that the effect of cross-coupling between the transfer coils is small for the Double-LCC circuit, and that the effect of cross-coupling between the receiver coils is small for the circuit with Series Multi-Pad Receiver. Experiments also showed that the Series Multi-Pad Receiver can obtain 30% more power than the Independent Multi-Pad Receiver.

KEY WORDS: Electric Vehicle, Dynamic Wireless Power Transfer, Multiple Coils, Cross-Coupling, Series Multi-Pad Receiver

1. Introduction

1.1. Background

Battery Electric Vehicles (BEVs) are gaining attention due to the push towards carbon neutrality[(1)]. However, the widespread adoption of BEVs has been hindered by the limited availability of recharging stations and technical limitations, such as limited cruising distance and long charging time. Increasing battery capacity would increase the cruising distance, but it would also make the vehicle more expensive and heavier.

To address these issues, research into Dynamic Wireless Power Transfer (DWPT) is ongoing. Wireless Power Transfer (WPT) refers to the transfer of electric power without wires[(2)],while DWPT is a technology that enables the transfer of electric power while driving by integrating a power transfer coil into the road and a power receiver coil on the bottom of the vehicle[(3,4)]. DWPT not only extends the cruising range of BEVs without increasing battery capacity, but also reduces the time required to recharge the battery after the vehicle has stopped.

While several studies [(5–7)] have been conducted on DWPT for heavy-duty vehicles with large payloads, which use multiple power receiver coils, most of these circuits have used a single power receiver coil or multiple coils connected in parallel. There has also been research into reducing component count in the circuit by connecting multiple power receiver coils in series or parallel with a resonant circuit[(8)], but no comparison with power transmission characteristics has been made for Independent Multi-Pad Receiver.

1.2. Purpose

Considering that DWPT involves the installation of several power transfer coils buried in the road and several power receiver coils in large vehicles, it is necessary to consider the effects of cross-coupling (CC). Cross-coupling refers to extra coupling in Wireless Power Transfer and is known to have a negative impact on power and efficiency [(9,10)]. In this paper, the power transmission characteristics of a system with Independent Multi-Pad Receiver and a system with Series Multi-Pad Receiver are compared, with the focus on the effect of CC.

1.3. Structure of This Paper

Chapter 2 presents the assumed circuit configuration, Chapter 3 outlines the theory of impedance in the circuit and the influence of CC. Chapter 4 displays the simulation results, Chapter 5 displays the experimental results, and Chapter 6 offers conclusions.

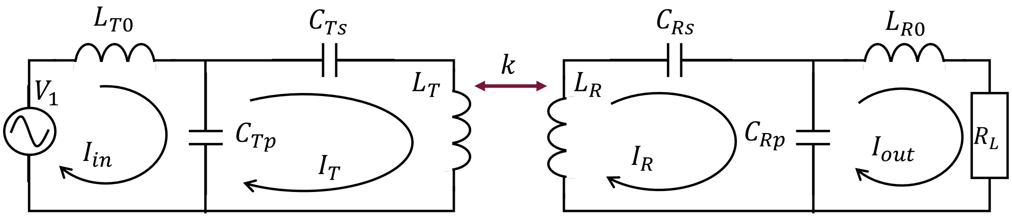


Fig.1 Double-LCC Circuit

2. CIRCUIT CONFIGURATION

2.1. Double-LCC Circuit

Among the resonant circuits of the WPT, the Double-LCC method shown in Fig. 1 has attracted attention because of its compatibility with the DWPT and its low standby loss, even if voltage is continuously applied from the power supply even when the car body is not located above the power transfer coil, since no large current flows and standby loss is low[11,12].

$$\omega_0 = \frac{1}{\sqrt{L_{T0}C_{Tp}}} = \sqrt{\frac{C_{Tp}+C_{Ts}}{L_T C_{Tp} C_{Ts}}} = \frac{1}{\sqrt{L_{R0}C_{Rp}}} = \sqrt{\frac{C_{Rp}+C_{Rs}}{L_R C_{Rp} C_{Rs}}} \quad (1)$$

equation (1) shows the resonance condition of the Double-LCC circuit. This resonance condition causes an anti-resonance in the loop of i_T when there is no coupling with the power receiver coil, and i_{in} becomes very small. In addition, part of the LCC circuit has gyrator characteristics. The gyrator characteristic refers to the characteristic of converting the constant-voltage characteristic into the constant-current characteristic and the constant-current characteristic into the constant-voltage characteristic. Due to this gyrator characteristic, i_T shows a constant-current characteristic in a Double-LCC circuit if internal resistance and resonance shift of coils, etc. are not considered.

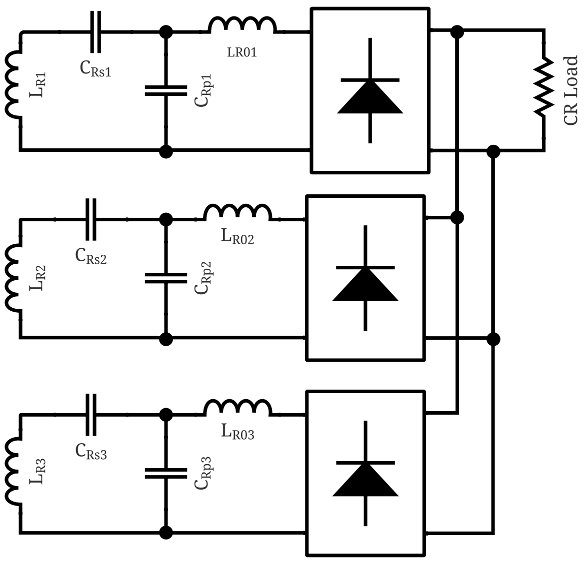


Fig.2 Independent Multi-Pad Receiver

2.2. How to Connect Multiple Receiver coils

2.2.1. Independent Multi-Pad Receiver

The power receiving system of the Independent Multi-Pad Receiver is shown in Fig. 2. In this system, the circuits are connected at the DC stage after rectification. This circuit allows load impedance control for each individual power receiving circuit.

