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Wireless power transfer: a review

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Abstract- The ubiquitous nature and the proliferation of mobile devices has made wireless power transfer (WPT) a very important area of research. The flexibility and cost effectiveness of charging these enormous devices in our world without having to connect physically to any electrical port especially when the user is indisposed to do so is a very attractive characteristic of WPT. Conventional means of charging the batteries of these mobile devices are wired which invariably meansthey requirephysical connection to power sources through electrical cables. Electric power istransmitted wirelessly when a magnetic field produced by the inductive coupling of coils or electrical field produced by the capacitive coupling between electrodes is transferred over a short distance through the air interface and later received by an antenna for utilisation. This article gives a detailed review of the existing wireless power transfer technologies, principles of operation, applications and the opportunities for future research in this area of emerging technology. However, WPT has some drawbacks but it is a disruptive technology with the ability to revolutionise the dynamics of mobile wireless systems, internet of things and otherallied future technologies.

Keywords: Wireless Power Transfer, Energy Harvesting, Wireless Charging, Inductive Coupling, Capacitive Coupling, Charging Flexibility.

1. Introduction

WPT, also referred to as Cordless Power Transfer can be described as the transmission of power or electricity without any form of physical connection between the load, and the power source. This can be applied where continuous delivery of power/ energy is required, and/or where the use of conventional wires prove to be dangerous, inconvenient, expensive, impractical or unwanted. In WPT technology framework, a transmitter devicesupplied from a power sourceproduces a period shifting electromagnetic field. The power is then transmitted crosswise through space to a recipient gadget.This crosswise transmission separates power from the field and the electrical load to which the power is supplied. The technological innovation of the WPT improves the portability and flexibility of devices, making them more convenient and safer for use. It can also eliminate the use of physical connections to power devices.

WPT or cordless charging system is required to power electrical devices where physical interconnection of wires are impractical, dangerous or poorly arranged. WPT has inherent advantages such as enablement of transmission over long distances; convenient and flexible use; inexistent or low wear rates since use of wires have been greatly reduced [1]. It has numerous applications such as charging of electric vehicles with contactless system,factory automation, and wireless power supply to portable or wearable electronic devices etc[2]. Theschematic of a WPT system is presented in figure 1.

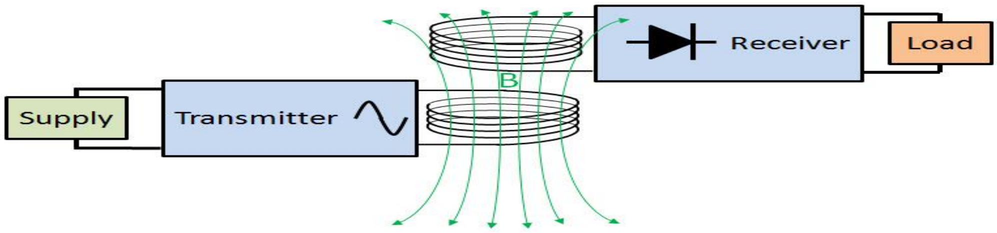

Figure.1: Schematic of WPT System (3)

2. History ofWPT

WPT dates as far back as the 19th century[4]. Based on theories already established by Michael Faraday and James Maxwell, Nikola Tesla in the 1890s started experiments on WPT, which he described as a very vital technology of "all-surpassing importance to man" [5]. Tesla constructed a huge coil and he supplied it with a 300 KW power at a frequency of 150 kHz, and atop sphere of 100 MV RF was attained. His experiment was considered a failure because of the dispersion of electrical power in all direction with 150 KHz radio frequency. His works on microwave power transmission and inductive coupling brought about the formation of the rudimentary principles of WPT. In 1901, Tesla, designed and constructed the Wardenclyffe tower (also called Tesla tower) which validated his principles on wireless power transfer [6].

John Schuder in 1961 proposed a transcutaneous energy system – to transfer power across the depth of the skin – which was used for implanted device. In 1964, William Brown wirelessly transferred electricity to a model aircraft thereby validating the viability of microwave power transmission. Peter Glaser proposed a solar powered satellite in 1968 which brought about a novel notion for microwave power transmission. In 2007, some MIT researchers successfully transmitted a power of 60W over a distance of 2m[4]. The innovative advances in the wireless power transmission can be divided into two viewpoints, which are:

(i) Long -distance and high-power remote vitality transmission
(ii) Short-range and low-power remote vitality transmission [7].

