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Dielectric Resonators in a Midrange Wireless Power Transfer System (WPTS): A Review

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Abstract

In wireless power transfer (WPT) systems, magnetic resonant coupling (MRC) is one of the most extensively utilised approaches. (This method is frequently used to increase distance while preserving power transfer efficiency) (PTE). Many studies have looked into novel technologies for extending the range of MRC while keeping PTE values high. The insertion of a resonator between the transmitter and reception coil is the most promising technology in MRC to yet. The resonator's implementation varies depending on design, size, and material type, but the results are still unsatisfactory.) PTE can be enhanced by using dielectric material resonators, which reduce ohmic loss, which is an issue with traditional resonators. This paper gives a broad review of the usage of dielectric material as a resonator in MRC WPT technology and its evolution. The basic operation of the MRC WPT is summarized, along with the most recent scientific advancements in the field of WPT related to dielectric material as a resonator. This research also provides an overview of the technique's existing limitations and problem.

Keywords: *WPT, PTE, Dielectric resonator, MRC.*

1. Introduction

WPT technology transfers power wirelessly at a set distance using two electromagnetic systems with the same resonance frequency. In general, despite the poor coupling at a targeted distance, both electromagnetic systems can trigger strong magnetic resonance if the natural resonance frequency is the same [1]. Prior to the development of magnetic resonance coupling, inductive coupling was the most common and widely used method (IC). (e idea of transferring power over the air was first proposed by Nikola Tesla, who pioneered the tests and ideas that surrounded it [2]. Despite its preference, IC could only transfer power over a short distance when compared to MRC since the system's efficiency was often harmed by the coil's ohmic resistance and misalignment [2]. In 2007, a Massachusetts Institute of Technology (MIT) researcher demonstrated efficient nonradiative power transfer over a distance of up to 8 times the radius of the coils using a 4-coil system of strongly coupled magnetic resonance that transferred 60 Watts of power with an efficiency of more than 40% and a distance of up to 2 metres [3, 4]. Because of the rising demand for wireless power transfer systems in recent years, research into WPT applications has expanded dramatically. Power transfer efficiency (PTE) is a primary emphasis since it decreases rapidly when the separation between the coils grows or the coils become misaligned [5, 6]. Because consumer applications necessitate extremely efficient end-to-end wireless power transmission, approaches that ensure optimum efficiency must be considered. Several ways have been examined and proposed in earlier publications [7, 8] to achieve optimal efficiency. Impedance matching and control schemes using microcontroller techniques, such as quality (Q) factor and coupling (k) coefficient control, coil construction, and misalignment, are among these ways [9]. To improve PTE, the adaptive impedance matching technique was earlier developed [10]. The downside of adaptive tuning, as opposed to automatic impedance tuning control, is the employment of a varactor diode in the circuit, which introduces additional losses. This lowers the system's overall efficiency. Previous research has demonstrated that altering the coupling (k) coefficient between the coils can improve efficiency. To ensure optimal efficiency, the spacing between the coils was manually adjusted to achieve an appropriate coupling coefficient (k) at a specific resonant frequency. Although the method produced positive results, manual modification was not a viable choice for its application. Several coil structure designs have been applied, ranging from flat printed structured coil (PSC) [11] to helix [12], square [13], and 3D [14] designs. Although the efficiency remained below the intended value, designs as basic as a circular framework and more sophisticated designs were utilised. In addition to its inefficient performance, the large and convoluted design makes it ineffective as a working gadget, which requires additional refinement. Horizontal and angular (azimuthal) misalignment are the two most common types of misalignment that can occur. Variations in coil construction [15] and the use of several resonators have been used in several attempts to tackle this problem. Because more than one resonator is employed and situated between the transmitter and receiver coils, altering the coil configuration to handle the misalignment issue affects the goal efficiency, and implementing many resonators is impractical. High ohmic losses in the traditional resonator are the source of problems with the MRC WPT system. When ohmic loss is substantial, the Q factor automatically falls, lowering system performance and allowing the energy to be "held" for a longer period of time. As a result, when the coils are separated and there is a mismatch between them, energy will degrade quickly. This study examines the use of dielectric material as a resonator in the MRC WPT system. The use of a dielectric resonator reduces the ohmic loss in a traditional resonator. The permittivity characteristic of dielectric materials has been established in studies in the field of material sciences to improve the Q factor. This paper aims to discuss fundamental elements of dielectric material related to WPT and up-to-date developments over the past few years.