2.2.2. Series Multi-Pad Receiver

The Series Multi-Pad Receiver is shown in Fig. 3. In this system, the power receiver coils are connected in series. This circuit requires fewer components, but the ratings of each component are more stringent. Although there are some studies that connect power receiver coils in parallel[8], connecting power receiver coils in parallel in the double-LCC circuit is equivalent to connecting circuits with voltage source characteristics in parallel due to gyrator characteristics, and would result in an unstable system, so it is not considered in this study.

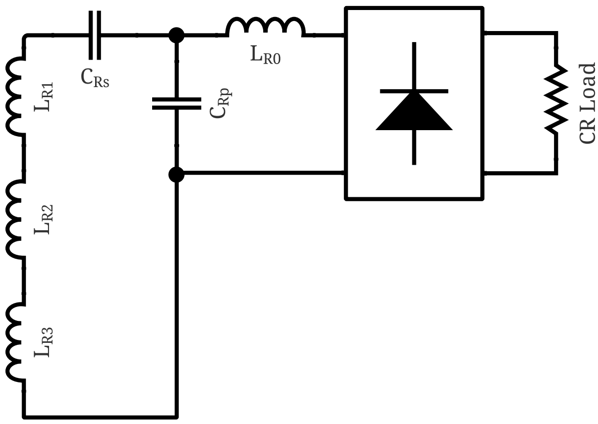


Fig.3 Series Multi-Pad Receiver

3. Theoretical Analysis of the Circuit

3.1. Impedance of WPT Circuit with Multi-Pad Receiver

Consider the admittance viewed from the power supply V_1 in the situation shown in Fig. 4, where each of the three receiver coils is coupled to the transfer coil. However, resonance misalignment and internal resistance are not considered in this section. First, in the case of the Independent Multi-Pad Receiver, the admittance viewed from the power supply V_1 is expressed as in equation (2).

$$Y_{in} = \frac{R_L}{(\omega L_{T0} L_{R0})^2}(M_1^2 + M_2^2 + M_3^2) \quad (2)$$

This is equivalent to the admittance of the general Double-LCC circuit shown in Fig. 1 when connected in parallel. At this time, the power supplied from V_1 is as shown in equation (3).

$$P_{in} = Y_{in} V_1^2 = \frac{R_L V_1^2}{(\omega L_{T0} L_{R0})^2}(M_1^2 + M_2^2 + M_3^2) \quad (3)$$

Next, the admittance from the power supply V_1 in the case of the Series Multi-Pad Receiver is shown in equation (4).

$$Y_{in} = \frac{R_L}{(\omega L_{T0} L_{R0})^2}(M_1 + M_2 + M_3)^2 \quad (4)$$

Similarly, the input power is obtained as in equation (5).

$$P_{in} = \frac{R_L V_1^2}{(\omega L_{T0} L_{R0})^2}(M_1 + M_2 + M_3)^2 \quad (5)$$

This is larger than equation (2) when the signs of all mutual inductances are the same. Therefore, it can be said that the Series Multi-Pad Receiver is able to obtain power more easily than the Independent Multi-Pad Receiver.

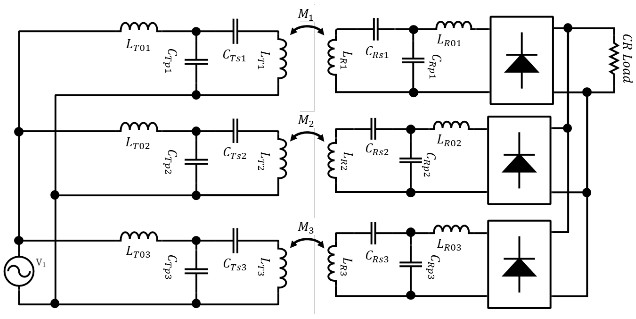


Fig.4 Multiple WPT circuit

3.2. Voltage Source Model of Cross-Coupling

The induced electromotive forces V_{MT} and V_{MR} generated in the power transfer coils and power receiver coils in WPT, respectively, can be expressed as equations (6) and (7). Let M_{TiRj} be the mutual inductance between the power transfer coils and the power receiver coils, M_{TiTj} be the mutual inductance between the power transfer coils, and M_{RiRj} be the mutual inductance between the power receiver coils, and let the coupling between themselves ($M_{TiTi}$and M_{RiRi}) be zero. Equations (6) and (7) show that each coupling can be written as a collection of current-controlled voltage sources.

$$V_{MT} = \sum_{j=1}^{m} j\omega M_{T_iR_j} I_{L_{R_j}} + \sum_{j=1}^{n} j\omega M_{T_iT_j} I_{L_{T_j}} \quad (6)$$

$$V_{MR} = \sum_{j=1}^{n} j\omega M_{T_jR_i} I_{L_{T_j}} + \sum_{j=1}^{m} j\omega M_{R_iR_j} I_{L_{R_j}} \quad (7)$$

