Analysis of Symmetric Two and Four-coil Magnetic Resonant Coupling Wireless Power Transfer

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***Abstract* –** This study examined the efficiency of power transfer for two-coil and four-coil spiral magnetic resonant coupling wireless power transfer (WPT) using distance to coil diameter (D/d_m) ratio and reflection coefficient, S_{21} value. Adding resonators reduced the total resistance in the two-coil WPT system while increasing the S_{21} values of the whole system. A same-size spiral coil was proposed for the system and simulated using computer simulation technology (CST). A prototype with similar specifications for a four-coil design was implemented for verification. The proposed method yielded an optimal efficiency of 76.3% in the four-coil system, while the two-coil WPT yielded a 23.2% efficiency with a 1.33 D/d_m ratio.

***Index Terms* –** Two-coil, four-coil, resonator, wireless power transfer.

I. INTRODUCTION

The wireless power transfer (WPT) technology uses a physical electromagnetic field to transmit energy. WPT was initiated by Nikola Tesla between 1891 and 1904. Tesla's WPT generated high alternating current using inductive coupling. In his experiment, Tesla lit three lamps at a 100-ft transfer distance using "Tesla Tower" [1]. Today, WPT is highly sought after for charging small electronic devices.

In 2007, the Massachusetts Institute of Technology (MIT) powered a 60-W light bulb ata 2-m distance from a transmitting coil via WPT [2]. This technology continued to expand in 2012 as the US Transportation Department used WPT to charge vehicles on railways and highways [4]. Studies on WPT are undertaken across many countries, particularly in the US, South Korea, China, and Japan [3, 4]. The ever-increasing demand for modern electronic devices (e.g., electric vehicles, mobile phones, and smart watches) becomes a driver for WPT, especially after its adoption for multiple applications.

Despite its high demand, WPT cannot transfer power over a long distance. Deterioration of power transfer efficiency (PTE) when distances exceed the coil diameter [21, 23]. This drawback may be resolved by incorporating an impedance matching network or inserting more loops except for a bulky outlook [2].

This study assessed the PTE of magnetic resonant coupling (MRC) WPT using two-coil and four-coil systems of the same size but without variable impedance matching. This MRC system consisted of

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two independent coils,i.e., receiver and transmitter resonating together. Both coils were wirelessly separated by air. Identifying the attributes of the magnetic field was essential since MRC depended on the magnetic coupling. Specifically, the magnetic field would substantially affect the coupling coefficient, mutual inductance, and, eventually, the overall MRC performance.

Apart from the design and shape, adding a resonator to each of the two coils was essential to enhance the system's efficiency [22, 24]. Adding two or multiple resonators generated a magnetic field and flux distribution of higher values, thus affecting system efficiency. A circular spiral coil shape was selected [7, 11, 13, 14, 20] in this study due to its exceptional performance. With less resistance,this spiral coil improved the mutual inductance value. Adding a resonator to the transmitter and receiver would increase the intensity of the magnetic field MRC, improving the power transfer capability. Enhancing the power transfer capability would increase the coverage of effective distance. Recognizing the importance of embedding a resonator to MRC, this study incorporated two and four spiral coils to assess their effects on MRC performance based on S_{21} values using via computer simulation and experimental validation.

II. MUTUAL INDUCTANCE, REFLECTION, AND TRANSMISSION COEFFICIENT

Mutual inductances happen when the magnetic flux from a transmitter coil cuts across the receiver coil to induce the voltage and current in the receiver coil. In some cases, the leakage inductance exceeds the mutual inductance in a loosely coupled system, reducing the magnetizing flux [1, 3].

Figure 1 shows the resonant coupled four-coil system as an analogous circuit model using lumped parameters (L_i, C_i, and R_i). The interactions of the transmitter and receiver coils are the most crucial for power transfer, and the efficiency is virtually determined by the distance between them. When all four coils resonate together, their inductive and capacitive reactance become equal, allowing the receiver coil to cut the oscillating field created in the transmitter coil sufficiently to transmit the power to the load. Therefore, the mutual inductance, M, and the coupling coefficient, k, are related by following equation:

$$M = kvL_1L_4, \tag{1}$$

where L_1 is the inductance of the receiver coil and L_4 is the inductance of the transmitter coil. Higher M means higher efficiency of the MRC. Meanwhile, the reflection coefficient, S_{11}, denotes the amount of power reflected from the receiver to the transmitter, whereas the transmission coefficient, S_{21}, signifies the amount of power transmitted to the receiver from the transmitter. Therefore, a lower return loss generates a higher S_{21} and promotes more power transfer.