3. Principle of Operation of WPT

Valenta et al in [8] described how wireless power can be harvested and the components required. In the transmission section, the power source generates microwave power. While the waveguide circulator protects the source from the reflected power, which is connected through the co-ax waveguide adaptor. The tuner matches the impedance between the source and transmitting antenna, and the directional coupler separates the attenuated signals. The transmitting antenna emits the power regularly through free space to the receiving antenna.At the harvesting node, the antenna receives the transmitted power and converts it into DC power using a rectifier circuit. The impedance matching circuit ensures maximum power transfer from the antenna to the rectifier; while the LPF removes fundamental and harmonic frequencies from the derived output.The block diagram of a WPT System is presented in Figure 2.

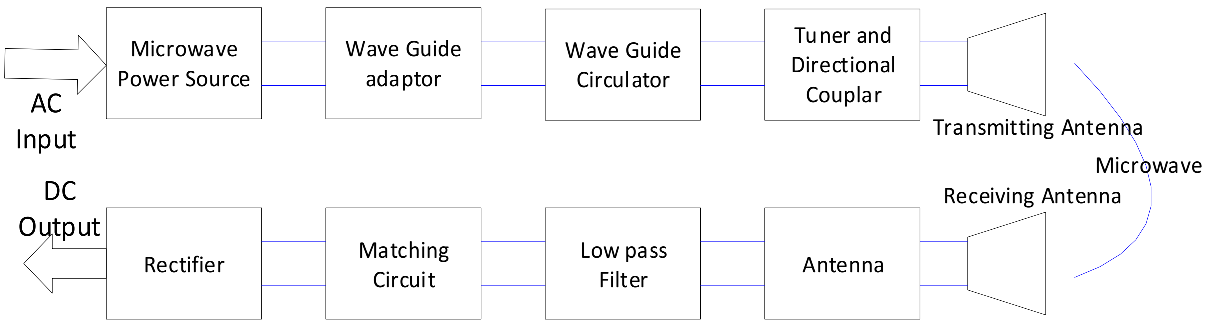

Figure.2: Block Diagram of a WPT System [4]

The metrics for characterizing energy harvesting circuits depend on the sensitivity and efficiency. The efficiency can be expressed as thepower-conversion efficiency, with the useful power supplied by the circuit as the output. Furthermore, it should be noted that the choice of equipment is heavily influenced by cost, transmit power and efficiency [9]; also, the direction and polarity of the antenna is determined by the specific areas in which the wireless power transfer is being applied to. However, necessary compliance to regulatory and safety standards are required [10].

WPT may be classified into two types, based on the distance of transmission. We have the near-field or non-radiative technique, and the far-field or radiative technique.

The *Near-field* technique basically involves the wireless transmission of power by a magnetic field through inductive coupling between separate coils of wire. The electric power can also be transmitted wirelessly by an electric field by the capacitive coupling of metal electrodes. This technique however, proves to be limited in range, with most applications typically requiring contact or close proximity of about a few centimeters between the power source and its destination[1].

The *far-field* or radiative approach, on the other hand, is characterized by longer range transmission of power, often reaching several kilometers in range. It may be further broken down into two sub-categories namely: Wireless Energy Harvesting (WEH), and Directive Power Transmission. Directive power transmission involves the use of a dedicated energy source from which power (typically in form of RF, microwave or laser) is beamed unto a pre-determined/targeted receiver positioned at a distance[3]. This is useful for solar powered satellite (SPS) applications as well as other intentional remote charging use cases. In the case of WEH, the direction of received power is unknown; It is the ambient energy signals present in the environment that are captured and converted to electrical energy for use [8].

WPT can be achieved using a number of methods[11]. They are:

3.1. Inductive Coupling
Most suitable for near -field power transmission, this technique utilizeselectromagnetic induction between coils of the transmitter and the receiver. Thesecoils are called repeaters and they increase power transfer efficiency which eliminates the inability to use WPT technologies over long distances.

3.2. Microwave
In this technique, the electrical energy is converted to microwave energy. Firstly, AC is converted to DC and DC to microwavesusing the magnetron. These waves are then transmitted from the base station to the receiver or mobile devices. After the transmission, a rectenna receives the microwave energy that is consequently converted back to electrical energy (DC) at the output.