3.3. Cross-Coupling between Transfer Coils

Fig. 5 shows WPT circuit configuration that takes cross-coupling between power transfer coils (Tx CC) and cross-coupling between power receiver coils (Rx CC) into account. Here, the power received by the receiving circuit is determined by V_{MR}, which is expressed by equation (8). As described in section 2.1, I_T has a constant current characteristic due to the gyrator characteristic of the LCC circuit, and V_{MR} has a constant voltage characteristic. In other words, even if an induced electromotive force is generated by Tx CC, I_T does not change and V_{MR} does not change. Therefore, the output P_{out} is not affected by Tx CC.

$$V_{MR} = \sum_{j=1}^{2} j\omega M_{T_jR_i} I_{L_{T_j}} \approx const. \quad (8)$$

On the other hand, equation (9) shows that I_{in} is affected. The final term on the right side is the term because of Tx CC, which causes an increase in I_{in} and phase shift, which is thought to reduce transmission efficiency.

$$I_{in} = \left\{ \frac{1}{r_{T0} + {(\omega L_{T0})^2}/{r_T}} + \frac{M_{T1R1}(M_{T1R1} + M_{T2R1})}{L_{T0}^2 Z_R} + \frac{M_{TT}}{j\omega L_{T0}^2} \right\} V \quad (9)$$

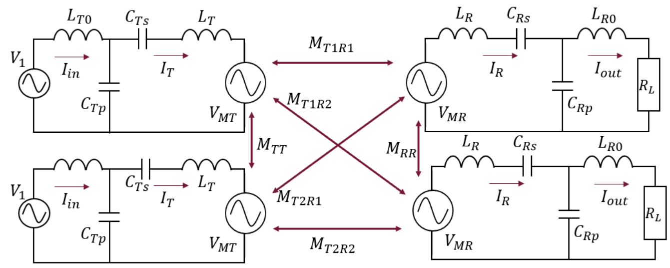


Fig.5 WPT Circuit with Cross Coupling

3.4. Cross-Coupling between Receiver Coils

3.4.1. Independent Multi-Pad Receiver

Next, cross-coupling between power receiver coils (Rx CC) of Independent Multi-Pad Receiver is considered. V_{MR} is expressed as in equation (10), showing that the change in I_R due to CC affects the output. Also, since I_R changes with Rx CC, V_{MT} is also affected, which in turn affects efficiency.

$$V_{MR} = j\omega M_{TR} I_T + \sum_{j=1}^{m} j\omega M_{R_iR_j} I_{L_{R_j}} \quad (10)$$

3.4.2. Series Multi-Pad Receiver

The minimum circuit configuration in a Series Multi-Pad Receiver that considers cross-coupling between the power receiver coils is shown in Fig. 6. V_{MR} is a composite of the induced electromotive forces generated in the two power receiver coils and is expressed as in equation (11)[13]. Equation (11) shows that Rx CC affects only the inductance value of the entire power receiver coil. Therefore, it can be adjusted by the element value of the LCC circuit in the subsequent stage, and if the resonance conditions are met, the output and efficiency are unaffected.

$$V_{MR} = j\omega(L_{R1} + L_{R2} + 2M_{RR})I_R + j\omega(M_{T1R1} + M_{T1R2})I_T \quad (11)$$

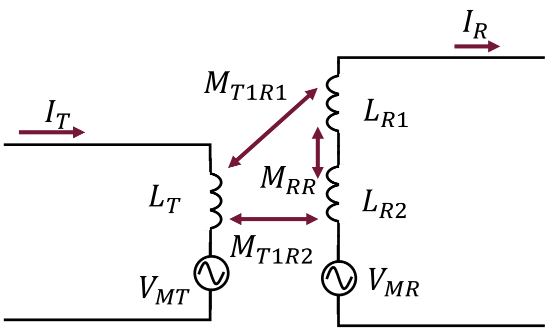


Fig.6 Series Multi-Pad Receiver with Rx CC

4. SIMULATION

4.1. Verification of Tx CC

Fig. 7 shows the transmission characteristics of Independent Multi-Pad Receiver with respect to Tx CC, where k_{TT} is the coupling coefficient of Tx CC. Fig. 8 also shows a similar diagram for a Series Multi-Pad Receiver. Figs. 7 and 8 show that Tx CC has little effect on the power characteristics as described in section 3.2. The effect on efficiency suggested in section 3.2 is also small.

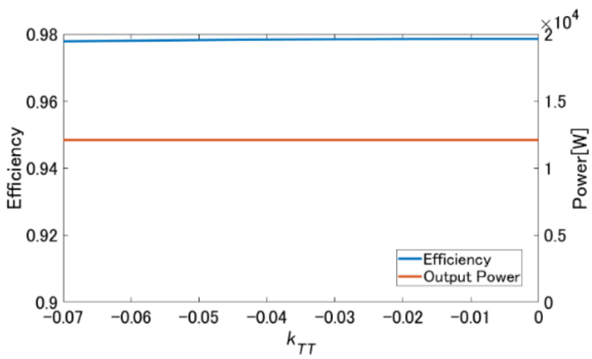


Fig.7 Effect of Tx CC on Independent Multi-Pad Receiver

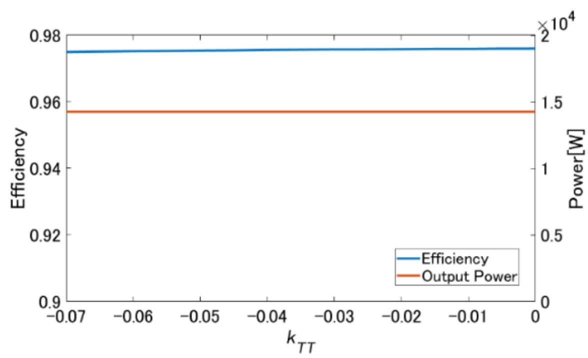


Fig.8 Effect of Tx CC on Series Multi-Pad Receiver

4.2. Verification of Rx CC

4.2.1. Independent Multi-Pad Receiver

Fig. 9 shows the transmission characteristics of Independent Multi-Pad Receiver with respect to Rx CC, where k_{RR} is the coupling coefficient of Rx CC. From Fig. 9, Rx CC has a negative impact on the output characteristics, as described in section 3.3.1.

