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Review

Approach-Based Analysis on Wireless Power Transmission for Bio-Implantable Devices

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Abstract: The wireless power transmission (WPT) is a systematic technology improve many constraints affecting implantable devices. Many methods have been introduced over the years for WPT. In this article, based on different approaches, we discuss and analyze philosophically the recent existing methodologies and techniques for efficient WPT in implantable devices. For each recent powering method or approach, the working principle and their outcomes are mapped. The performance, efficiency, operating frequency and stability of the systems have been highlighted and listed.

Keywords: power transmission efficiency (PTE); inductive power transmission (IPT); rectenna; impedance matching; implantable devices

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1. Introduction

Various practices of WPT systems appeared in 20th century. In 1926 the first article appeared on a directional antenna tuned with high gain [1]. A report was published during the 1960s on the utilization of microwaves for the transmission of power wirelessly [2]. In 1973, with the use of radio frequency, the identification of WPT starts [3]. In 1970, inductively coupled power transmissions were carried out for other medical applications [4–12]. At the end of the 1970s, the same type of transmission was taken for large-power transmission. Some studies that were conducted in the 1980 failed because of the power ratings of the devices used in their power supplies, limiting high-frequency utilization and its efficiency [13]. In the mid-1990s, the commercialization of inductively powered transmission in most of the biomedical applications occurred [14]. Transformers of coreless-type PCB appeared using resonance circuits, as presented in [15]. In 2007, In a physics research study, a 60 W bulb was wirelessly powered with 40 W at a spacing of 2 m [16]. Moreover, using more than two coils, a multi-coil-based WPT for implantation had been proposed [17,18].

Today, IPT-based systems are still under development in numerous areas. As per recent advancements, the battery-based biomedical implants can be replaced by WPT systems with Wireless Body Area Network (WBAN). Batteries have limitations in terms of replacement cycles. Therefore, the patient must be operated on without battery failures. If not so, it can cause serious problems to the patient and sometimes lead to death. Hence, it is a serious issue when working on existing battery-based technology, as the battery life is limited in its current status. This challenge can be counteracted by a highly efficient WPT system. In this review analysis, we have categorized the various WPT systems based on the techniques or approaches used in it and listed their performance and remarkable outcome information in tables under each category.

2. Wireless Power Transfer

Implants are nothing but biomedical devices that are positioned inside the body or on its surface. Most of the implants are reconstructive surgeries that replace missing or failed parts of the body. Some implants provide medications, track the functions of the body or give assistance to organs and tissues. Bio-implants are produced from bone, human skin or any other tissue of the body. Apart from this, few implants are produced from plastics, metals or ceramics, etc., Implants can be used up to the point that the original organ gets its normal functionality back, while the permanent placement of implants is also possible in case of complete damage or failure of a particular organ. Some major challenges of having implanted medical devices are giving continuous power to them and tracking their functions. Power levels vary for different implantable devices as per their application. Normally, a pacemaker needs power of about 1 milliwatt maximum, whereas a retinal prosthetics needs around 40 mW of power and so on.

Hence, an efficient WPT system is required for implantable devices to avoid such interruption during the function of the device. The basic WPT model is illustrated in Figure 1, where the power link is established by magnetic coupling of coils and so that power is transferred to the load. Even though many wireless power transfer systems are found using various recent techniques, advancements and improvements in terms of efficiency, distance coverage and stability are still required.