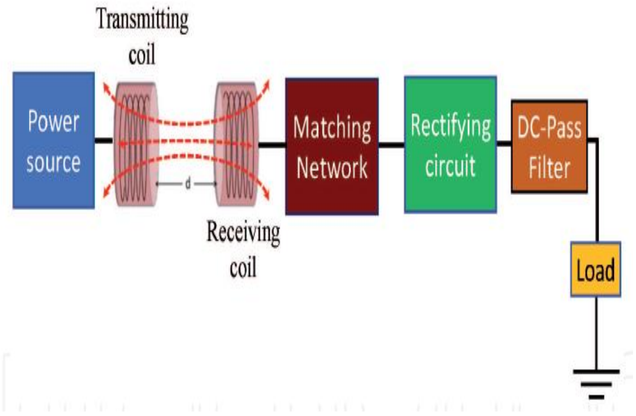

Fig.1 Wireless Power Transfer System

2. Related Work

Xianyi Duan et al. (2021) proposed system is based on a grounded loop to reduce the leakage of the electric field, resulting in less interaction with the human body. As a result, a transmission efficiency higher than 70% is achieved at a transmission distance of approximately 25 cm. Under the maximum-efficiency conditions of the WPT system, the use of a resonator with a grounded loop reduces the induced electric field, the peak spatial-average specific absorption rate (psSAR), and the whole-body averaged SAR by 43.6%, 69.7%, and 65.6%, respectively. The maximum permissible input power values for the proposed WPT systems are 40 and 33.5 kW, as prescribed in the International Commission of Non-Ionizing Radiation Protection (ICNIRP) guidelines to comply with the limits for local and whole-body average SAR [16].

Thanh Son Pham et al. (2021) investigated the efficiency of a magnetic resonant wireless power transfer (MR-WPT) in conducting medium and found out an optimal frequency for designing the system. In conducting environment, the eddy current loss is generated by the high-frequency alternating currents in the coils. It is manifested by increased radiation resistance of resonator coil leads to decrease the quality factor (Q-factor), which reduces the wireless power transfer (WPT) efficiency in conducting medium. The Q-factor of the resonator coil strongly depending on the conductivity, frequency, and thickness of conducting block. Two MR-WPT systems operating at 10.0 MHz and 20.0 MHz are implemented to study the effect of conducting medium on efficiency. The achieved results indicated that the 20.0 MHz system has higher efficiency at a conductivity smaller than 6.0 S/m. However, at the larger conductivity, the 10.0 MHz system is more efficient. The results provide a method to determine the optimal frequency of a WPT system operating in the conducting medium with various conductivities and thickness blocks. This method can be used to design MR-WPT systems in numerous situations, such as autonomous underwater vehicles and medical implants [17].

Esmaeel Zanganeh et al. (2021) develop a wireless power transfer system based on non-radiating sources implemented using colossal permittivity dielectric disk resonator and a subwavelength metal loop. We demonstrate that this non-radiating nature is due to the hybrid anapole state originated by destructive interference of the fields generated by multipole moments of different parts of the non-radiating source, without a contribution of toroidal moments. We experimentally investigate a wireless power transfer system prototype and demonstrate that higher efficiency can be achieved when operating on the non-radiating hybrid anapole state compared to the systems operating on magnetic dipole and magnetic quadrupole modes due to the radiation loss suppression [18].

Libo Tian et al. (2021) presented a LCT system with a movable intermediate coil and adjustable system frequency, which can promote the efficiency of the WPT system under misalignment condition. First, the influences of the position and compensation parameter of intermediate coil on the system efficiency during migration are summarized. The optimal compensation parameter and optimal position selection method of intermediate coil are proposed. Then, the influence of frequency on system efficiency is studied, and the detailed control strategy of intermediate coil's position and system frequency is proposed. A 3-kW prototype WPT with the proposed three-coil LCT is manufactured and experimental validations are also performed. The results show that the efficiency declines of three-coil LCT with the proposed control strategy is 1.8% when the lateral offsets reach 300mm, namely 43% of the outer diameter of coil [19].