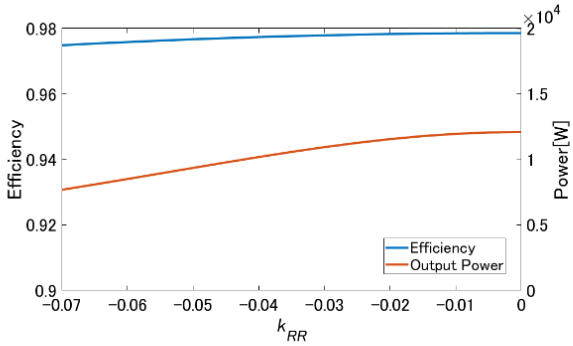


Fig.9 Effect of Rx CC on Independent Multi-Pad Receiver

4.2.2. Series Multi-Pad Receiver

Fig. 10 shows the transmission characteristics of Series Multi-Pad Receiver with respect to Rx CC, which shows that the power transmission characteristics of Series Multi-Pad Receiver are not affected by Rx CC, as described in Section 3.3.2.

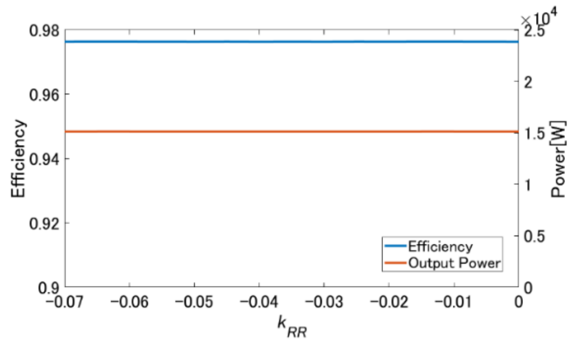


Fig.10. Effect of Rx CC on Series Multi-Pad Receiver

4.3. DWPT Simulation

To show DWPT characteristics for two receiver circuit, both the designs are simulated under the same operating conditions. Simulations were carried out for a system with five transmission circuits and three receiving circuits as follows, with two patterns of distances between the receiver coils (d_{RR}), 52.5 mm and 200 mm, to investigate the effect of CC between the receiver coils.

4.3.1. Simulation Conditions

A schematic diagram of the system to be simulated is shown in Fig.11. The various parameters used in the simulations are listed in Table 1. Here, the values of C_{Rs} are varied to satisfy equation

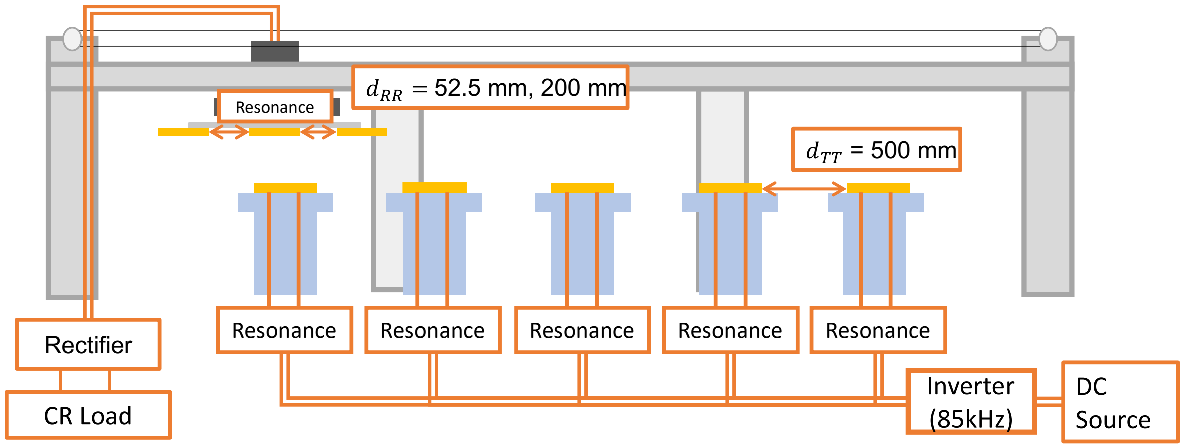


Fig.11 Schematic Diagram of the System to be Simulated

(1) due to differences in the circuit configuration. When d_{RR} = 200 mm, C_{Rs} is 27.9 nF. When d_{RR} = 52.5 mm, C_{Rs} is 29.87 nF. The input voltage V_1 set at 200 Vrms. A frequency of 85 kHz is selected as the transmission frequency f_{sw} for the prototype designed to follow the SAE standard(14). The load was a constant resistance load that obtained the most power and efficiency in the experiments described below. The coupling coefficient between the receiving and transfer coils varies between 0 and 0.12 depending on the misalignment of the receiver coil. The coupling coefficient of Rx CC was assumed to be 0 and -0.052 when the distance between the receiver coils was 200 mm and 52.5 mm respectively. The distance between the transfer coils was assumed to be 500 mm, which is the length of a transfer coil, and there was no Tx CC. These coupling coefficients were investigated by electromagnetic field analysis.