The S_{21} parameter [eqn(2)] below is used to compute PTE

$$S_{21}\text{dB} = 20\log S_{21}, \tag{2}$$

$$n_{21} = S_{21}^2 \times 100\%. \tag{3}$$

Eqn (2) denotes S_{21} in dB value but converted to percentage in eqn (3) to compare performance. Therefore, this study measured S_{21}, inductance, and k of the system for investigating the performance of MRC with two-coil and four-coil WPTs. Several methods are used to determine inductance. They include Maxwell formula, Grover's method, Neumann's integrals, and finite element analysis (FEA) [1].

Several authors [3] attempted to derive accurate equations for$k$, yielding complicated formulas due to the complexity of the coupling mechanism in multi-turn structure [1, 3]. In general, knowing the frequency range of the application is crucial. At very low frequencies, the capacitive (electric) coupling also affects k [2]. Thus, a full-wave simulation remains essential for predicting the whole system's performance even though$M$ and $k$could be computed [using eqn(1)–(3)].

In this study, two software packages were used. The first was the FEA software known as An soft Maxwell (version x, name of developer, country). It determined k and M. The second one was the computer simulation technology (CST) software (version x, name of developer, country). It determined the S_{21} value. These software packages were used to model the MRC for the two-coil and four-coil in simulation in a three-dimensional (3D) environment. The FEA software was chosen because this technique did not require complex manual calculation while yielding consistent and reliable outputs for different types of systems.

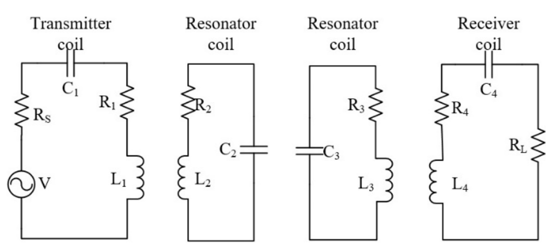


Fig. 1. The equivalent circuit model of a four-coil system.

III. METHODOLOGY

The comparative study impact of resonator on the performance of WPT was compared using An soft Maxwell. This software assessed the coupling factor effect on the WPT system. Figure 2 shows the plane view of the coil design for the two-coil and four-coil systems.

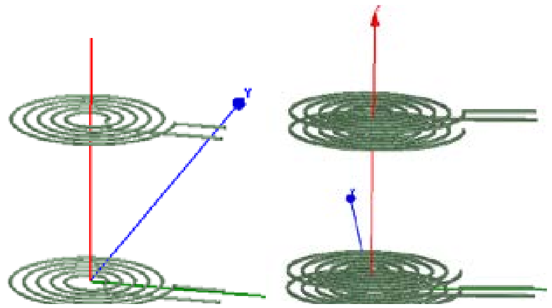


Fig. 2. The simulation of two-coil and four-coil systems using Ansoft Maxwell.

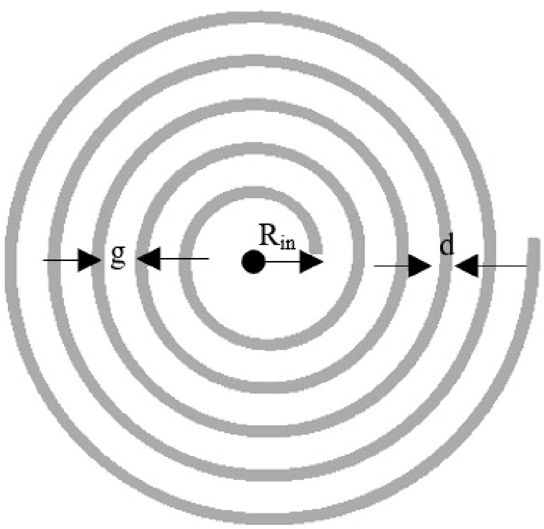


Fig. 3. The proposed geometry of the spiral coil.

Table 1 gives the specifications upon which coils were designed.

The radius of the wire and the coil thickness followed the exact Litz wire for small applications. Following the study of [11], no additional capacitor was added to tune the frequency of these coils for simultaneous resonance. PTE was compared with the CST software to assess the resonators' performance.