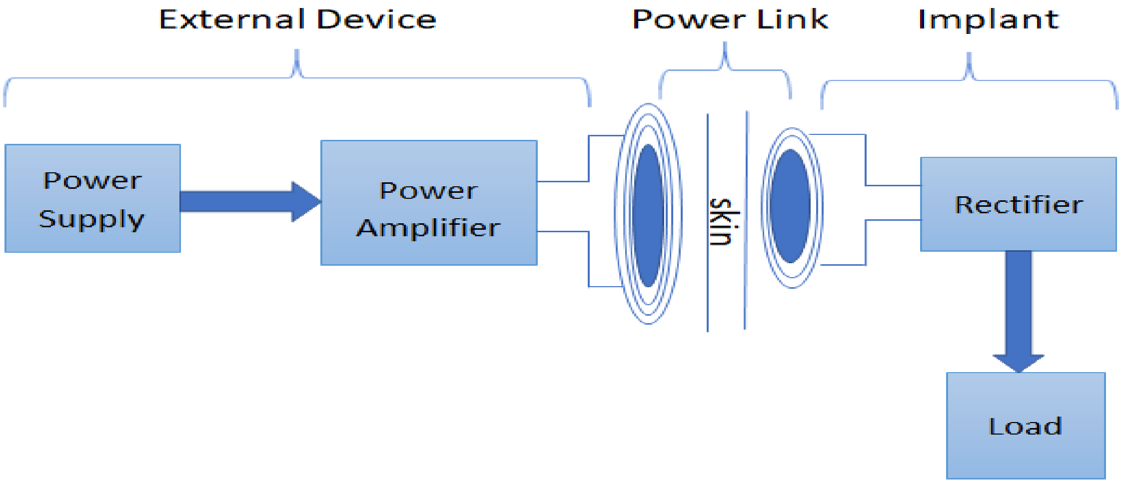

Figure 1. Basic WPT model.

3. Analysis of Various WPT Approaches

A variety of techniques and approaches for WPT in implantable medical devices are found so far. Some recent approaches, as well as modified techniques are briefly reviewed here.

3.1. WPT Systems Based on Different Transmitting and Receiving Coils Technique

Normally, to attain a highly efficient power gain in WPT systems, the transmitting and receiving coils should be strongly coupled. However, in many cases, the presence of weakly coupled WPT cause an inefficient power transfer. Some of the WPT systems proposed for better efficiency on the basis of modified transmitting coils are grouped here and listed in Table 1.

In article [19], the authors introduced an array technique to boost the system's gain for weakly coupled systems, which uses a multi-coil transmission array (Tr) to supply the receiving devices (Rr) in near-field. This is achieved by increasing the gain of the power at the self-resonant frequency and creating the effective phase factors of the elements of the transmission array. Here, a (1×1) cm^2 Rr coil at a space of 20 cm of power gain has been implemented along with a (3×3) Tr coil array consisting of nine (3 cm $\times$ 3 cm) elements, plus a single big Tr coil with the equivalent dimensions as the matrix for a neutral comparison. With this set-up, the power gain of the converter increased to up to 16.4 dB.

Table 1. WPT systems based on different transmitting and receiving coil technique.

Ref.	Approach	Operating Frequency	Performance	Remarkable Observation
[19]	System with multi-coil transmitting array technique	460 MHz	0.66% efficiency (3×3 array)	(i) 16.4 dB power gain attained; (ii) Covering distance of WPT is 200 mm; (iii) The higher the array level, the more the gain improves.
[20]	System with sandwiched transmission coil technique	160 kHz	Load power up to 5 W; 88% PTE; high flexibility	(i) Specifically for cardiac pacemakers; (ii) Low-resonant frequency is advantageous
[21]	WPT system with switchable pi-match network	6.78 MHz	Tr distance— up to 180 mm; Constant output voltage— 16.8 V; Efficiency: 78%	two-coil system using switchable Pi-match network.
[22]	The tissue channel technology	13.9 MHz	PTE: 0.39% for 1 mm implant with depth of 5 cm in pork tissue	Uses body tissue as an energy transfer channel but implant should be in contact with tissue.
[23]	Transmitting coil with optimal radius ratio	180 KHz	Up to 77% PTE	No need to utilize multi-coil adoption
[24]	Capacitor-segmented coils	40.68 MHz	Up to 31% PTE; Coverage: 20 mm	SAR: 5 times lower than non-segmented coils
[25]	3-coil approach	50 kHz	Up to 48% PTE; Power: 80 mW; Coverage: 15 cm	Memetic algorithm used

Another approach of double-sandwiched coils for both Tr and Rr is discussed in [20] in which a low-resonant frequency of 160 kHz is used so that the safety level of patients is extended. This system is especially useful for wireless charging of the battery of medical micro-robots for pacemakers. The design of the sandwiching form of Tx coil, which is demonstrated in Figure 2, accomplishes the feasibility level and flexibility status of the spacing distance for various types of micro-level medical robotics and provides a power of up to 5 W and a PTE of utmost 88%.