4.3.2. Independent Multi-Pad Receiver

The results of the DWPT simulation of the individual power receiving circuits are shown in Fig. 12 and 13. Fig. 12 shows the mutual inductance and the power transmitted and received when the distance between the receiver coils is 200 mm. Fig. 13 shows the mutual inductance and the power transmitted and received when the distance between the receiver coils is 52.5 mm. From Fig. 12 and 13, the power is higher when multiple receiver coils are coupled with the transfer coils.

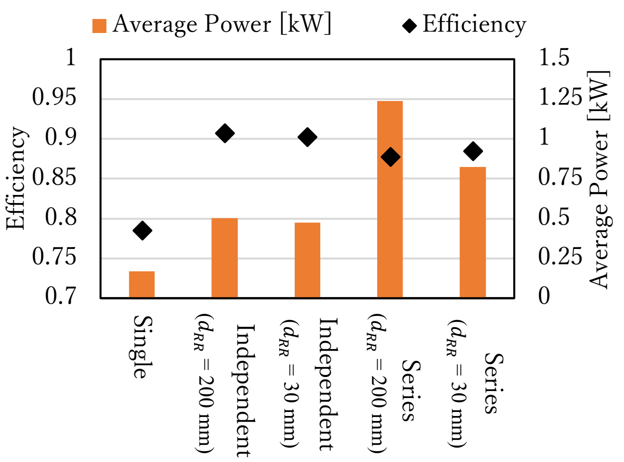


Fig.16 Efficiency and Average Power in DWPT Simulation

Table 1 Parameters of Simulation

Parameter	Value
V_1	200 V
f_{sw}	85 kHz
Receiver Velocity	60 km/h
Tx Coil Dimensions	500 × 200 mm
Rx Coil Dimensions	200 × 200 mm
L_T	205.8 uH
L_{T0}	49.3 uH
C_{Tp}	71.11 pF
C_{Ts}	22.4 pF
L_R	51.52 uH
L_{R0}	31.14 uH
C_{Rp}	112.6 pF
C_{Rs}	172.0 pF

4.3.3. Series Multi-Pad Receiver

The results of the DWPT simulation of the series multi-pad receiver are shown in Fig.14 and 15. Fig. 14 shows the mutual inductance and the power transmitted and received when the distance between the power receiver coils is 200 mm. Fig. 15 shows the mutual inductance and the power transmitted and received when the distance between the power receiver coils is 52.5 mm. From Fig. 14 and 15, the power is higher when multiple receiver coils are coupled to the transfer coils.

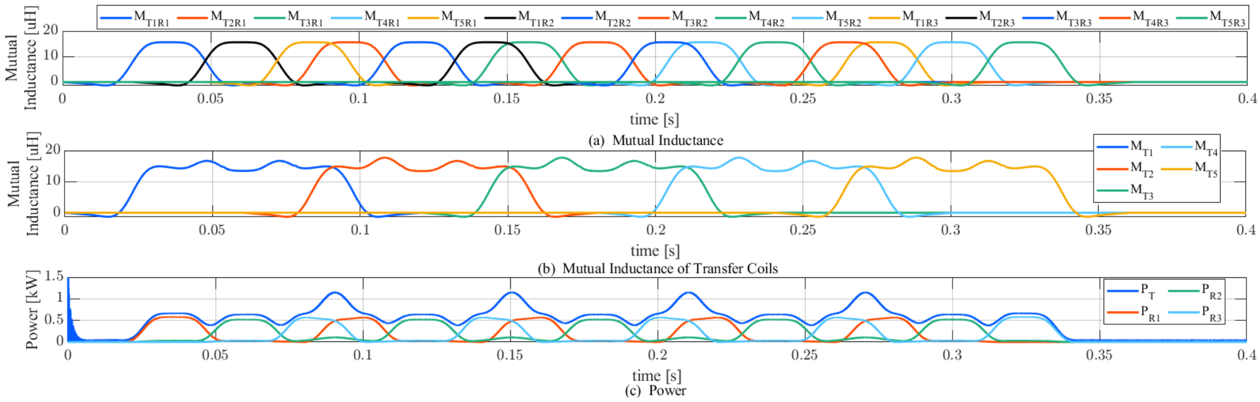


Fig.12 DWPT Simulation Result of Independent Multi-Pad Receiver (d_{RR} = 200 mm)

