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RESEARCH ARTICLE - ENGINEERING

Powering Implanted Devices Wirelessly Using Spider-Web Coil

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Abstract

Implantable biomedical (IBM) systems and biomedical sensors can improve life quality, identify sickness, monitor biological signs, and replace the function of malfunctioning organs. However, these devices compel continuous battery power, which can be limited by the battery's capacity and lifetime, reducing the device's effectiveness. The wireless power transfer (WPT) technique, specifically magnetic resonator coupling (MRC), was utilized to address the limited battery capacity of IBMs. By using WPT–MRC, the device can obtain power wirelessly, thereby reducing the need for frequent battery replacements and increasing the device's potential. In this research, spider-web coil (S-WC) based MRC–WPT was conceived and carried out experimentally to enhance low-power IBM's rechargeable battery usage time. The presented S-WC–MRC–WPT design uses series–parallel (S–P) configuration to power the IBM. Both transmitter and receiver coils exhibit an operating oscillation frequency of 6.78 MHz. The paper reports on experiments performed in the laboratory to assess the performance of the proposed design in terms of output DC at three different resistive loads and transmission distances with alignment conditions among the receiver and the transmitter coils. Various transfer distances ranging from 10 to 100 mm were investigated to analyze the DC output current (Idc). Specifically, under a 30 V voltage source (VS) and a transfer distance of 20 mm, the DC output current was observed to be 330, 321, and 313 mA at resistive loads of 50, 100, and 150 Ω, respectively.

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Keywords: Current; Implantable Biomedical; Magnetic Resonant Coupling; Spider-Web Coil; Wireless Power Transfer.

1. Introduction

Over the last few years, WPT has been the focus of intense studies to simplify the diffusion of electric inventions into our lives. Examples include implanted medical devices, sensors, drones, robots, electric vehicles, and home electronic appliances [1-4].

Innovations in the IBM system augmented continuous observation, diagnosis, and treatment. IBMs have a considerable interest in realizing solutions to different medical cases. With increasing device complexity and sophistication, power consumption has increased. Therefore, one of the main challenges in IBM system development is providing sufficient power. The batteries used in IBMs have limited lifespans and fixed capacities and pose a hazard of chemical leakage into the body. Substituting these batteries can pose surgical complications, such as infection, haemorrhage, and anaesthesia reaction, in addition to the high surgery cost. This presents an obvious incentive to explore alternative solutions, such as WPT, to address these challenges [5, 6]. Instead of using ordinary cables, WPT technologies wirelessly transport energy from the main transmitter's primary power source to a receiver on the other side. This technology is based on the principles of electromagnetic field coupling, which allows energy transfer between two devices without physical contact [7, 8].

WPT can be achieved through two main methods: far–field (radiative) and near-field (non-radiative) wireless transmission. The far-field transmission uses electromagnetic waves propagating through space and covering long distances. In contrast, near-field transmission uses magnetic induction or electric fields to transfer energy over short distances [9, 10]. IBMs and biomedical sensor systems often rely on near–field wireless power transfer for energy harvesting and transmission. Near-field WPT utilizes several types of coupling, including inductive coupling, magnetic resonant coupling (MRC), capacitive coupling, and magneto dynamic coupling [11]. The primary categories of near-field WPT thoroughly explore the advantages, limitations, and associated equations for each WPT type extensively investigated in our research [12]. Moreover, the main advantage and disadvantages of the main near-field WPT categories of the three WPT systems are summarized in Table 1 [8, 9, 11, 13]. However, WPT can potentially revolutionize powering and charging devices, including IBMs. Moreover, the main topological models of wireless charging systems that including the (a) Series–series (S–S) topology, (b) series-parallel (S–P) topology, (c) parallel–series (P–S) topology, and (d) parallel–parallel (P–P) topology also were clarified with the calculation of each topology in [12].

