Electrical Engineering Technical Journal, ISSN: 3007-9772, Vol. 2, No. 2, 2025, Pages 33-38
DOI: https://10.51173/eetj.v2i2.30

Electrical Engineering Technical Journal
Journal homepage*: http://eetj.mtu.edu.iq*

RESEARCH ARTICLE

Wireless Power Transfer for Biomedical Implants Using Series–Parallel Spider-Web Coil Configuration

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Article Info.

Article history:

Received
19 May 2025

Accepted
29 June 2025

Published in Journal
30 June 2025

Abstract

Biomedical sensors and implants are regarded as a significant technology for improving the quality of healthcare, as they enable proactive illness management and ongoing monitoring of the patient vital signs. Like many other devices, they are restricted to a limited amount of energy, and this leads to a challenge in terms of the lifespan of the device. This study aims to address this issue by designing and implementing a wireless energy transmission system specifically designed for such devices. The proposed design is based on utilizing spider-web and the series–parallel configuration to provide sufficient energy transmission for the device. The model has been examined under various conditions, including changes to the transmission distance between coils, the source voltage level, and operating frequency. Examined performance metrics including the output DC voltage and power transfer, as well as the overall efficiency of power transfer, proving that the strategy is feasible. As many biomedical implants such as pacemakers required 5 volts to operate, the study target voltage was 5 V. Two source voltages (10, and 20 V) were demonstrated. The design was examined at six operating frequencies, ranging from 1.78 MHz to 6.78 MHz. The most acceptable results were achieved at 1.78 MHz. Power transfer efficiencies at a 10 mm transmission distance were 91.5% and 91.15% for source voltages of 10 V and 20V, respectively. The proposed design demonstrates high efficiency which is appropriate for powering BMI wirelessly.

Publisher: Middle Technical University

Keywords: Biomedical Implant; Magnetic Resonance Coupling; Spider Web Coil; Near-field Transmission.

1. Introduction

The spectrum of applications for wireless power transfer (WPT) technologies is growing and now includes consumer-grade electronics, electric vehicles, and drones [1, 2] and even biomedical sensors as well as biomedical implants [3]. One of the foremost difficulties with biomedical implants (BMIs), rest in the dependency on batteries, which pose risks of chemical leakage within the body as well as being limited in capacity, lifespan, and posing potential battery surgical replacement risks [4]. So not only do these batteries put patients at risk of suffering repeated life-threatening infections and enduring complications—such as bleeding—and add to the growing health care expenditure, they also undergo the risk of needing numerous healthcare interventions [5]. These issues underscore the growing importance of WPT as a viable alternative to conventional battery reliance. In general, WPT involves the transmission of electrical energy from one point (i.e., transmitter) to another (i.e., the receiver) without the use of physical connectors or wires [6]. The general classification of WPT systems can be subdivided into two broad categories, including a far-field radiative techniques and near-field non-radiative techniques. Far-field techniques focus on the use of electromagnetic radiation, such as microwaves or radio frequencies, that propagate through space [7, 8]. In contrast near-field methods deliver power wirelessly through a tight coupled fields and woks on short ranges mainly based on magnetic induction and capacitive coupling [9]. As pointed out in several related studies [10], BMI and BMS systems are based on near-field wireless power transfer techniques for energy harvesting and transmission. Mahmood et al. [11] focused on developing an MRC WPT system specifically designed for wireless powering of a heart rate monitoring sensor. The focus of the study was on the performance evaluation of different coil configurations, which included spiral coil as both transmitter and receiver, spider as both transmitter and receiver, and spiral coil on the transmitter side with spider topology as a receiver. System-level integration was aimed not only at the transmitter and receiver coils but also included an Arduino, wireless transceiver module, and a dedicated monitoring unit for real-time data acquisition and transmission. Among the examined setups, the spiral–spider configuration proved the most dominant, with 87% power transfer efficiency achieved over a 5 cm transmission distance of 10 watts output power. These results clearly demonstrate that optimal coil topology design markedly improves the efficiency and effectiveness of WPT systems, especially when deployed for biomedical sensing applications. Ahire et al.[12] presented a new WPT system design based on MRC technology for BMI applications. The design proposed a ferrite core coil and was focused on achieving maximum power transfer efficiency with minimum electromagnetic interference. The main aspects of their proposed design were on the optimization of the coil material and magnetic shielding techniques. Comparative analysis of coil materials, including copper, aluminum, and gold, were conducted to enhance the overall system performance. Moreover, an examination of the magnetic shielding role in boosting transfer efficiency was conducted. The results showed that the highest power transfer efficiency was obtained from gold coils. Our earlier research [13] introduced a WPT system capable of delivering efficient and stable energy suitable for charging BMIs, particularly cardiac pacemakers based on series–parallel configuration was employed due to its ability to maintain a consistent output voltage across a practical transmission distance—an essential requirement for implantable device applications. The system design further incorporates a spider-web coil structure, implemented using MRC techniques, to enhance energy transfer efficiency and stability within the biological environment. To facilitate effective power transfer over a realistic distance, the transmitter side implemented the topological pattern.