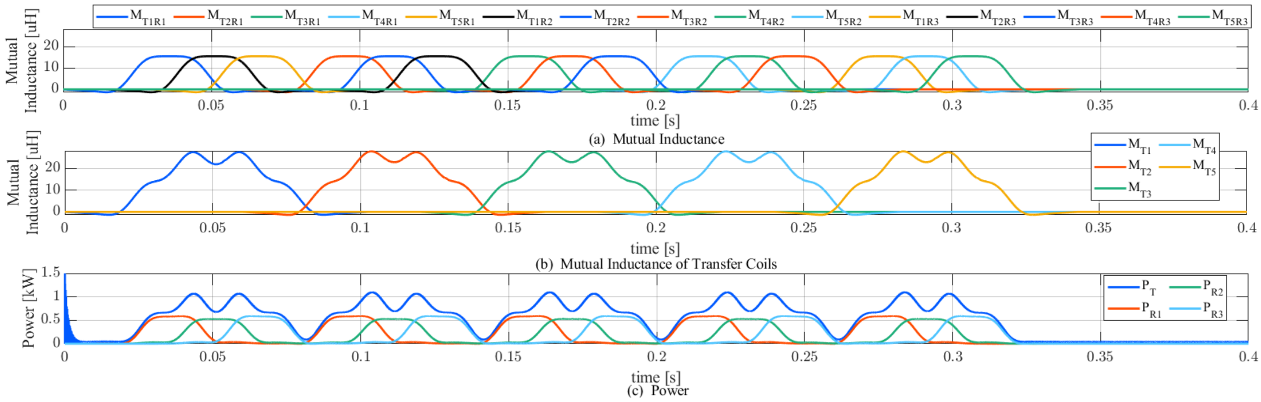


Fig.13 DWPT Simulation Result of Independent Multi-Pad Receiver (d_{RR} = 52.5 mm)

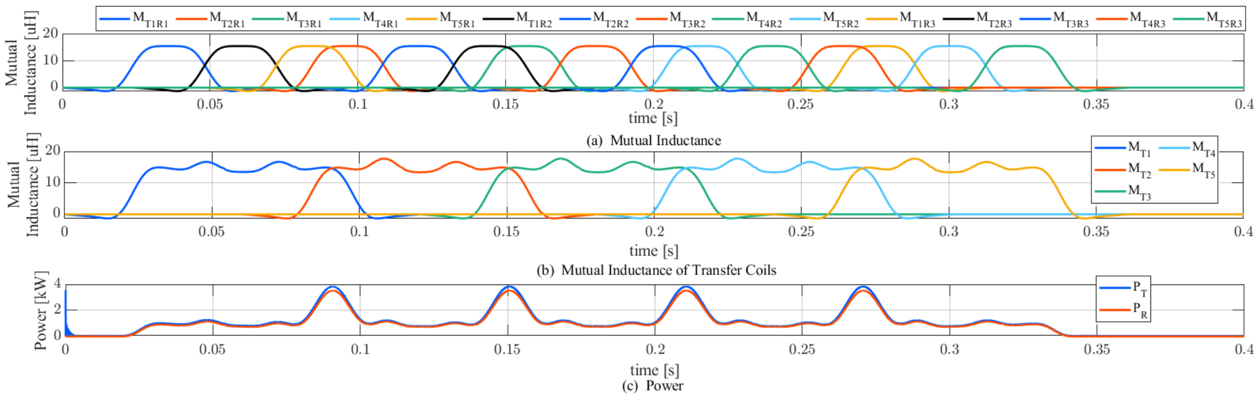


Fig.14 DWPT Simulation Result of Series Multi-Pad Receiver (d_{RR} = 200 mm)

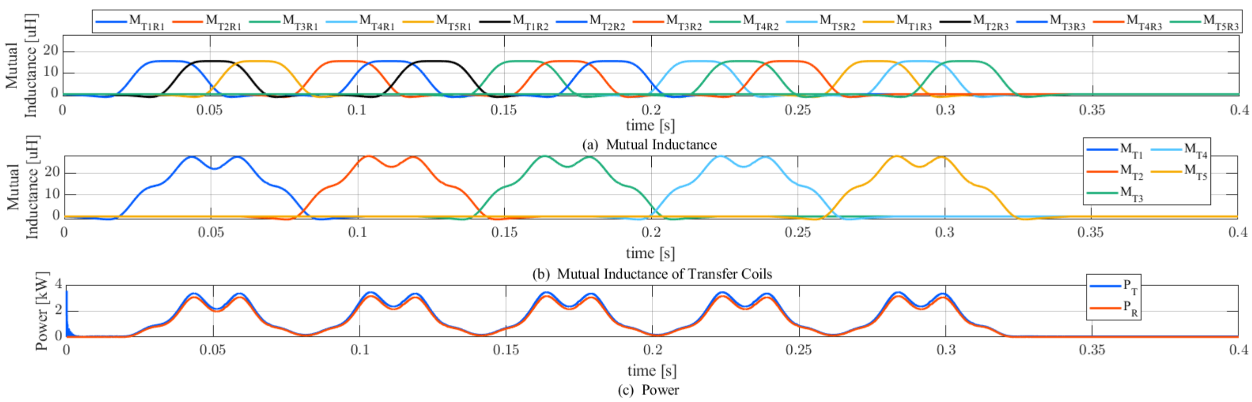


Fig.15 DWPT Simulation Result of Series Multi-Pad Receiver (d_{RR} = 52.5 mm)

4.3.4. Comparison of Simulation Results

The system efficiency and average power calculated from the simulation results are shown in Fig. 16. Average power is the integral over the entire range of power divided by the total time. Single Receiver is the simulation result for a single receiver coil. The system efficiency in Fig. 16a shows that a system with multiple power receiver coils can achieve an efficiency of around 90 %. The system efficiency also increases due to the wider range of power transmission with respect to the Single Receiver. The average power of the Independent Multi-Pad Receiver in Fig. 16b shows that the power of the Independent Multi-Pad Receiver is about three times that of the Single Receiver. It can also be seen that the Series Multi-Pad Receiver obtains even more power. In the Series Multi-Pad Receiver, the received power decreases when the distance between the power receiver coils is reduced, but this is due to the small maximum efficiency load and is not an effect of the Rx CC.