Nomenclature & Symbols			
C	Capacitance Filter	R_X –S-WC	Receiver Spider Web Coil
GaN	Gallium Nitride	S–P	Series–Parallel
IBM	Implantable Biomedical	S-WC	Spider Web Coil
Idc	Output Current	T_X –S-WC	Transmitter Spider Web Coil
ISM	Industrial, Scientific, and Medical	WPT	Wireless Power Transfer
MRC	Magnetic Resonant Coupling	ZVS	Zero Voltage Switching
RL	Resistive Load		

Table 1. Comparison of different WPT technologies

Near-Field WPT Type	Advantage	Disadvantage
Inductive coupling	High efficiency at a short distance Suitable for biomedical applications when the distance between implanted Rx and outer Tx is small Simple configuration, versatile, and widely utilized	Limited range The heating effect at a high level of power. Needs fitted alignment Produces eddy current over metal Inappropriate for mobile use
Magnetic resonator coupling	High efficiency at medium distance Longer transfer distance reaching several meters Alignment is not a precondition suitable for mobile applications	Complex setup Decreased power transfer efficiency due to axial mismatch between the coils on the transmitter and receiver part
Capacitive coupling	High delivered power High transfer efficiency Power is transferred by metal Simple implementation	Short-range transfer distance Required large coupling area

By reducing the need for wires and batteries, WPT offers a more convenient and efficient way to power and charge devices while reducing the risk of complications associated with battery replacements [14]. In the existing research, the S–P topology is supposed to attain an appropriate current source characteristic suitable for powering the IBM battery signified by the load. In this paper, the S–P configuration is assumed to realize a suitable current source characteristic appropriate for powering the IBM battery represented by the load. S-WC coils are utilized on the advocated design's transmitter and receiver sides.

Moreover, choosing a suitable topology for WPT designs depends on the requisite functions. Therefore, the suggested design is based on S/P topology. However, selecting the series configurations on the primary side is essential for distance transfer. In contrast, the parallel configuration on the secondary side has current source attributes and is suitable for battery charging [15, 16].

The following are some of the critical contributions of the offered research:

- Using S-WC based on WPT-MRC involves an S–P topological approach designed and realized practically for powering IBM.
- The achieved DC output current was explored regarding supply voltage and transmission distances at three examined resistive loads.
- The adopted design effectively realized a DC output current that can power the IBM battery wirelessly.

2. Related Work

IBM significantly improves the quality of life for many individuals who have lost function due to injury, disease, or other medical conditions. IBM is designed to be surgically implanted into the body to replace or support a damaged biological structure and improve overall health. Most IBMs require power, such as pacemakers, left ventricular assist devices, defibrillators, and neurostimulators [17-19]. However, a tiny battery was implanted along with these IBMs. As IBM technology continues to advance, battery lifetime complications were considered. When the battery efficiency begins to decrease, the IBM may need to be replaced, or the battery may need to be recharged, corresponding to the type of the IBM. Various techniques of WPT were essential in supplying an efficient power to charge these IBMs. Fadhel et al. [8] propose a modified WPT system for medical implants to improve power transfer efficiency and reduce heating in the implant that operates at a frequency of 13.56 MHz. Their design uses a resonant inverter and a Class-E power amplifier to improve the performance metrics of the design. The design comprises a resonant receiver, transmitter circuit, and impedance-matching network. Their adopted coil design was a printed circuit coil. The system was tested in both simulations and experimental work. The results showed that the modified system achieved a maximum output power of 6.34 W with an efficiency of 75.1%. The system can be suggested to use various medical implants, including pacemakers and neurostimulators.

Ahire et al. [20] propose a novel WPT system based on MRC technology and uses a ferrite core coil for biomedical implant applications. The system attempted to increase transfer efficiency while decreasing electromagnetic interference. The design aims to improve the coil material and magnetic shielding methods. The design involved comparing coil materials such as copper, aluminum, and gold. The study investigated the effect of magnetic shielding on the efficiency of the WPT system. The results showed that the gold coils provided the best performance metrics regarding power transfer efficiency, and magnetic shielding significantly improved the WPT system transmission efficiency. Campi et al. [21] presented a resonant inductive coupling WPT system for deep IBMs such as neural implants. To transfer the power wirelessly through the skin and the tissue, the design uses two resonant coils, one implanted inside the body and the other outside—the primary coil selection based on a Helmholtz theory to achieve an approximately uniform magnetic field. The effectiveness of the suggested technology was confirmed by creating and evaluating three separate WPT coil demonstrators. The results show that their presented system can transfer power wirelessly to a deep cylinder-shaped shape with or without a metal case. Also, the results demonstrate that powering deep implants with titanium housing without needing a ferrite cover can also be accomplished.