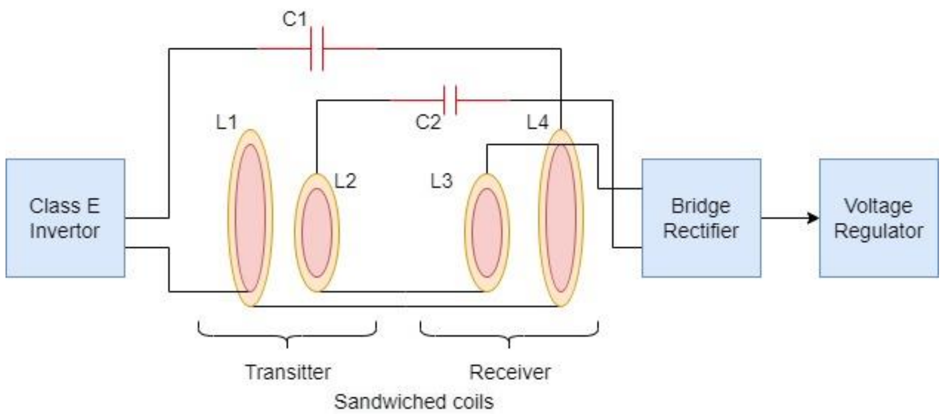

Figure 2. Sandwiching arrangement of coils on transmitter and receiver of WPT system.

Moreover, to address the issue of poor efficiency and less transmission coverage area of WPT in implantable devices, ref. [21] presented a system with a switchable pi-match network, where a new two-coil system was used. In that two-coil system, Primary has a

90 mm external diameter and Secondary has a 65 mm external diameter. The system at 6.78 MHz frequency allows a transmission distance of up to 180 mm, achieving the output voltage of about 16.8 V constantly with a transmission efficiency of up to 78%. This is achieved using the specified switchable pi-match network. This is a remarkable attainment of efficiency.

Along with these approaches for implantable devices, quite new techniques have been discussed. Study [22] uses the tissue of the body as an energy transfer medium, in which two medical electrodes were placed on the bodily skin surface to provide power to a miniature implant without contravening the IEEE-SAR Standard. This tissue channel technology for a 1 mm implant achieved a PTE of 0.39% in a declination of 5 cm inside the tissue. Another approach is shown in [23], where by changing the radius of the transmit coil to almost the equivalent level of the coil radius of the receiver and by adjusting the space between both coils to about 1 cm without changing the radius of the receiver coil, a transmission efficiency of up to 77% can be reached without any need of adopting multi-coils for transmission.

A WPT system [24] in which spiral coils lying in a planar form with the integration of capacitances, called capacitance-segmented coils, was applied to work in the WPT interface. By this capacitive-coil segmentation and at the operating frequency, dielectric losses, along with some current distributions (non-uniform), are concealed by repealing the inductive role of every coil segment. In this work, wireless power connection with the transmitter coil of 30 mm and receiver coil of 10 mm were designed and validated. Through this, with a 31% of efficiency in tissue that covers a space of 20 mm, a PTE 10 times greater and a SAR rate five times smaller, when compared to non-segmented models, can be attained. Additionally, operating at 150 MHz in the air, it is up to 1.5 times more efficient than other systems of the same size.

Tomasso Campi et al. gave a primary coil configuration on the basis of the Helmholtz principle to introduce a magnetic field inside the human body in the range of intermediate frequencies [26]. While analyzing coil-based WPT approaches, various techniques have been proposed in various research papers, where magnetic resonance WPT using a 3D dual-coil approach [27] is one of them. It works with 3D coils. Several optimal designs of primary, as well as secondary WPT coils have also been exposed to improve WPT performance and avoid potential safety issues due to electromagnetic fields (EMF) [28].

Moreover, a three-coil system for power transmission with one receiver coil and two transmitter coils is proposed in [25], where its structural design is optimized via a memetic algorithm. Actually, this algorithm unites the characteristics of the method of artificial bee colonies along with the covariance matrix method, which is an adaptive evolutionary strategy type. Hence, this system helps to increase the reception of power at the receiver by about 48%, and also the power transfer coverage distance increased by up to 15 cm. The model circuit for such a three-coil (2 Tr and 1 Rr) approach is given in Figure 3.

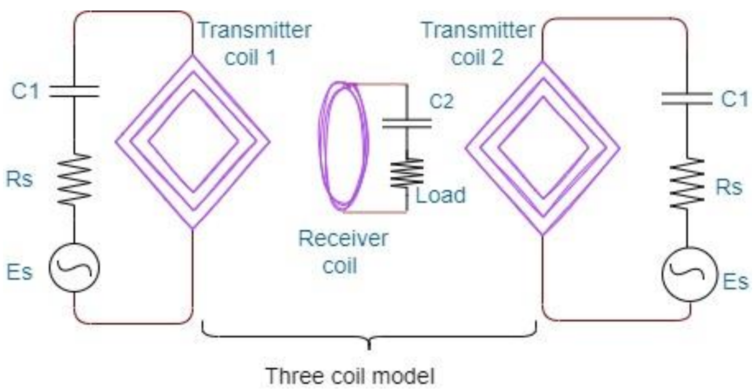

Figure 3. The model of three coil power transfer system.