2. Materials and Methods

This study introduced the design and implementation of a wireless power transfer system based on MRC, termed as WPT based SP-SWC, specifically for BMI, such as cardiac pacemakers. The chosen design is based on spider-web coil and S–P topology. To facilitate effective power transfer over a realistic distance, the transmitter side implemented the series topological pattern [14] However, due to its current-source behavior, which makes it especially well-suited for secure and reliable battery charging in BMI applications, a parallel design was employed on the receiver side. The system delivers a stable DC output voltage suitable for safe and efficient wireless charging. The employed spider-web coil design is known for its low parasitic capacitance and high inductance, making it suitable for implantable devices [15, 16]. The outer diameter of the proposed transmitter SWC- coil was 8.5 cm, while the inner diameter was 6 cm with fourteen turns. While the outer diameter of the proposed receiver SWC- coil was 3 cm, while the inner diameter was 2.8 cm with four turns. Table 1 shows the main parameters of the proposed design. In addition to the transmitter coil, the transmitter-side equipment consists of zero-voltage switching (ZVS) Class-D differential-mode power amplifier within EPC9065 board, and operating voltage source. A digital function generator is used as a source of controlling the signal input by driving a spider-web transmitter coil and a tuned compensation capacitor. Figure 1 shows the main component of the proposed work. Although the receiving module includes a spider-web coil with an equivalent inductance, a resonance-providing compensation capacitor, diodes to rectify AC to DC, a filter capacitor, and a 1.12 kΩ resistive load. To ensure thermal stability during operation, a cooling fan was incorporated into the test platform. Resonant frequency capacitors were precisely determined for each operating frequency to achieve maximum energy transfer on both sides. A range of power supply voltages 10 V, and 20 V—were tested to determine the optimal performance conditions.

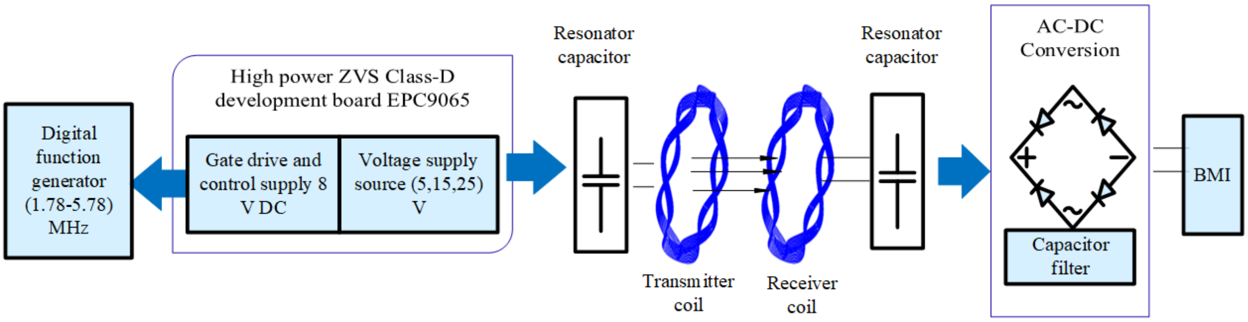


Fig. 1. The main component of the proposed setup.

TABLE 2: Key parameters of the proposed design.