Cetin et al. (2022) [22] suggested a WPT-MRC prototype converter utilizing LC-S configuration to charge a pacemaker wirelessly. The significant features of this topology are the small number of components and sound characteristics in the output current. The design considers the essential issues in the WPT system, efficiency, implantation, and safety. The system resonates at 300 kHz. The transmitter coil is in the air during the experiment, while the receiver coil is in a saline solution. Utilizing the lithium-ion battery in the study because of its high-power density. The study also involves discussions of the main safety issue of the prototype and comparing it with the previous studies. The results demonstrate that the power transmission efficiency is 82.39% for an eight-millimeter separating the receiver and transmitter coils. The results demonstrate that the power transmission efficiency is 82.39% for an eight-millimeter distance between the receiver and transmitter coil. From the reviewed articles, we demonstrated that many limitations and challenges are affecting the wireless power of IBM. Therefore, the S-WC–MRC–WPT design has been adopted in this study to overcome some of these issues. The study focuses on the output current needed to realize the load charging for three different values of the examined load.

3. Methodology

In the proposed design utilizing S-WC–MRC–WPT, an S–P topology was used to power the IBM system wirelessly, as shown in Fig. 1. The chosen technique was practically designed and implemented. The system oscillates at 6.78 MHz. To perform the optimal DC (Idc) sufficient for energizing IBMs wirelessly, under three different resistive loads and various values of voltage sources at various distances were investigated. This study proposes the proposed S-WC–MRC–WPT design to address the limited battery capacity in IBM devices through the presented design. However, the design employs a spider-web coil winding technique to charge the IBM battery wirelessly. Although slightly used in IBM charging designs, the S-WC winding technique offers low parasitic capacitance [23] and high inductance due to its large surface area. Experimental implementation and testing of the adopted design in various values of loads (50, 100, and 150Ω) and transmission distances between both investigated spider-web coils (extending from 10-100 mm in 10-mm increments) were conducted. For each test, three distinct resistive loads (50 Ω, 100 Ω, and 150 Ω) were chosen based on recommendations found in various research works about biomedical applications [24, 25]. The transmitter coil remained fixed through the experiment at the same time as the receiver location was adjusted. Various power values ranging from 5-60 V in 5-V steps were used to determine the optimal voltage for performance at each distance. A comparison was investigated amongst every supply at every single distance. The output current is initially assessed when the transmission distance is 10 mm, the supply voltage is 5 V, and the load resistance is 50 Ohms. The distance is then increased in ten-millimeter steps until the 100-mm of the air gap. These steps are repeated for each voltage value up to 60 V. Fig. 2 shown later, depicts the suggested experimental setting S-WC–MRC–WPT system. The implemented design of S-WC–MRC–WPT for biomedical implants utilizes the following adopted materials and methods:

- The S-WC form shape is made using transparent PVC sheets. Above the spider coil form, a copper coil with a diameter of 20 AWG has been wrapped with four turns coiled on the transmitter spider-web coil (T_X –S-WC) and three turns wrapped on the receiver coil (R_X –S-WC).
- For the T_X –SWX examined, the external and internal radii were 61 mm and 52.5 mm, respectively, while for the R_X –SWX, they were 57.5 mm and 52.5 mm, respectively.
- The self-inductance of R_X –SWX and T_X –SWX were 5 and 10 µH, respectively.
- All necessary equipment and supplies were set for both the transmitter and receiver sides.
- The adopted S-WC-MRC design aimed to provide sufficient voltage to supply the IBM system with sufficient power. It comprises the transmitter and receiver units with specific devices and tools to achieve the desired objectives.
- After preparing the whole design constituents, three investigations were carried out to assess S-WC–MRC's performance under different loads. The design system and parameters are clarified in more detail.