3.2. WPT Based on Role of Impedance Matching Approach and Hybrid Technique

This section discusses another group of WPT systems listed in Table 2, which have been proposed with the focus of an impedance-matching role or hybrid technique.

Table 2. WPT systems focusing on an impedance-matching role.

Ref.	Approach	Operating Frequency	Performance	Remarkable Observation
[29]	Impedance-matching technique in magnetic coupling resonance	144 MHz	46% PTE	10 mW input power achieved without affecting power efficiency provided without using matching circuits
[30]	Resistive matching (complex conjugate match) with an AC boost converter	987 kHz (Piezo-electric receiver)	AC boost method: load power = 1 mW; 74% PTE	Power transfer attained maximum level in providing ultrasonic power to IMDs
[31]	Titanium alloy on the WPT link	13.56 MHz	Connection link Efficiency improved	Grade 2 gives more efficiency than Grade 5 titanium alloy.
[32]	Powering through 2-contact resonant capacitive link (Hybrid ASK-FSK technique)	1 MHz	For air kapton gap of capacitive link, up to 90 mW of power and 70% PTE attained	(i) DTR up to 170 kbps achieved; 12 mW of PDL; (ii) Suitable for high-density micro-stimulation implants

Sota Masuda et al. [29] developed a WPT system with its equivalent circuitry and showed the realization of impedance matching. This method is capable of reaching the input power utmost 10 mW and efficiency of up to 46% without the use of impedance-matching circuits, which is shown in Figure 4.

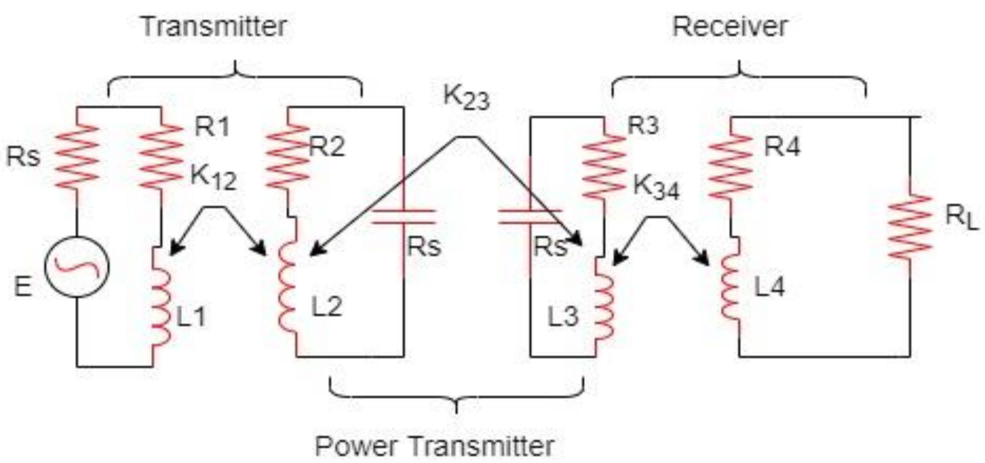

Figure 4. WPT system without using any impedance-matching circuits.

In order to raise the energy conversion in the implants using ultrasound receivers, a suitable complex conjugate among the piezoelectric receiver circuit and the energy transformation circuit is perceived as a worthy power transfer. Placing a boost converter before the rectifier circuit allows near perfect resistance. This boost converter converts the alternating current potential to a square wave, which is modulated using the PWM method. This helps to avoid the additional work of transforming impedance between the receiving circuit and the module of rectifier in the WPT system [30]. Hence, the overall efficiency of the WPT gets improved.

In [31], the WPT link was examined with the impact of various titanium alloys at the operating frequency of 13.56 MHz. Usually, poor resistivity in the IMDs decreases the efficiency of the connection. Here, a simple analytical representation has been conferred to understand that effect by comparing the alloys of two different grades. Here, the link-efficiency attained was greater for the Grade 2 alloy than for the Grade 5 alloy at 13.56 MHz. So, the electrical properties of the titanium alloy should be carefully considered when designing the WPT link in the system to meet the desired target for link efficiency.