Transmitter coil	Proposed value (Unit)	Receiver coil	Proposed value (Unit)
Outer diameter	8.5 (cm)	Outer diameter	3 (cm)
Inner diameter	6 (cm)	Inner diameter	2.8 (cm)
Number of turns	14 (turns)	Number of turns	4 (turns)
Operating frequency	1.78-6.78 (MHz)	Operating frequency	1.78-6.78 (MHz)

The performance parameters were studied under various source voltages, transfer distance, and operating frequencies to achieve optimal performance parameters, including output voltage, delivered power, and power transfer efficiency. The resulting data revealed that the system delivers a 5 V DC output voltage in experimental conditions suitable for charging BMIs. These findings validate the suggested strategy and its effectiveness in improving the durability and safety of battery-powered BMIs. Additionally, several operating frequencies were explored, with one MHz steps between 1.78 and 6.78 MHz. The results demonstrated that power transfer efficiency improved significantly at intermediate frequencies within the 10 kHz to 10 MHz range, consistent with prior research indicating this frequency band is both effective for near-field coupling and biologically safe [17]. Frequencies below 1 MHz were avoided due to the risk of excessive heat generation in close proximity, while the upper frequency limit of 6.78 MHz was selected based on the supported range of the development board, aligning with the lowest industrial, scientific, and medical (ISM) frequency band.

After configuring the system, measurements began with a 10 mm transmission distance between the transmitter and receiver coils, a 10 V source, and a 1.78 MHz operating frequency. The DC output voltage, delivered power, and power transfer efficiency were calculated based on the measured voltage and current. The transmission distance was then increased in 10 mm steps up to 100 mm, repeating the measurements at each distance. This process was repeated for source voltages of 10 V, and then across operating frequencies up to 6.78 MHz, to evaluate the impact of distance, voltage, and frequency on system performance. Figure 2 shows the experimental setup of the proposed design.

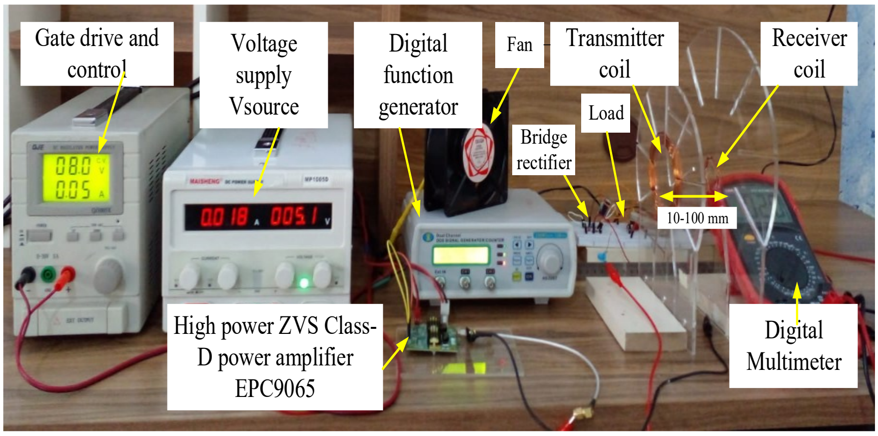
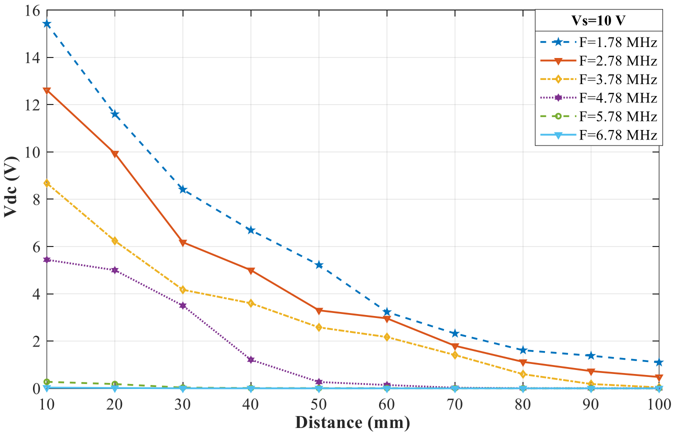


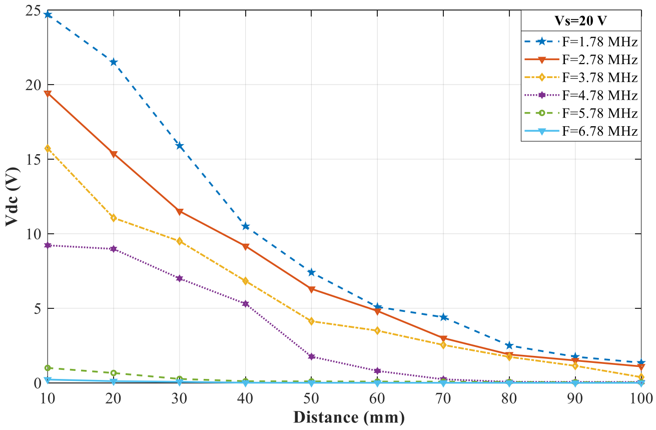
Fig. 2. Experimental setup of the proposed design.