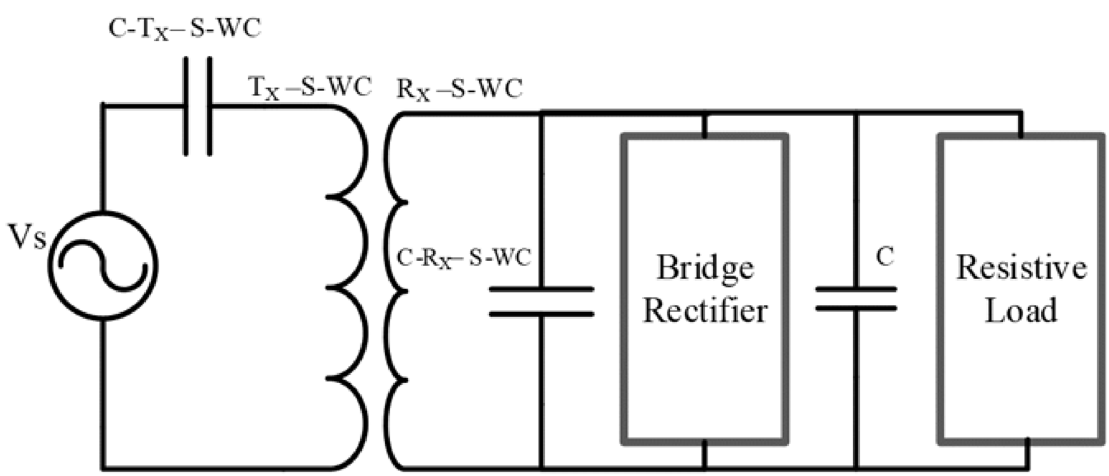


Fig. 1. Schematic diagram of the S-WC–MRC–WPT system using S–P configuration

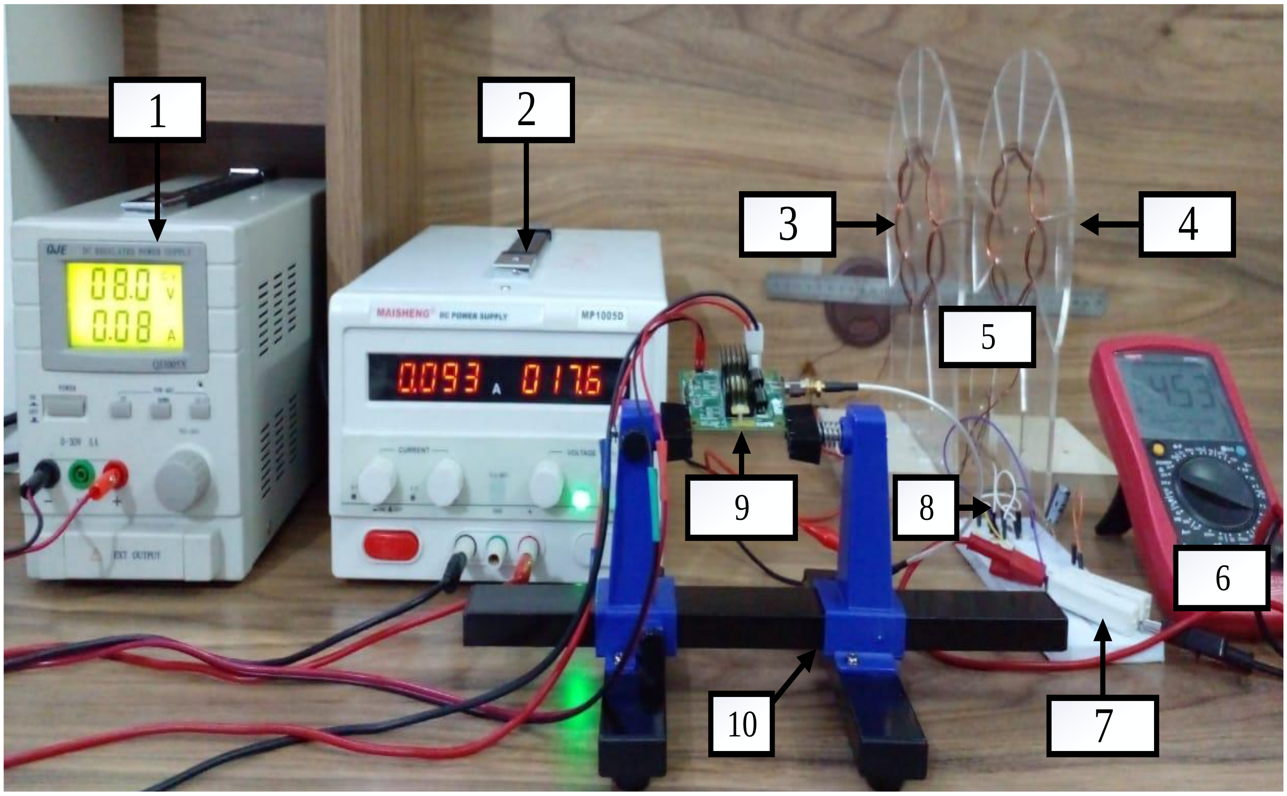


Fig. 2. Experiment Configuration of S-WC–MRC–WPT; (1– supply voltage of control and gates of the transistor's drive, 2– voltage supply, 3– transmitter coil, 4–receiver coil, 5– transmission distance, 6– digital multimeter, 7– load, 8– bridge rectifier, 9–high power ZVS class D power amplifier EPC9065, 10–holder

4. S-WC-MRC-WPT Implementation

The design methodology utilized for this project was based on S-WC-MRC and S–P configuration. The adopted S-WC–MRC–WPT system comprises transmitter and receiver units. The first unit involves a differential-mode amplifier utilizing Class-D power technology with zero-voltage switching (ZVS), two power supplies, a compensated capacitor, and TX–S-WC to transform the electric field into a magnetic field. On the other hand, the second unit consists of RX–S-WC for converting magnetic fields into electrical signals, a compensated capacitor, a bridge rectifier that characterizes by the small size and affordable price and is based on Schottky diodes supported by a filter, and a resistive load. The S-WC of the transmitter and receiver plays a crucial role in the system design. To achieve this, the power supply's produced DC is transformed into an AC sinusoidal generating a frequency of 6.78 MHz, utilizing Gallium Nitride (GaN) constructed power controlling technology with ZVS technology. The ZVS utilized in this configuration relies on the functionality of the EPC9065 development board. It operates at a frequency of 6.78 MHz and is not restricted to the lowest ISM band. The development board EPC9065 comprises dual DC power feeders, one to power the oscillator circuit and the other to power the GaN transistors. The development board EPC9065 manual [26] indicates that the 7.5V to 12V DC is employed for logic gates input voltage while the 80V is utilized for amplifier input voltage. In the presented work, the supply voltage of the transistor's gate is stable at 8 V, sufficient to run the drive transistors. The ZVS is linked to the transmitter directly, and the current passes over the T_X–S-WC coil, creating an electromagnetic induction that passes through the R_X–S-WC in the receiver circuit. Consequently, the R_X–S-WC coil induces a current, allowing the T_X–S-WC coil to transmit energy to the R_x–S-WC wirelessly.