Asish Koruprolu et al. proposed and demonstrated in [32], for the first time, an experimental workbench model of an approach of supplying power wirelessly for biomedical IMDs over a capacitive connection, which is two-contact resonant. Here, the data were simultaneously sent in hybrid form (ASK-FSK) of encoding, i.e., amplitude shift plus frequency shift, keying on the single chosen medium. It is highly suitable for the implants of micro-stimulation, where the telemetric rate for data transmission does not depend on the frequency of the service provider. For realization purposes, a concept tabletop setup with flexible and adaptable patches of capacitance of 20 mm × 20 mm with a 3 mm thick portion of beef meat was used. Proper impedance matching is also attained by the capacitive coupling at resonant. To complete a current loop and supply power to the biomedical implant, two of those pairs of capacitance patches would be required. The operational frequency is determined by inductors connected in series, allowing the L–C combination to resonate. In this system, for the gap called air-kapton, which is between the patches of inductance and patches of capacitance, the data-transferring rate of about 170 kbps and power of up to 90 mW with a PTE of 70% have been attained; for the same construction, with a separation of 3 mm wide bovine tissue samples, the power obtained by the load was 12 mW and the PTE was up to 36%. Hence, comparatively, the proposed work improves the PDL and the efficiency of the system.

3.3. WPT Systems Based on Power Control and Regulation Improvement

In this section, the WPT systems developed based on power control and regulation improvement are being studied theoretically and listed in Table 3.

Table 3. WPT systems based on power control and regulation improvement.

Ref.	Approach	Operating Frequency	Performance	Remarkable Observation
[33]	WPT with 1X mode or 2X mode reconfigurable R^3 rectifier	13.56 MHz	Output power of 10 to 100 mW; max efficiency of 92.6%	Stable power control attained by using a data backscattering uplink technique
[34]	System with adjustable compensation network	570 kHz	Constant output voltage	Components minimized@ Receiver without abating efficiency
[35]	Distance and load-insensitive inductive approach	Not specified	Receiver efficiency over 88%; overall PTE 76%	Automatic power adjustment attained by closed-loop control scheme; its response time is 69 ms
[36]	WPT with switched capacitive converter (SCC)	13.56 MHz	Desired output: 5 V (for 1.3–3.3 V input); 57–74% efficiency	(i) Stable output voltage; (ii) Reduced switch size; (iii) Especially for neuro-stimulator implants.
[37]	Receiver (RVM-Rx) with VPTD technique	13.56 MHz	67.8% efficiency @Rx	MDTL and ODTL used

A WPT system operates at the frequency of 13.56 MHz with a either 1X or 2X mode resonant regulation rectifier (R^3) and the power control has been proposed for implants [33] in which the maximum measured power on receiver side is 102 mW and efficiency at receiver is 92.6% whereas regulation or control is pull off by two mechanisms. In the first mechanism, the domestic pulse width modulation (PWM) on the receiver side manages the on and off time of duty cycle to switch the rectifier for the change of modes 1X and 2X as per requirement. Secondly, Backscattering uplink technology is used to adapt the transmission power of the primary coil by having 0.35 μm CMOS process. Here, the R^3 is a reconfigurable rectifier.

An adjustable compensation network has an advantage where the capacitor matrix can be modified [34]. It gives sustained voltage power supply with no regulation loop on the side of receiver, which favors IMDs. Normally this system will work correctly for various load resistances and coupling coefficients. By this approach, with a coil spacing of 32 mm to 40 mm and a load resistance of 100 Ω to 0.5 kΩ, the capacitors arrangement can be spontaneously adapted to provide a sustained voltage of almost 3.5 V to the load.

In order to obtain smooth output power, another technique [35] provided automatic power adjustment by using closed loop control scheme. Here, the system is based on inductive power transfer which has a converter (DC to DC) on the primary side and a circuit to track or monitor the load voltage on the secondary side, as well as a communication process using the coils. The tracking circuit of load voltage identifies the value of output voltage and whenever it deviates from the theoretical scale of values, it sends a warning by communicating the transmitter wirelessly. Then, the Transmitter manages the converter output voltage as per the warning received to maintain the charging potential at sustained level. Here, the observed response time in the closed control loop was approximately 69 ms and efficiency at receiver was above 88%.

Another WPT system with a step-up Switchable Capacitor Converter (SCC) designed [36] in a CMOS technology environment by reducing the count of outer components to put properly the load and flying capacitors. This convertor aims the requirements of a neural stimulator implant for the purpose of retinal reconstructive surgeries provided by an inductive link-based WPT. The SCC can dynamically self-reconstruct and self-adjust over the range of 1.3 V to 3.3 V input potential, attaining the required 5 V potential output with 57–74% of efficiency. Here, the Absolute switch size helps to maximize overall reconfigurable SCC efficiency.