Figure 3 shows the geometry of the spiral coil geometry based on the parameters of Table 1 parameter use Litz wire as the coil prototype. Figure 4 shows the distance measurements for the two- and four-coil systems for simulations and experiments. For the four-coil system, the distance was measured from the transmitter's resonator to the receiver's resonator. The distance between the coils and the resonator for the transmitter and receiver was set at a maximum of 5 mm, and the distance varied from 5 to 7cm.

Table 1: The proposed coil parameters for the simulation

Coil parameter (cm)	
Wire diameter, d	0.1
Coil progress/gap, g	0.4
Inner radius, R_{in}	0.5
Number of turns, n	5

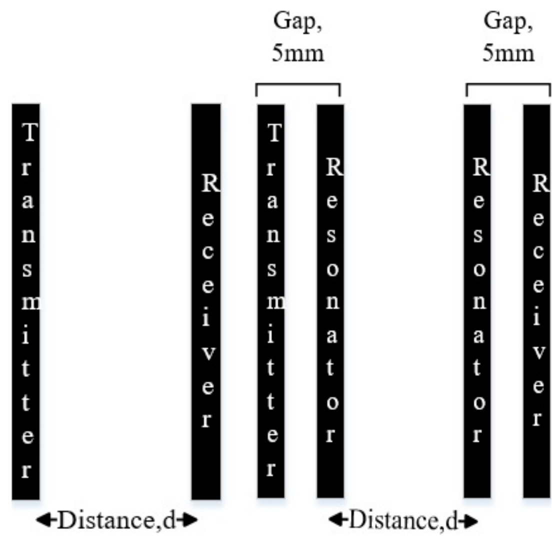


Fig. 4. The distance measurement for the two-coil and four-coil systems.

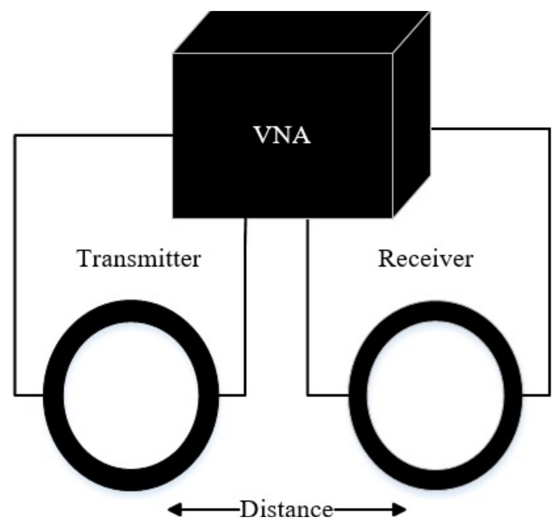
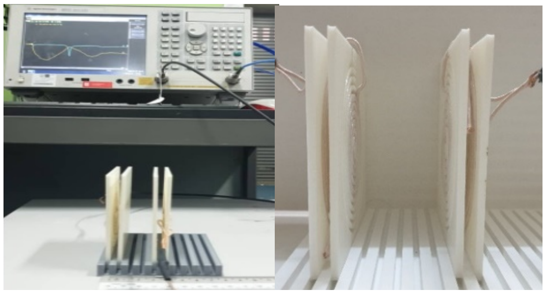


Fig. 5. The measurement setup.

Figure 5 shows the measurement setup for the experiments. The vector network analyzer (VNA) was connected to the transmitter and receiver for measuring S_{11} and S_{21}.

The distance from the receiving to the transmitting coils was altered manually. Values of S_{21} were recorded



(a) (b)

Fig. 6. The measurement setup for the four-coil MRC.

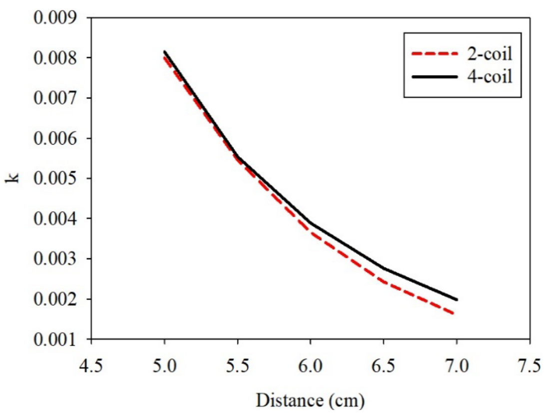


Fig. 7. Comparison of the coupling coefficient (k) for the two-coil and four-coil WPTs.