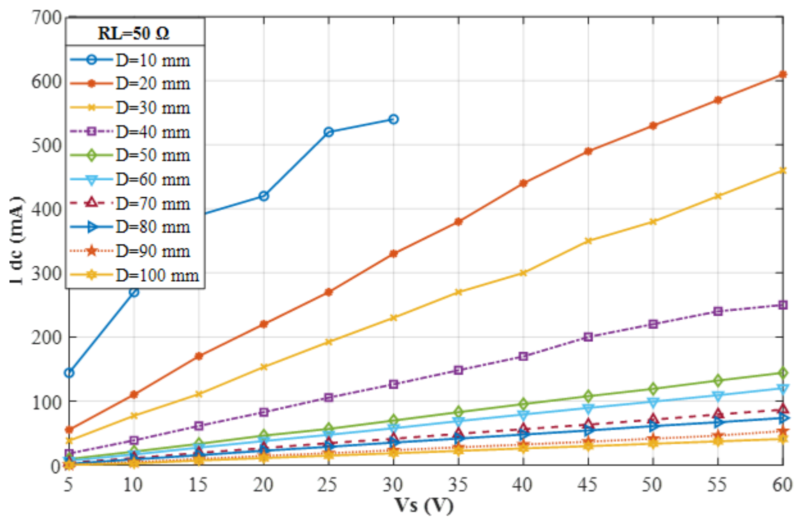
The transmission phase involves using a bridge rectifier, generating power that can be utilized. For efficient power transfer, the T_X–S-WC and RX–S-WC coils must resonate at the identical oscillating frequency [27]. The MRC technique has become increasingly prevalent for transferring power between two coils with a specific air gap for medical applications and implantable medical devices. Nevertheless, there is a loss of energy during the transfer from the TX–S-WC to the RX–S-WC coils, resulting in a reduced current within the RX–S-WC coil compared to the TX–S-WC coil.

5. Results and Discussions

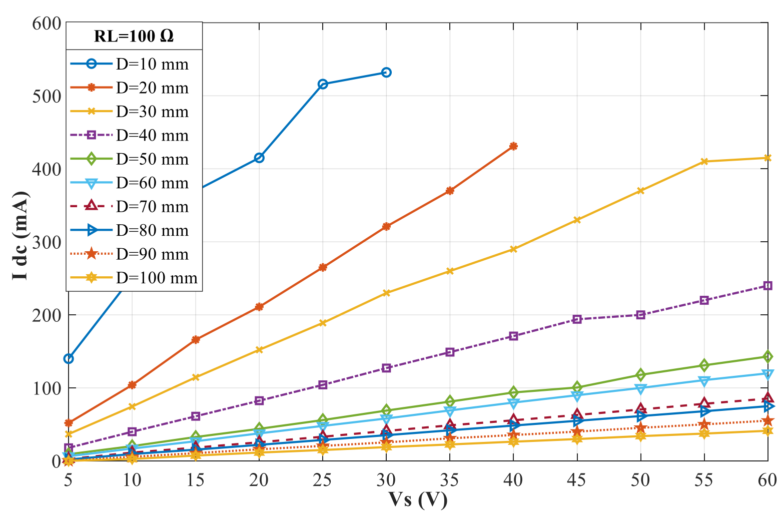
The experiment involved the wireless powering of biomedical implants using S-WC–MRC–WPT, and the results were demonstrated and measured experimentally. The analysis focused on the yield current at a resonance operating frequency of 6.78 MHz, which falls within the limit of the ISM band. Various combinations of voltage sources, transmission distance, and resistive loads were studied to determine the optimal DC voltage supply required for charging medical implants and measuring the related current following the adopted design. In the adopted S-WC–MRC–WPT technique, the DC yielded currents (Idc) were evaluated by multimeter within the framework of the suggested experiment, S-WC–MRC–WPT design in Section 4, Fig. 2. The V_S was changed from 5-60 V for every 5 V as a stepwise. The Idc was calculated for each value of V_S for three load tests.

Similarly, data was collected for ten different transmission distances between the transmitter and receiver coils. The range of this transmission distance varied between 10-100 mm with a step size of 10 mm. Figure 2 illustrates the relationship between voltage variation (VS) in volts, represented on the x-axis, and the corresponding direct current (Idc) measurement in milliamperes, depicted on the y-axis. An increment in Idc has been observed as the V_S increases from 5-60 V for a similar transmission distance. It was stated that reliable performance is attained when the transmitter and receiver are located near. As shown in Fig. 3a, when the examined load was 50 Ω, the transmission distance between the TX-S-WC and RX-S-WC coils was 20 mm, the V_S was 30 V, and the Idc measured 330 mA.