Se-Un Shin et al. [37] proposed a voltage resonance mode receiver (RVMRx) to charge the battery at receiver. An inductor-capacitor tank circuit at the receiver has been configured and separated from the obtained output by a resonance interleaving approach, resulting in optimum transfer of power without depending on the phase of operation. Therefore, the efficiency of energy transfer is insensitive to the charging conditions such as the variation of the battery voltage. A scheme combines of MDTL (minimum diode time tracking loop) and ODTL (optimum duty tracking loop) lead to energy conversion efficiently through adaptive operating state regulation. The RVMRx prototype module in a CMOS process of 0.18 μm can function at a 13.56 MHz great resonant frequency with an RX coil of smaller size (7 mm × 7 mm), while reaching a maximum efficiency in power received by the receiver of around 67.8% which is for charging of the battery.

In addition to this, a new technique was developed for WPT [38] based on the duty cycle of the signal. Instead of sending waves continuously, they only send for a short particular time and then pause for some time. This allows increasing transmit power during active periods while maintaining average transmit power and specific absorption rate (SAR). The input voltage to the rectifier is then significantly increased, allowing the rectifier to rectify the input with a higher PCE, improving PTE.

3.4. WPT Systems Based on Antenna Modifications

Some of the WPT systems (listed in Table 4) were developed by using different or modified antennas for the betterment of their performance. In this section, this is discussed briefly.

Table 4. WPT systems based on antenna modifications.

Ref.	Approach	Operating Frequency	Performance	Remarkable Observation
[39]	System with dual band PIFA	915 MHz	Boost up of directivity of antenna and radiation efficiency	(i) Covering distance of WPT is 50 cm; (ii) Improves PTE 4.4 times the System without PIFA
[40]	Non-leaky WPT and T-shaped ground slotted antenna	402–405 MHz (MICS)	Apprx. 4 mW power attained	Power leakage control attained using Near Field Plate
[41]	A triple-loop -echnique-based WPT	13.6 MHz	13.5% PTE at 20 mm distance coverage	A 3-coil inductive link also established to improve PTE
[42]	Design with Reactive near field of antenna	2.45 GHz (ISM)	1.8% PTE	1.92 W/Kg SAR and Antenna misalignment issue also addressed
[43]	Intermodulation technique for antenna alignment	Rectenna 2T of 2.448 and 2.452 GHz; 4-MHz intermodulation	Minimizes the interference in NRIC link; Implantation depth is 2 mm.	(i) Strengthen the power link efficiency; (ii) Less harm to human tissue
[44]	Inductive Coupling (for BMID)	400 MHz	−30.12 dB wireless power connection and high efficiency	(i) 3D bowtie receiver antenna for implant lodged in CSF fluid connected with an external loop-type antenna; (ii) avoiding restore of a discharged battery through surgery
[45]	New Antenna sensor (for wireless endoscopy system)	2450 MHz	Smaller size; High gain and sensitivity;	(i) Antenna sensor: peak gain of −9.7 dBi; (ii) Stomach disease can also be detected
[46]	Antenna with split resonant rings	272 MHz to 1504 MHz; Relative Bandwidth: 138.7%	Peak gain: −32@MICS and −34@ISM	(i) Antenna size reduced to 91.44 mm^3; (ii) WPT with metasurface extends battery life for implants.

A rectenna implantable in the arm, assisted by a rectifier and a new antenna called planar inverted F-antenna (PIFA) was designed for power transmission and data telemetric services wirelessly in radio communication for medical devices (401–406 MHz), in industry, science and medicine, with (902.8928 MHz) frequency bands [39]. The rectifier circuit is included with the help of a ground plane of the taken antenna in this system. The antenna size taken is $16 \times 14 \times 1.27$ mm^3 and the techniques for slot loading given to the selected radiator provide a dual band operation and also good minimization in the antenna size. This body of work addressed the stability level of PIFA at resonance, its radiation measures and responses in terms of security in detail. In addition, a matching layer attached to the arm was introduced to enhance the power connection and transfer efficiency at small input powers. Hence, in this body of work, the overall system called rectenna was constructed and thoroughly checked for coverage distance and efficiency.