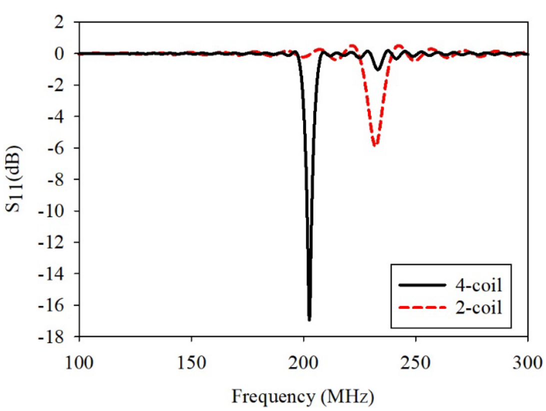


Fig. 8. The S_{11} parameter.

based on the distance variation. The performance of each system was experimentally evaluated using the setup of Figure 6.

IV. RESULTS AND DISCUSSION

Figure 7 shows the simulation of k for the two- and four-coil WPTs based on eqn (1). The values of

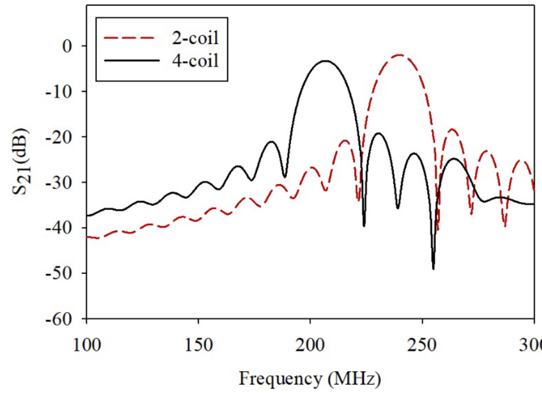


Fig. 9. S_{21} parameter.

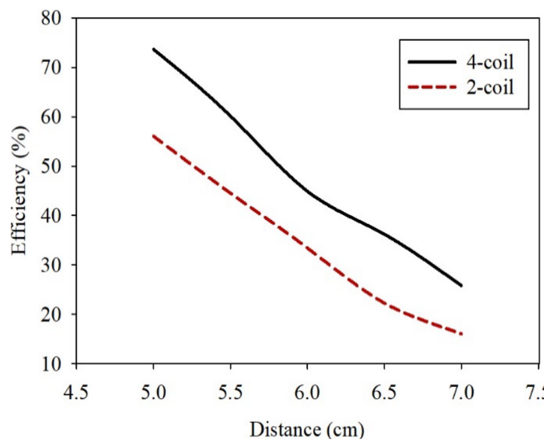


Fig. 10. Simulation results of the two-coil and four-coil systems.

k decreased exponentially when the distance increased. In general, the four-coil WPT performed better than the two-coil WPT.

The two-coil system results served as reference values to compare the improvement before and after incorporating the resonator. The CST material was composed of pure copper. The distance varied from 5 to 7 cm with a 0.5-cm increment.

Figures 8 and 9 show the simulation values of S_{11} and S_{21} for the two- and four-coil systems, respectively. In general, the four-coil WPT performed better than the two-coil system.

Figure 10 shows the simulation outcomes for both systems,yielding a 25.8% efficiency for the four-coil and a 16.0% efficiency for the two-coil system at a 7-cm distance. The four-coil system's efficiency increased by 9.8%, indicating that the resonator coil had enhanced the performance of the MRC system.

An experimental model was built to verify the accuracy of modeling. The coil was measured using VNA,

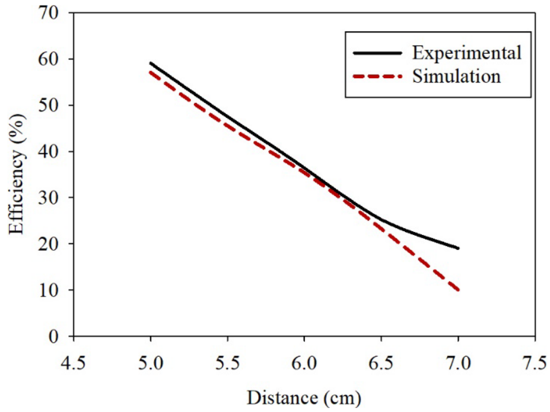


Fig. 11. Simulation and experimental results for the two-coil system.