Esraa Mousa Ali et al.(2021) an automated impedance matching circuit is proposed to match the impedance of the transmit and receive resonators for optimum wireless power transfer (WPT). This is achieved using a 2D open-circuited spiral antenna with magnetic resonance coupling in the low-frequency ISM band at 13.56 MHz. The proposed WPT can be adopted for a wide range of commercial applications, from electric vehicles to consumer electronics, such as tablets and smartphones. The results confirm a power transfer efficiency between the transmit and receive resonant circuits of 92%, with this efficiency being sensitive to the degree of coupling between the coupled pair of resonators [20]

Jacek Maciej Stankiewicz and Agnieszka Choroszucho (2021) presented wireless charging system with the use of periodically arranged planar coils. The efficiency of two wireless power transfer (WPT) systems with different types of inductors, i.e., circular and square planar coils is compared, and two models are proposed: analytical and numerical. With the appropriate selection of a load resistance, it is possible to obtain either the maximum efficiency or the maximum power of a receiver. Therefore, the system is analyzed at two optimum modes of operation: with the maximum possible efficiency and with the highest power transmitted to the load. The analysis of many variants of the proposed wireless power transfer solution was performed. The aim was to check the influence of the geometry of the coils and their type (circular or square) on the efficiency of the system. Changes in the number of turns, the distance between the coils (transmit and receive) as well as frequency are also taken into account. The results obtained from analytical and numerical analysis were consistent; thus, the correctness of the adopted circuit and numerical model (with periodic boundary conditions) was confirmed. The proposed circuit model and the presented numerical approach allow for a quick estimate of the electrical parameters of the wireless power transmission system. The proposed system can be used to charge many receivers, e.g., electrical cars on a parking or several electronic devices. Based on the results, it was found that the square coils provide lower load power and efficiency than compared to circular coils in the entire frequency range and regardless of the analyzed geometry variants. The results and discussion of the multivariate analysis allow for a better understanding of the influence of the coil geometry on the charging effectiveness. They can also be valuable knowledge when designing this type of system [21]

3. Classification of WPTS (Wireless Power Transfer System)

WPT techniques can be broadly categorized into two types: near-field and far-field. Near-field techniques are adopted for applications where the distance between the transmitter and receiver is within a few millimeters or centimeters, for example charging handheld devices, radio frequency identification (RFID) tag technology, induction cooking, and wireless charging or continuous WPT in implantable medical devices. In contrast, far-field methods are able to achieve longer distances. They can be used for applications where the distance between the transmitter and receiver is within several kilometers. An example of far-field methods consists of transmitting power from a geostationary satellite to ground devices. Then, due to their long-range capability, the far-field methods have been recently labeled as a promising solution to supply power to mobile electric devices (MEDs) operating in harsh conditions where people cannot access and the use of conductive cables is infeasible [22,23]

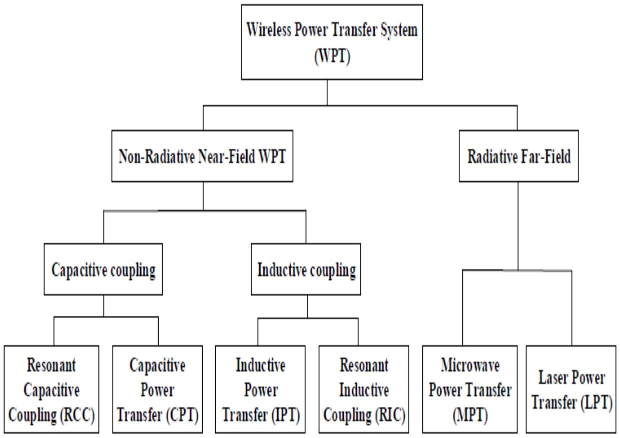

Fig. 2: Classification of WPTS

Non-Radiative Near-Field WPT

In near field or non-radiative techniques, power is transferred over short distances by magnetic fields using inductive coupling between coils of wire, or by electric fields using capacitive coupling between metal electrodes.[24][25][26][27] Inductive coupling is the most widely used wireless technology; its applications include charging handheld devices like phones and electric toothbrushes, RFID tags, induction cooking, and wirelessly charging or continuous wireless power transfer in implantable medical devices like artificial cardiac pacemakers, or electric vehicles. This means the area within about 1 wavelength (λ) of the antenna. In this region the oscillating electric and magnetic fields are separate and power can be transferred via electric fields by capacitive coupling (electrostatic induction) between metal electrodes, or via magnetic fields by inductive coupling (electromagnetic induction) between coils of wire. These fields are not *radiative*, meaning the energy stays within a short distance of the transmitter. If there is no receiving device or absorbing material within their limited range to "couple" to, no power leaves the transmitter. The range of these fields is short, and depends on the size and shape of the "antenna" devices, which are usually coils of wire. The fields, and thus the power transmitted, decrease exponentially with distance, so if the distance between the two "antennas" D_{range} is much larger than the diameter of the "antennas" D_{ant} very little power will be received. Therefore, these techniques cannot be used for long range power transmission.