Another modified antenna model proposed in [40] has an antenna which is multi-band in its shape and applicable for implantable and ingestible devices. It has three bands of frequency. The first one is the implanted medical communication service (MICS) and its range is 402–405 MHz. The second band is the mid-range frequency band between 1.45–1.6 GHz. The last band is the industrial, scientific and medical (ISM) band and its range is 2.4–2.45 GHz. These bands are used for wireless telemetry, WPT, and energy-saving biomedical devices. To extend the range of such antenna to apply in on ingestible devices, the performance of said antenna has been measured with minced pork in the ISM frequency band. An altered form of the midfield energy transferring model has been assimilated to depict the WPT scheme in the implantable 3-dimensional printed capsule. In addition, an NFP plate has been used to manage the power dissipation of the WPT transmitter. In this work, authors discovered that using a ground slot portion in the Rx antenna, antenna performance could be improved and SAR could be reduced. Additionally, it is shown that by involving an NFP plate in the WPT transmission of medium field, the power transferring performance and efficiency of WPT can also be increased.

A resonator for implants (subcutaneous) was developed, which provides a new pattern for impedance matching to the existing loop antenna [47]. The metal pad, which is made of concentric model-tuning components, was put up and distributed inductance and capacitance to inductive loop (planar model), which improved the resonance highly. This gives a good qualification factor to attain proper coupling. In another approach [48], an embedded receiving antenna, which is polarized circularly and integrated with a voltage-doubler rectifier for wireless microwave power transfer in the 2.4–2.48 GHz ISM band, was studied and presented. Similarly, another approach for RF energy collection and data transmission was presented [49]. The authors introduced multiple radiating branches and etched C-shaped slots to create multiple resonant frequencies. This created a wide double band and improved the WPT.

Byunghun Lee et al. [41] propose a triple-loop WPT system with an imperium power control mesh, automatic resonant tuning (ART) receiver (Rx) and transmitter resonant compensation (TRC). The system cancels the load and coupling swing and also reimburses for variations in the inductive connection to improve the PTE of implantable medical devices. Tx had been constructed in a commercially off-the-shell radio frequency identification reader working at a frequency of 13.56 MHz. By varying the value of varicap, the Tx mesh determines the optimum capacitance, which is in parallel with the transmitting coil. The imperium power control mesh keeps the Rx power at the required range in response to the distance of coupling, misalignment of the position of coil and load changes. The Rx loops are carried out in special integrated circuits (IC) called power management IC to skip or prevent any degradation in PTE and process variability by Rx coil surroundings. This three-loop system reduces the total PTE by around 10.5% compared to a same type open-loop system, and by around 4.7% compared to a similar type closed-loop system at 2 cm nominal coil spacing. Here, the TRC contributes 2.3%, and ART loops contribute 1.4% efficiency to the system's total PTE, which is 13.5%. Notably, the first WPT system, which includes three loops, aggressively reimburses for circuit and environmental fluctuations and enhances total energy efficiency that is from controller output on Tx to the respective module on Rx. Such a smooth transmission takes place by using a three-coil and three-loop model as expressed in Figure 5.

The WPT connection consists of a double-ring groove antenna, which is used as the Rx element and a single-patch-type antenna, which is taken as the Tx element. Here, the Rx element is implanted [42] in a one-layered tissue of skin prototype and the operating frequency of patch-type antenna is 2.45 GHz in ISM, while the double-ring groove is assigned to obtain broadband properties that involve the full ISM frequency band. The well-built coupling of transmitting and receiving antennas in the reactive near field ensures more PTE.