5. DWPT Experiment

A picture of the experimental prototype of the DWPT system with multiple power receiver coils is shown in Fig. 17. This is the same system shown in Fig. 11. The experimental prototype of the system, which is identical to the simulation carried out in Section 4.3, is shown in Fig. 17 with the power receiver coil units driving at 5 km/h in the direction from left to right. The circuit parameters added or changed from Table 1 are shown in Table 2. A constant

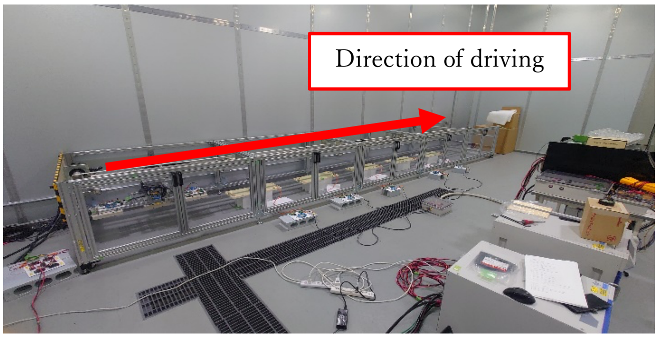


Fig.17 Testbench of DWPT

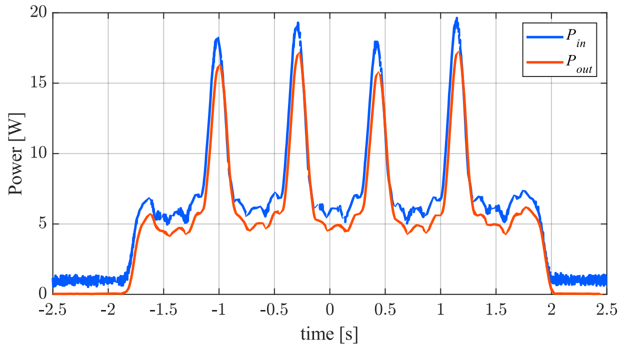
resistance load was used as the load, with the highest efficiency directly above the transfer coil.

Table 2 Experimental Parameters

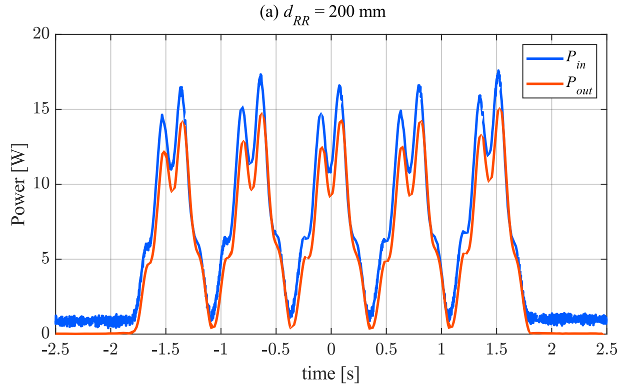
Parameter	Value
V_1	20 V
Receiver Velocity	5 km/h
Air Gap	94 mm

5.1. Independent Multi-Pad Receiver

The results of the DWPT simulation of the Independent Multi-Pad Receiver are shown in Fig. 18. Fig. 18a shows the power transmitted and received when the distance between the receiver coils is 200 mm and Fig. 18b shows the power transmitted and received when the distance between the receiver coils is 52.5 mm. Fig. 18 shows that, as in the simulation, the power is higher when multiple receiver coils are coupled to the transfer coils. Average

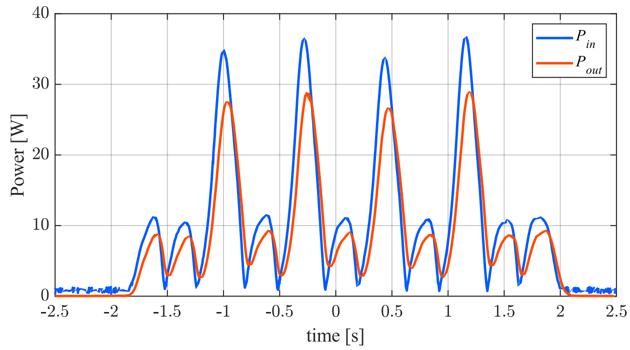


(a) d_{RR} = 200 mm

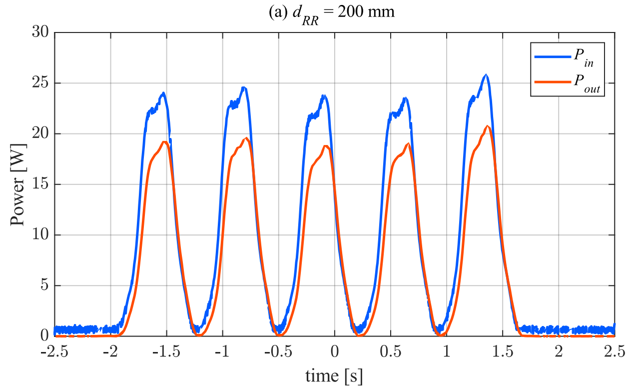


(b) d_{RR} = 52.5 mm

Fig.18 DWPT Experimental Results for Independent Multi-Pad Receiver



(a) d_{RR} = 200 mm



(b) d_{RR} = 52.5 mm

Fig.19 DWPT Experimental Results for Series Multi-Pad Receiver power was 5.34 W at d_{RR}= 200 mm and 5.21 W at d_{RR}= 52.5 mm. Efficiency was 0.872 at d_{RR}= 200 mm and 0.809 at d_{RR}= 52.5 mm.