3. Results

DC output voltages were measured using a multimeter for source voltages of 10, and 20 V across operating frequencies from 1.78 MHz to 6.78 MHz, and transmission distances ranging from 10 to 100 mm increments. Results showed that for a fixed frequency and distance, increasing the source voltage led to higher output DC voltages. The highest output voltages were observed at the shortest transmission distances, while increasing frequency generally caused a decline in output voltage. For example, at 1.78 MHz and a 10 mm transmission distance, the output voltages were 15.43 V, and 24.7V for source voltages of 10, and 20 V, respectively. At 2.78 MHz, output voltages dropped to 12.62V, and 19.43V for the same settings. As frequency increased to 6.78 MHz, a consistent decrease in output was observed, confirming that lower frequencies and shorter gaps yield better performance. Notably, 5 V output—targeted for biomedical implant charging—was achieved under specific low-frequency and low-gap conditions. When the transmission distance was 50 mm and the source voltage 10 V, the required voltage (i.e., 5V) was achieved. At the same time, when the transmission distance is 60 mm and the voltage source is 20 V, it can also be obtained. Figure 3. shows the performance metrics of the achieved result for the system, using the proposed design for various operating frequencies and various transmission distances. When the source voltages were 10, and 20 V. While the system's class-D amplifier offered high efficiency, it requires careful thermal and current management, especially at near distances. Future work may explore class-E amplifiers to optimize performance across wider frequency ranges and utilizing a hybrid coil in the setup.



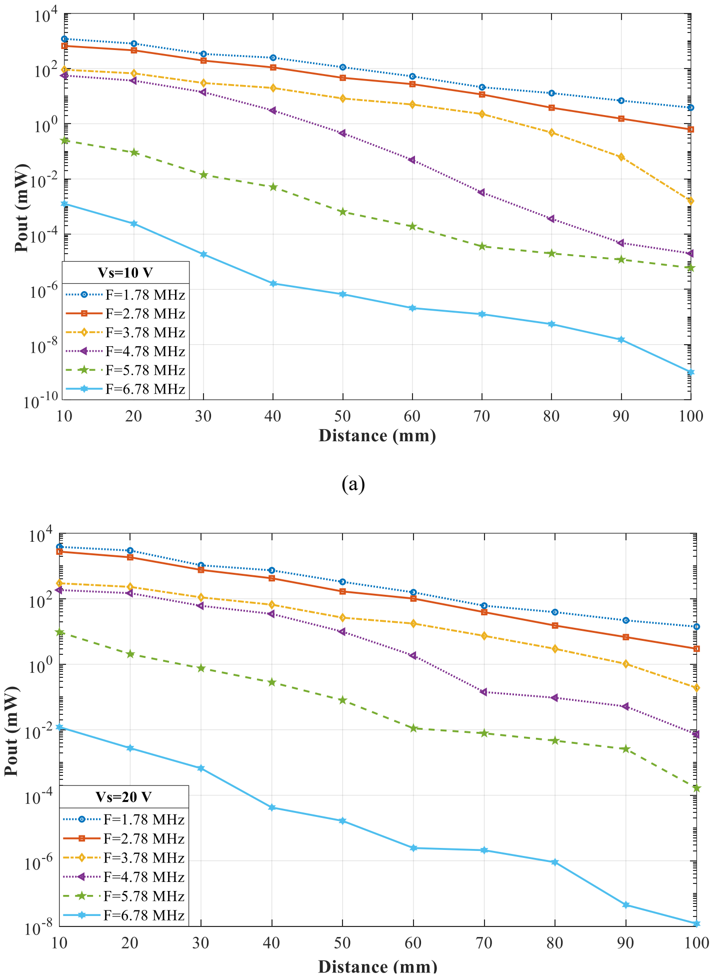
(a)



(b)

Fig. 3. Performance metrics of output DC voltage for the proposed system for all examined frequencies and transmission distances. Voltage source: (a) 10 V, and (b) 20 V.