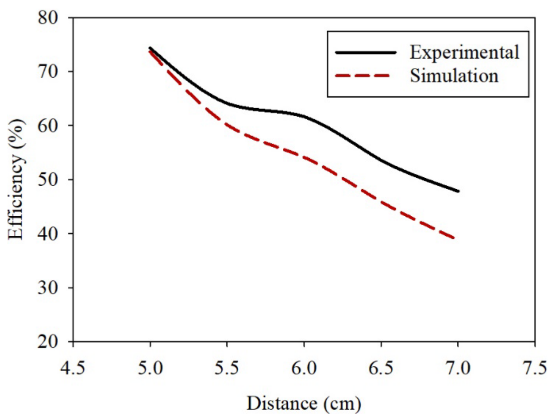


Fig. 12. Simulation and experimental results for the four-coil system.

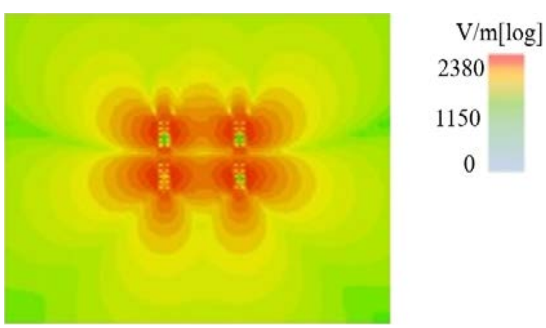


Fig. 13. The cross-sectional distribution of the electric field (E-field) at a 5-cm distance.

and the S_{21} value was recorded. The efficiency performance plotted against distance is illustrated in Figures 11 and 12 which show the efficiency performance versus the distance for the two- and four-coil systems, respectively. The system's efficiency improved by 24% when

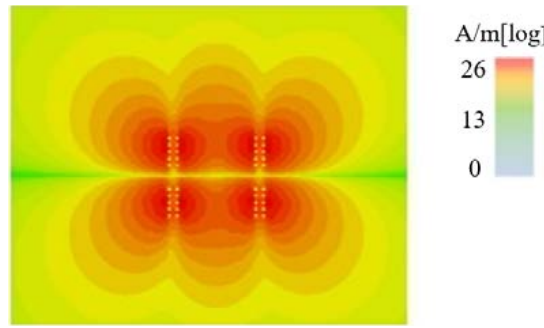


Fig. 14. The cross-sectional distribution of the magnetic field (H-field) at a 5-cm distance.

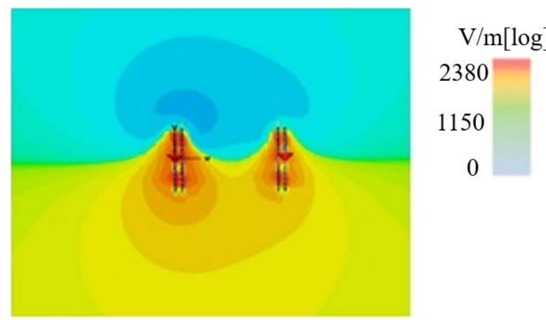


Fig. 15. The cross-sectional distribution of the electric field (E-field) view at a 7-cm distance.

the four-coil WPT was used. The efficiency exceeded 50% at a 6.5-cm distance, indicating that this design performed better even when the distance exceeded the coil size. This design performed better than several other systems (Table 2). In general, the efficiency deteriorates rapidly, not exceeding 0% if the ratio of distance (D) to coils is higher than the coil diameter, d_m [13]. Thus, PTE decreased substantially when $D>d_m$.

The coil used in the simulation consisted of copper, while the Litz wire was used in the experimental validation. Consequently, the simulation and the actual measurements varied slightly. A higher PTE for a longer distance was probably because the Litz wire could reduce the skin effect [11, 13], increasing the magnetic field.

Figures 13 and 14 show the cross-sectional distribution of the electric field (E-field) and magnetic field (H-field) of the four-coil system, respectively, based on the CST simulation at a 5-cm distance. Strong E-field and H-field were distributed and concentrated near the transmitter and receiver coils with the resonator.

Figures 15 and 16 show the cross-sectional distribution of the E-field and H-field of the four-coil system, respectively, based on the CST simulation at a 7-cm distance. A lower distribution of E-field and H-field indicated weak or low PTE.