Resonance, such as resonant inductive coupling, can increase the coupling between the antennas greatly, allowing efficient transmission at somewhat greater distances, although the fields still decrease exponentially. Therefore, the range of near-field devices is conventionally divided into two categories:

- ***Short range*** – up to about one antenna diameter: $D_{range} \leq D_{ant}$. This is the range over which ordinary nonresonant capacitive or inductive coupling can transfer practical amounts of power.
- ***Mid-range*** – up to 10 times the antenna diameter: $D_{range} \leq 10\ D_{ant}$. This is the range over which resonant capacitive or inductive coupling can transfer practical amounts of power.

Inductive Coupled Wireless Power Transfer

The Inductive coupled WPT is the most used method for wirelessly charging low powered devices so far [24]. It transfers power from one coil to another and has been used for powering RFID tags, medical implants [23], in the fields of sensors, wirelessly charging electronic devices and in the car manufacturing industry. The operating frequency of inductive coupling is in the kilohertz range and is typically used within a few millimeters to a few centimeters (20 cm) from the targeted load and its power varies between watt and kilowatt based on transmission efficiency. The advantages of the inductive coupling WPT system include ease of implementation, convenient operation. It is non-radiative and due to its low transmission frequency, it is considered safe for humans [23]. It has a high transfer efficiency of up to 95% at short distances, it eliminates sparks and other hazards in situations like coal mining and there is no danger of either electrocution or short circuit under any power range condition as a result of the coupling being magnetic. However, a limitation of standard inductive charging is that it performs well in considerably short distances of communication, increasing the communication distance adversely drops the performance.

Magnetically Coupled Resonance Wireless Power Transfer (MCR WPT)

Magnetically coupled resonance wireless power transfer (MCR-WPT) follows the same basic principles as Inductive coupled wireless power transfer. It also transmits power from a source to a load [25]. However, this magnetically coupled resonant makes use of magnetic resonant coils, which operate at the same resonance frequency [23]. By using magnetically coupled resonant over standard inductive coupling, it is possible to achieve up to fifty percent efficiency for power transmission over longer distances without uttering coil size and power consumption. MCR-WPT technology has attracted significant attention from academia and industries because it can cover all aspects of human life from consumer and medical electronics, smart homes to electric vehicles, showing great potential for further application. The operating frequency ranges from a few hundred kHz and tens of MHz. MCR WPT has advantages of long-distance within several meters, unaffected by weather environments, line of sight (LOS) is not required when devices are charged, compared to Inductive coupled wireless power transfer, Magnetically Coupled Resonance Wireless Power Transfer has higher transfer power and efficiency and is considered to be one of the most potent techniques for mid-range WPT applications at present. The non-radiative nature of the Coupled magnetic resonant system presents no threat to the environment when compared with the microwave and laser WPT. However, MCR WPT experiences a decrease in efficiency as a result of the axial mismatch between the receiver and transmitter coils, decreased efficiency with increased distance, and complex implementation.

Capacitive Power Transfer (CPT)

Capacitive Power Transfer (CPT) involves the transmission of energy between electrodes such as metal plates. A charged retaining capacitor is formed by receiver and transmitter electrodes. The transmitter creates an alternating voltage on the transmitting plate, from which the oscillating electric field via electrostatic induction induces on the receiver plate, an alternating potential, which turns into alternating current flow in the load circuit. Though capacitive power transfer is cheaper than

Inductive coupling and magnetically coupled resonant, however, CPT requires close contact between the two metal surfaces. Hence, it is greatly limited by range requirements. The major drawback with capacitive WPT systems is that electric fields do not share the safety characteristics of magnetic fields, since their relative field strength is much greater, posing a hazard to both humans and electronic devices. Also, the achievable amount of coupling capacitance is dependent on the available area of the device. However, it is difficult to create sufficient power density required for charging when considering normal-sized portable electronic devices which indeed poses a design challenge.

Radiative Far-Field

In far-field or radiative techniques, also called power beaming, power is transferred by beams of electromagnetic radiation, like microwaves or laser beams. These techniques can transport energy longer distances but must be aimed at the receiver. Proposed applications for this type are solar power satellites, and wireless powered drone aircraft. Beyond about 1 wavelength (**λ**) of the antenna, the electric and magnetic fields are perpendicular to each other and propagate as an electromagnetic wave; examples are radio waves, microwaves, or light waves [28][29][30][31].