3.3. Laser

Electrical energy is transformed into a laser beam that can be channeled to a given receiver, which later converts the laser beam back to electrical energy.The Laser can be powered by an electricity generator, a high-intensity-focused light, or the sun. The transmitted Laser is received by photo-voltaic cells, which converts it to electrical signal. It is suitable for long distances alongside its compact size and lack of signal interference; however, it tends to be harmful. Also, efficiency during conversion is not up to 50%, signal can be deterred while in the atmosphere and a line of sight is needed. This method is perfected mostly for military and aerospace purposes.

The quantity of power transferred in a given WPT system can be controlled by modulating the known frequency of the transmission signal around the resonant frequency that is formed by the tuning capacitor and the coil inductance. This can also be achieved using an alternative method which involves varying the voltage of the transmitter bridge; power level can be varied autonomously by either increasing or decreasing the given rail voltage as required by the load. This method is however less popular than the former method but can be implemented in situation where frequency modulation alone cannot be used to achieve required range of power levels. It also shows that charging should be done at a frequency well below or above the resonant frequency, to ensure the safety of the charged platform [12].

4. Review of Selected Works

Zhang et al in [13], considered the Electromagnetic or radio frequency (RF) signal powered WPT specifically. Since RF signals are able to simultaneously transmitboth information and power, the authors performed an integrated study on the simultaneous wireless information and power transfer (SWIPT).The paper particularly studied a multiple-input multiple-output (MIMO)[14,15] wireless communication system which comprises of three separate nodes, where one receiver harvests the power while the other decodes the information separately from the transmitted signals common to the two receivers. Two different scenarios were also investigated, the first in which both of the receivers were isolated and see different MIMO channels, and the other when they were located together and see the MIMO channel from the same transmitter.

The transfer of power and information, simultaneously over wireless channels could provide increased convenience in the use of mobile devices. However, current practical designs of receivers impose technical limitations in realizing such systems. This is because current hardware systems used for harvesting of energy from RF signals are incapable of decoding information directly [16]. To gain hypothetical ground, the authors proposed a general collector task, namely dynamic power splitting (DPS), which candivide the received signal with various power ratio, decoding information and harvesting energy differently.

In [17], the authors demonstrated that WPT technology can be used to cut the ‘last rope’, enabling users to flawlessly power their portable gadgets through the air as exemplified in how information is transmitted. Preliminary research into the use of magnetically coupledresonators for this application has yielded favorable outcomes. The authors presented new investigation that yields basic knowledge into the structure of systems including metrics for comparing the varying geometrics and operating conditions. A circuit model was also displayed together with the derivation of important concepts such as critical coupling, frequency splitting, behavior of the system when uncoupled etc.

The critical review in [18] showed the different research activities that was carried out on magneto-inductive WPT with the distance of transmission greater than the dimensions of the coil of the transmitter. The review gives a brief description of the principles of operation of a wide range of WPT system and the overview of the principles of maximum power transfer as well as the principles of maximum energy efficiency. The implications and the differences between these two methodsare explicitly discussed with respect to their distance of transmission and energy efficiency qualities. The differences between the energy efficiency and the transmission efficiency of the system are also reviewed. Other design issues such as safety concerns and the decrease of winding resistance were also discussed in the paper.

Low et al in [19] focused on an approach proposed to achieve a very efficient WPT system that accomplishes a low-power loss by using the Class-E mode of operation. This system can accomplish an efficient power-delivery response over a range of load resistances with no control system or a feedback loop but depends on its natural impedance reaction or response to be able to accomplish its desired power-delivery profile over a wide range of load resistances, while maintaining a high efficiency to prevent any heating issues. The proposed design comprises of multichannel which has an independent gate drive to enable the control of the delivery of power.

Lee et al in [20] proposed an equivalent or a corresponding circuit model for the wireless transfer of power of 60W and above and examines the system based on the proposed model. The proposed model was validated using finite-element analysis (FEA) and some experimental results. Also, for high-power applications, there were investigations of the losses in WPT systems. Due to the high operating frequency, losses due to proximity and skin effects were shown to be quite prominent in the system.Aspatial coil layout, which reduced the losses due to proximity and skin effects, was discussed. The coupled inductors are capable of transmitting power or electricity at short distances; and the distance is proportional to the mutual inductance.The problem of wireless power and information transfer over a noisy coupled-inductor circuit was considered in [21]. This circuit comprises of a frequency-selective channel that has an additive white gaussian noise (AWGN). The most suitable trade-off between the transferred power and achievable rate can be determined using the total available power. The practical applications of these systems were also discussed in the paper.