Table 2: Comparison of the proposed design with related previous works

No	**Efficiency and distance**, D(cm)	**Coil type and size**, d_m (cm)	**Resonator type and size**, d_m (cm)	D/d_m	**Advantages/ Shortcoming**
1. (J. Zhang & Cheng, 2016)	30 cm distance with 55% PTE	Helical, 11 turns, 31.5	Helical, 11 turns, 31.5	D/d_m = 0.95	Big, bulky design
2. (Chung, Lee, Kang, & Park, 2016)	25cm distance with 80% PTE	Helical, 30	Helical, 30	D/d_m = 0.833	Resonator position varies to 15cm and 25cm from the transmitter PTE value not mentioned
3. (Dang & Qahouq, 2015)	50 cm distance with 85% PTE	Spiral, 10 turns, 40	Spiral, 10 turns, 40	D/d_m = 1.25	Big design
4. (Moghadam & Zhang, 2016)	100cm distance with 60% PTE	Planarized, 14	Planarized, 60	D/d_m = 1.67	Big design
5. (Jonah, Member, Georgakopoulos, & Member, 2013)	10 cm distance with 56.4% PTE	Circular copper, 10	Circular copper, 10	D/d_m = 1	Vary the position of resonator
6. (C. Zhang, Zhong, Liu, & Hui, 2014)	60cm distance with resonator in the middle 53.1% PTE, closer to receiver coil 69.3% PTE	Helical, 11 turns, 30	Helical, 11 turns, 30.	D/d_m = 2	Big, bulky design Resonator position 0.38 cm near to receiver coil
7. (Jolani, Chen, & Yu, 2015)	10cm distance with 83% PTE	Planar rectangular spiral, 2 turns, 5.9	Planar rectangular spiral, 5.9	D/d_m=1.67	3-layer planar resonator and loaded with capacitor
8. (Liu & Wang, 2016)	45 cm distance with 51.3% PTE	Helical, 11 turns, 11	Helical, 11 turns, 11	D/d_m = 4	Resonator position in the middle of transmitter and receiver. Big, bulky design with wire height 5.8cm
9. (Chin, Chung, Shuenn, Soon, &Lih, 2017)	1 cm distance with 19.1% PTE	Printed spiral coil, 3 turns, 0.5	Helical, 3 turns,0.5	D/d_m = 2	Efficiency is very low Bulky design Wireless implantable application
10. (Chen & Zhang, 2015)	15.2 cm distance with 70% PTE	Spiral, 10 turns, 5.5	Spiral, 10 turns, 12.5	D/d_m=1.22	Big design
11. This work	7 cm distance with 76.34% PTE	Spiral, 5 turns Transmitter= Receiver= 5	Spiral, 5 turns Resonator= 5	D/d_m=1.4	Same size of transmitter, receiver and resonator Resonator position is close to transmitter and receiver

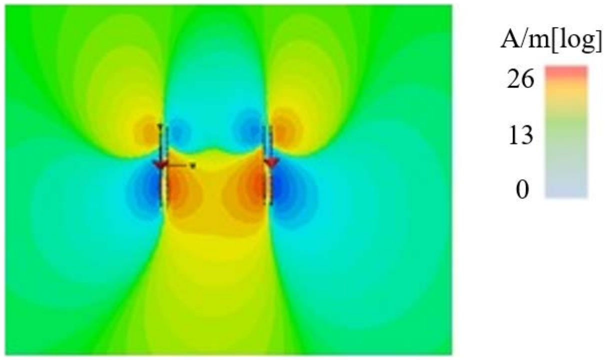


Fig. 16. The cross-sectional distribution of the magnetic field (H-field) view at a 7-cm distance.

The distance as a ratio of the coil diameter using the proposed design was 1.33 higher than the experimental result in the ratio (Table 2). The studies of [8] and [10] also yielded a higher ratio, but their bulky design was unsuitable for WPT applications. Likewise, the study of [11] yielded a higher ratio,but the system was optimized with a capacitor-loaded WPT with the resonator placed between the transmitter and receiver coils in [6]. Such an implementation is impractical for the actual application. By contrast, in this study, no capacitor was added to reduce the complexity in hardware implementation, thus yielding a small and compact design. Besides, both resonator coils in this study were similar in size, with the transmitter and receiver coils positioned close to both receiver and transmitter coils. The results appeared promising,with a consistent resonant frequency recorded despite the varied distance, along with improved PTE.

V. CONCLUSION

The design proposed in this study suits the MRC WPT concept with additional benefits in size and simplicity. This study recorded MRC WPT with a high PTE of 76.3% at a transfer distance exceeding 1.33 times the coil diameter. Overall,incorporating a resonator increased the PTE efficiency,enhancing the distance beyond the coil diameter, particularly when compared with the two-coil system.

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