This part of the energy is *radiative*, meaning it leaves the antenna whether or not there is a receiver to absorb it. The portion of energy which does not strike the receiving antenna is dissipated and lost to the system. The amount of power emitted as electromagnetic waves by an antenna depends on the ratio of the antenna's size D_{ant} to the wavelength of the waves λ, which is determined by the frequency: $\lambda = c/f$. At low frequencies f where the antenna is much smaller than the size of the waves, $D_{ant} << \lambda$, very little power is radiated. Therefore the near-field devices above, which use lower frequencies, radiate almost none of their energy as electromagnetic radiation. Antennas about the same size as the wavelength $D_{ant} \approx \lambda$ such as monopole or dipole antennas, radiate power efficiently, but the electromagnetic waves are radiated in all directions (omnidirectionally), so if the receiving antenna is far away, only a small amount of the radiation will hit it Therefore, these can be used for short range, inefficient power transmission but not for long range transmission.

However, unlike fields, electromagnetic radiation can be focused by reflection or refraction into beams. By using a high-gain antenna or optical system which concentrates the radiation into a narrow beam aimed at the receiver, it can be used for ***long range*** power transmission. From the Rayleigh criterion, to produce the narrow beams necessary to focus a significant amount of the energy on a distant receiver, an antenna must be much larger than the wavelength of the waves used: $D_{ant} >> \lambda = c/f$.

Practical *beam power* devices require wavelengths in the centimeter region or below, corresponding to frequencies above 1 GHz, in the microwave range or above.

Microwave Power Transfer (MPT)

Microwave Power Transfer (MPT), which is based on electromagnetic radiation, utilizes the far-field radiation effect of the electromagnetic field to transfer power in free space. A high power transmission level is ensured using this technology when initialized at the base stations and fed to the mobile devices and receiving station. For this to be effective, two points must fall within the line of sight. With the aid of Magnetron, the technology, when deployed with geosynchronous transmission and reception satellites, boosts the power of objects obtained from the base station. MPT is effective in the area of energy conversion; however, the difficulty experienced in trying to focus the beam over a small area presents challenges [28]. Power transmission begins with the conversion of electrical energy to microwaves, which is then captured by the rectenna. In using this technology, Alternating Current (AC) is not directly converted to the required microwave energy. Conversion to Direct Current (DC) must first be done and then to microwave utilizing magnetron. The rectenna receives the transmitted waves and efficiently changes the microwaves to electricity in the form of DC, then back to AC [28.]

Laser Power Transfer (LPT)

Laser power transfer (LPT) transmits power under visible or near-infrared frequency. It uses highly concentrated laser light aiming at the energy receiver to achieve efficient power delivery over long distances. The receiver of laser powering uses specialized photovoltaic cells to convert the received laser light into electricity [29]. LPT has an advantage of energy concentration. However, laser radiation could be hazardous and it requires Line of Sight (LOS) link as well as accurate pointing towards the receiver which could be challenging to achieve in practice. It also requires complicated tracking mechanisms and a large spectrum of devices. Compared to microwave WPT, laser beaming is more vulnerable to atmospheric absorption and scattering by clouds, fog, and rain, which greatly hinders its practical applications. A strong laser beam constitutes serious health hazards to humans and this method is quite expensive to actualize.

Solar Powered Satellite (SPS). It is the largest application of WPT and it makes use of satellites with giant solar arrays and placing them in Geosynchronous Earth Orbit. These satellites play a pivotal role in generating and transmitting power as microwaves to the earth.

Advantages of Wireless Power Transfer

- It is convenient as cable connection is not needed. [26].
- It is cost-effective.
- It comes in handy as a multi-device charging device.
- Wireless power transfer provides better product durability by delivering reliable power transfer in critical conditions like wet, dirty, and moving environments.
- Wireless power transfer also offers the simplicity of product design. Standard features like power ports can be sealed off to the extent that a completely waterproof device is achieved.

Disadvantages of Wireless Power Transfer

- Wireless chargers are relatively more expensive at the design stage than a conventional wall socket charger despite their rising popularity.
- While using a wireless charger might sound very easy, it is not. To charge a device wirelessly, you have to position the device the right way on the charger. Some chargers even have marked areas and they also direct you the position of the phone. Though this is changing with design upgrades, it's still miles away from being seamless.
- Fog, and rain, also affect the practical application of laser and microwave WPT.

With the presence of other communication systems, interference by microwaves occurs, which becomes a disadvantage.

4. Conclusion

The selected researchers have created and experimented with different compensation approaches for different applications based on the literature reviewed in this study to optimise the performance of the wireless power transfer system utilising various optimization techniques. Despite extensive research in the field of wireless power transfer, WPT's full potential has yet to be realised in terms of transfer power and distance, frequency, and coil dimensions because the current designed transmitter and receiver coils are too large to be integrated into consumer devices and cannot be considered portable because the coil would take up space in the working area. As a result, there is a need to continue study in this subject because there are numerous interesting applications suited for wireless power transfer.

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