However, corresponding to their use, BMI requires specific power requirement ranging from few microwatts to tens of milliwatts [18]. For this design the delivered output power was demonstrated according to the measured voltage and current. Figure 4 shows the delivered power against the transmission distance between the transmitter and receiver for the examined frequency.

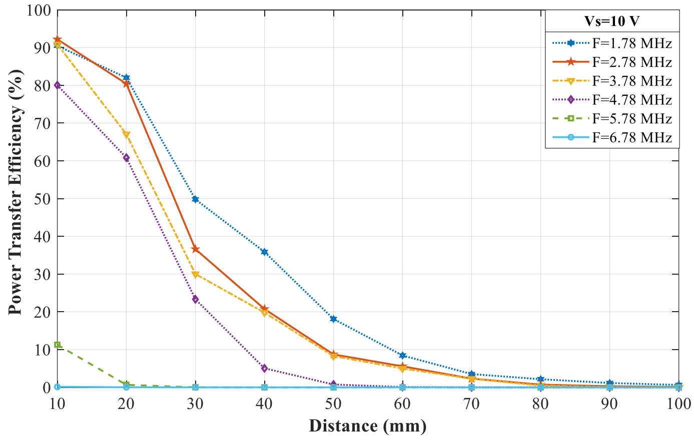


(a)

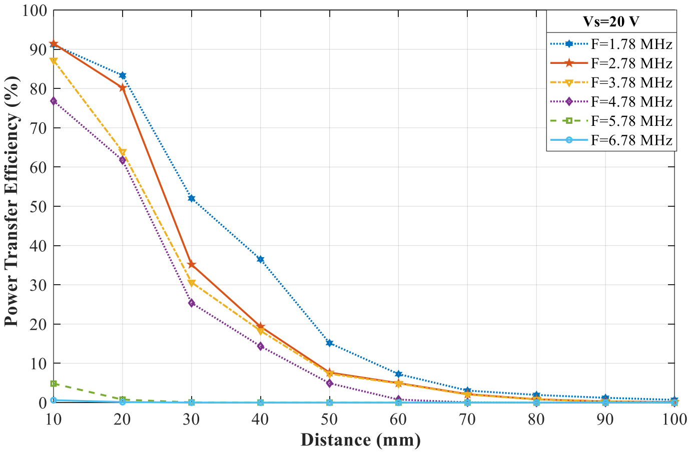
(b)

Fig. 4. Performance metrics of delivered output power for the proposed system for all examined frequencies and transmission distances. Voltage source: (a) 10 V, and (b) 20 V.

Besides the delivered power, efficiency is considered the most effective performance metrics of the medical application. Therefore, it was examined at all the tested frequencies and for the examined voltage source (i.e., 10, and 20 V). Figure 5 illustrates the efficiency of the proposed metrics for each examined parameter.



(a)



(b)

Fig. 5. Performance metrics for power transfer efficiency using for the proposed system for all examined frequencies and transmission distances. Voltage source voltages: (a) 10 V, and (b) 20 V.

4. Conclusion

This study presented the design, implementation, and evaluation of a wireless power transfer (WPT) system based on magnetic resonance coupling, aimed at wirelessly charging biomedical implants—specifically, cardiac pacemakers. The proposed SP–SWC system was experimentally tested under various conditions, including six operating frequencies, two input voltage levels (10, and 20 V), two coil designs, and ten transmission distance distances ranging from 10 mm to 100 mm. A fixed load of 1120 Ω, representative of typical pacemaker electrode resistance, was used throughout the experiments. Results demonstrated that the system successfully delivered the target 5 V output under several conditions, with shorter transmission distances and lower operating frequencies yielding the most efficient performance. For example, at 1.78 MHz, the required voltage was achieved at 10–50 mm (10 V), and up to 60 mm (20 V). However, as the transmission distance and frequency increased, a gradual decline in output voltage and transfer efficiency was observed. While the prototype was tested in air, future research will focus on evaluating performance in biological tissue, examining specific absorption rate (SAR), thermal effects, and safety compliance. In addition, future work will address the effects of coil misalignment—a common challenge in practical implant applications—on system reliability and power delivery. These findings contribute to the development of more reliable and efficient WPT systems for next-generation biomedical implants.

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