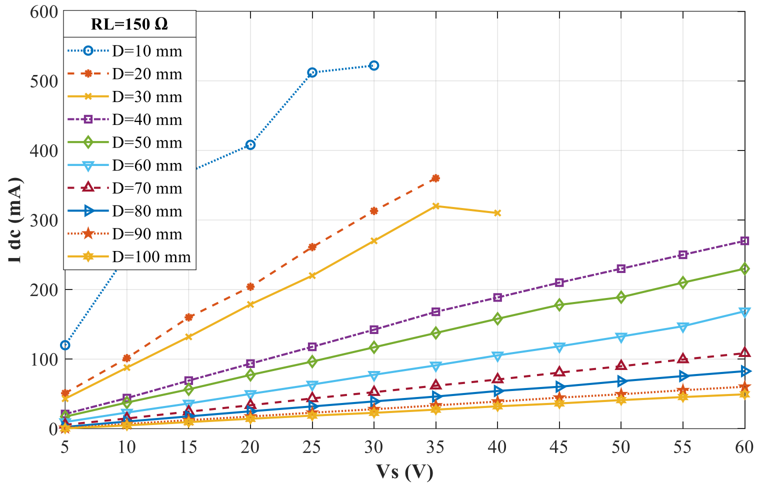
When the transmission distance is less than ten millimetres, the Idc decreases, and the V_S drops to 30 V at a load resistance of fifty ohms owing to increased internal heat. Fig. 3 reveals no Idc after 30 V of VS because when the transmission distance is less than 20 mm, the Idc is variant and unstable. In contrast, the measured Idc was 330, 321, and 313 mA for the 20 mm air gap, 30 V as V_S when the adopted technique is loaded by 50, 100, and 150 Ω, respectively. The performance evaluation of the S-WC–MRC–WPT was conducted by measuring the output current at various examined loads while maintaining a constant output voltage of 5 V. The Idc values were measured at distances of 60, 80, and 90 mm, corresponding to loads of 50 Ω (Fig. 3a), 100 Ω (Fig. 3b), and 150 Ω (Fig. 3c), respectively. These measurements were obtained under a V_S of 60 V. The body's safety limit for electromagnetic absorption is determined by the average Specific Absorption Rate (SAR) across a specified amount of tissue. Sedehi et al. [28] conducted a SAR analysis with a proposed power frequency of 6.78 MHz. The calculated SAR was within the maximum safe power rating, indicating that the potentially harmful effects on the human body are expected to be minimal. The input side link impedance for S–P topologies is relatively low at the resonant frequency, allowing a considerable amount of input current to pass through the primary coil inductance. As a result of the maximal magnetic field surrounding the coil, an appropriate induced voltage and current were produced in the secondary coil to recharge the biomedical implant battery. Because of their superior power transfer efficiency and ability to offer continuous current and voltage at the output, the S–P topology is one of the best suited for biomedical implant applications [29].



(a)



(b)



(c)

Fig. 3. The variation in DC output current concerning varied input voltages when the transmission distances range between 10-100 mm under three resistive loads (a) 50 Ω, (b) 100 Ω, and (c) 150 Ω

6. Conclusion

Different techniques have been developed to provide IBMs with efficient wireless power to work correctly and eliminate wired powering limitations. This work has been carried out near-field WPT based on MRC techniques. Experimental work was performed in the laboratory to explore the functioning of the proposed S-WC–MRC–WPT Technique. S–P topology has been suggested for the examined experiment to a wirelessly charged IBM. Different values of voltage sources were applied during the experiment; also, ten values of the transmission distance were examined for three loads to investigate the design. Neither the human body nor the safety of electromagnetic fields has been evaluated in the presented implementation. The output current in the system depends on the transmission distance for each examined load. The impedance matching of the oscillating system influences the output current. As the load increased to 150Ω, the output current decreased compared to when 50Ω was examined. However, when load resistance becomes higher than the impedance of the resonant design, it decreases the WPT design's efficiency. It is sensible for future research to utilize cost-effective and inexpensive components instead of power supply devices and EPC9065 board. Moreover, the proposed design's performance can be further evaluated by investigating and analyzing the transmitter and receiver's main signals using an oscilloscope. This analysis will provide valuable insights into the design's effectiveness.

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