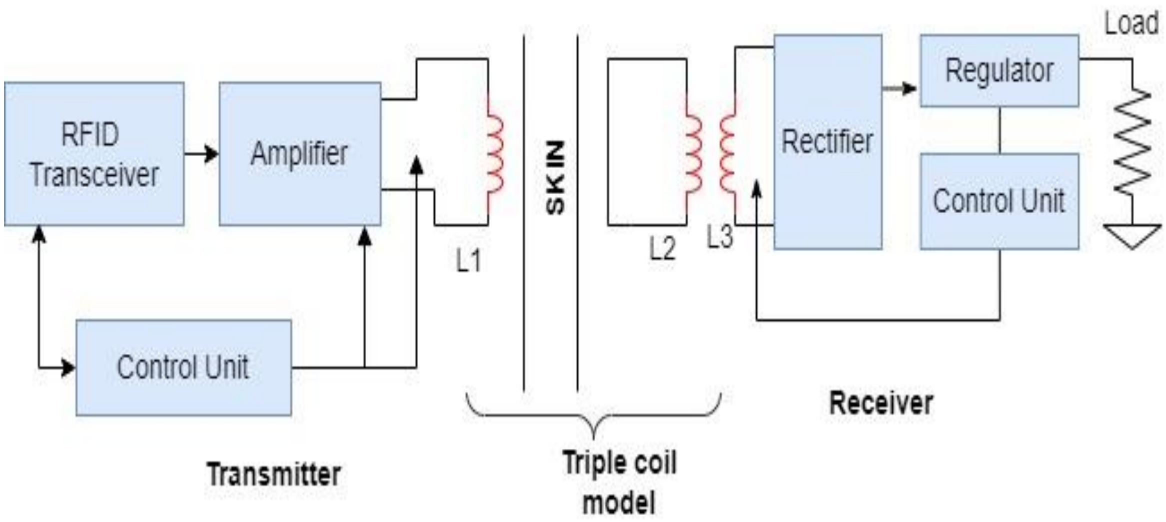

Figure 5. A 3-loop and 3-coil linked inductive WPT transmission.

Normally, wireless power transmission often faces the problems of antenna orientation and the misalignment in the antenna's polarization, which degrade the WPT efficiency and safety aspects for human tissue. Article [43] proposed an antenna alignment method that uses intermodulation to safely correct the misalignment of WPT antennas where a 2-tone (2T) waveform response is used to improve rectification and create intermodulation. Intermodulation energy is returned through a magnetically resonant coupling element. Because of the monotonous relationship between the performance of intermodulation and the level of misalignment of the antenna, the internal (inside the body) antenna could be aligned with the external (outside the body) antenna. This approach provides less damage to the tissue and no intrusion between the excitation of the 2T response and the magnetically coupled inductive connection. This approach has been experimentally validated.

The inductive method of charged brain implantable medical devices (BIMD), instead of a battery powered BIMD, can provide good powering and keep away from the resection restore of a discharged battery. This has been studied and experimented on by Mohamed Manoufali and Beadaa Mohammed [44]. A 3D bowtie antenna lodged in cerebrospinal fluid (CSF) connected with an outer loop-type antenna reduces the high intrinsic reactive portion of the input impedance. A cerebrospinal fluid (CSF) spook was made to experimentally check the energy transfer efficiency between external and internal antennas. A measurement of the 0.9 mm^3 fabricated implantable internal antenna prototype on the CSF spook (phantom) provided results in a -30.12 dB wireless power connection, which exceeds current survey work in terms of the efficiency and size of the link for implantable 3-dimensional antennas.

Along with these, let us examine another wireless system, Guang-bo Wang et al. proposed in [45] a wireless capsule endoscopy system, which is specified with more gain and a highly sensitive small antenna sensor. In this system, the antenna is miniaturized by applying a two-layer radiation patch without reducing the radiation gain. The antenna sensor provides the merit of a peak gain utmost -9.7 dBi with a volume of $(2.6 \times 3 \times 0.381)$ mm^3 in the (2.4–2.4835 GHz) ISM frequency band. Additionally, stomach ailments can be found by the resonant frequency of the antenna's sensor. Overall, the small capacity, increased gain, and high sensitivity from the proposed antenna form an excellent role for endoscopy wireless systems.

Finally, let us examine another WPT system [46] that is designed by amalgamating a meta-surface with magnetic negative characteristics (MNG) to enhance efficiency as the MNG of meta-material has strong magnetic resonant behavior. The implantable antenna used in this system has split resonance rings to reduce its size. Here, meta-surface is placed 6 mm from the receiver antenna, which is 5 mm from surface of the skin and so the meta-surface will be 1 mm away from the surface of the skin in its converse direction. With this set-up, this antenna exhibits ultra-wide band properties that can offset from 272 MHz to 1504 MHz, with 138.7% relative bandwidth. In addition, the antenna is extremely dense at 91.44 mm^3 (12 mm $\times$ 12 mm $\times$ 0.635 mm) when compared to other designs. By integrating the split resonant ring, the proposed antenna was stimulated to have wideband characteristics in the required band. In addition, with the consideration of biosecurity for practical use, an efficient WPT system was integrated into the meta-surface to enable the charging of the embedded device and extend its life.

4. Conclusions

Recent methodologies and techniques proposed by various authors for efficient WPT in implantable devices have been discussed and focused on empirically. The performance and results of such approaches have also been pointed out. Power transfer efficiency, operating frequency and the stability of the system along with remarkable observations of each technique have been highlighted, which will be helpful for young researchers who want to acquire theoretical details of various WPT models.

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