5.2. Series Multi-Pad Receiver

The results of the DWPT simulation of the Series Multi-Pad Receiver are shown in Fig. 19. Fig. 19a shows the power transmitted and received when the distance between the receiver coils is 200 mm and Fig. 19b shows the power transmitted and received when the distance between the receiver coils is 52.5 mm. Fig 19 shows that, as in the simulation, the power is higher when multiple receiver coils are coupled to the transfer coils. It can also be seen that the peak power of the Series Multi-Pad Receiver is higher than that of the Independent Multi-Pad Receiver. Average power was 8.01 W at d_{RR}= 200 mm and 6.64 W at d_{RR}= 52.5 mm. Efficiency was 0.833 at d_{RR}= 200 mm and 0.772 at d_{RR}= 52.5 mm. At the same d_{RR}, about 27% to 50% more power was obtained for the Independent Multi-Pad Receiver.

6. CONCLUSION

The impact of cross-coupling on a system composed of Independent Multi-Pad Receiver and Series Multi-Pad Receiver was studied. The results indicate that the Double-LCC circuit exhibits strong resilience against cross-coupling in the power transfer coils. Furthermore, it was discovered that in the Series Multi-Pad Receiver, cross-coupling between the power receiver coils manifests as an alteration in the overall inductance of the receiver coils, which can be mitigated through tuning of the resonance circuit. Cross-coupling between power receiver coils constitutes a major obstacle in the design of power receiver coils layouts, and the utilization of a Series Multi-Pad Receiver can overcome this challenge.

Simulation and experimental results demonstrate that both the Independent Multi-Pad Receiver and Series Multi-Pad Receiver achieve adequate efficiency. The average power of the Independent Multi-Pad Receiver increased in proportion to the number of receiver coils, whereas the Series Multi-Pad Receiver exhibited a higher rate of average power increase.

Future work should address the smoothing of the received power when charging the battery and the potential for magnetic field leakage.

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REFERENCES

(1) Guri Natalie Jordbakke, Astrid Amundsen, Ingrid Sundvor, Erik Figenbaum, Inger Beate Hovi, “Technological Maturity Level And Market Introduction Timeline Of Zero-Emission Heavy-Duty Vehicles,” 2018.

(2) Kurs A, Karalis A, Moffatt R, Joannopoulos JD, Fisher P, Soljacic M, “Wireless Power Transfer Via Strongly Coupled Magnetic Resonances,” *Science*, vol.317, no.5834, pp. 83–86, Nov. 2007.

(3) Li S, Mi CC, “Wireless Power Transfer For Electric Vehicle Applications,” *IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS*, vol.3, no.1, pp. 4–17, Apr. 2015.

(4) Mahesh A, Chokkalingam B, Mihet-Popa L, “Inductive Wireless Power Transfer Charging For Electric Vehicles-A Review,” *IEEE Access*, vol.9, pp. 137667–137713, Sep. 2021.

(5) Yamada Y, Sasaki K, Imura T, Hori Yoichi, “Design Method Of Coils For Dynamic Wireless Power Transfer Considering Average Transmission Power And Installation Rate,” *2021 IEEE Southern Power Electronics Conference (SPEC)*,2021.

(6) Obayashi S, Shijo T, Suzuki M, Moritsuka F, Ogawa K, Ogura K, Kanekiyo Y, Ishida M, Takanaka T, Tada N, Takeuchi F, Take S, Yamauchi Y, Yang W-H, Kamiya Y, “85 KHz Band 44 KW Wireless Rapid Charging System For Field Test And Public Road Operation Of Electric Bus,” 2019.

(7) Jang YJ, Jeong S, Ko YD, “System Optimization Of The On-Line Electric Vehicle Operating In A Closed Environment,” *Computers and Industrial Engineering*, vol.80, pp. 222–235, 2015.

(8) Varghese BJ, Zane RA, Kamineni A, Tavakoli R, Pantic Z, Chou C, Liu L, “Multi-Pad Receivers For High Power Dynamic Wireless Power Transfer,” *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*,2020.

(9) Imura T, “Cross-Coupling Canceling Method For Wireless Power Transfer Via Magnetic Resonance Coupling,” *IEEJ Transactions on Industry Applications*, vol.134, no.5, pp. 564–574, 2013.

(10) Li X, Zhang Z, Si W, Wang R, Liang Z, “Analysis And Optimization Of Equivalent Load For Multichannel Transmission Of Wireless Power Transfer,” *IEEE TRANSACTIONS ON MAGNETICS*, vol.57, no.2,2021.

(11) Sasaki K, Imura T, “Combination Of Sensorless Energized Section Switching System And Double-LCC For DWPT,” *2020 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*,Nov. 2020.

(12) Li S, Li W, Deng J, Nguyen D, Mi CC, “A Double-Sided LCC Compensation Network And Its Tuning Method For Wireless Power Transfer,” *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY*, vol.64, no.6, pp. 2261–2273, Aug. 2015.

(13) Kawakami T, Imura T, Hori Y, “Basic Study On The Distance Between Receiving Coils For Dynamic Wireless Power Transfer To Heavy Vehicles,” Pp. 29–34 in *Technical Committee on Semiconductor Power Converter IEEJ Industry Applications Society*. 2022.

(14) SAE International, “Wireless Power Transfer For LightDuty Plug-In/Electric Vehicles And Alignment Methodology J2954,” Oct. 2020.