While it should be noted that convenience and overall cost per watt for the charging system are the key primary advantages and drivers of wireless power transfer technology, there however still exists various methods of achieving WPT. Magnetic field resonance as an example offers the best power transfer efficiency and larger wireless power transmission at near-field distances. Kim et al in [22], focused on the principles of magnetic field resonance WPT techniques while highlighting the effects of EM field noise from WPT and the related shielding methods for different applications. In the use of magnetic field resonance, the design of the coils, low-loss circuits, matching circuits and also the shielding structures are important factors that needs to be considered. The efficient combination of this concepts helps ensure maximum power transfer.

A resonant WPT system as shown in figure3, comprises of magnetically coupled transmitting and receiving coils; power electronic circuits; which includes voltage regulators, rectifiers and inverters. To maximize the power that is capable of being transferred between the magnetically coupled coils, a capacitor can be used, and also to reduce the magnitude of the reactance.

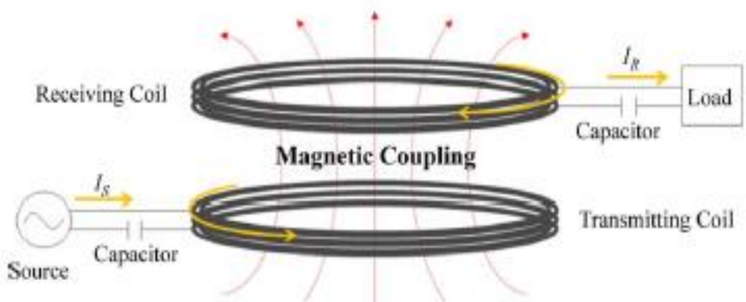

Figure 3: A Resonant WPT System

When there is power transfer from the transmitting coil to the receiving coil, there is generation of an electromagnetic field by the current which flows through the coils. This generated field is known as the EMF noise around the coils. Also, reactive resonant current loop is an approach that can be used in cancelation of this magnetic field and for passive shielding. This is done for minimal power loss due to shielding.

Kurs et al challenged the use of radiative method of WPT. It argues that although radiation is a perfectly suitable method for transferring information, it however still pose a number of challenges for power transfer applications because of the resultant low power transfer efficiency [23]. The authors also argued that there tends to be better efficiency of energy exchange with relatively little dissipated energy when two resonant objects of the same resonant frequency are coupled together.

Sample and Smith in [24] described the applications of two WPT systems using experimental results. The Wireless Identification and Sensing Platform (WISP) which are tiny sensors that consume electric power in the order of 2μW to 2mW, and can be used at several meters of distance from the commercial off-the-shelf UHF (915MHz) RFID reader. The second system is used to harvest UHF or VHF energy from TV towers around, thus making the total amount of available power depending on its range and also its broadcast transmitting power. The authors reviewed an investigation where 60μW was harvested at approximately 4km range.

As communication system performance are limited by the battery life of the devices, authors in [25] argued that wireless powered communication could provide stable and continuous microwave energy allowing for a network with improved flexibility, better robustness and greater throughput. The limitations of battery charging were also discussed in [26]. The authors proposed the use of WPT to solve the challenge of energy per lifetime of wireless sensor networks which require continuous and prolonged use life.

5. Applications

There are diverse applications of WPT in several industries, though, these applications have unique specifications such as power rating, distance and size. However, the fundamentals of metamaterials have been so designed in order to increase the energy efficiency for transmission using factors such as chirality, permeability and permittivity [27].

WPT can be used to charge moving targets like fuel free airplanes, moving robots, and also electric vehicles, thereby solving the energy density constraints and minimizing the cost of the energy storage systems which constitutes a significant portion in the cost of electric vehicles. Li et al proposed such in [28] that the obstacles of range, costs and charging could be mitigated through WPT. Hata et al in [29] also made the proposition of using WPT in electric vehicles to reduce the energy storage size and to extend the mileage range of electric vehicles.

WPT can also be applied in medical implants, for detection and also treatment of human body ailments, as these gadgets need nonstop power to function appropriately, over long periods of time. The external device charges the implanted medical device utilizing inductive coupling [30].

Also, the applications of WPT in renewable energy was highlighted by Chhawchharia et al in [6], especially in Space Solar Power System (SSPS), Unmanned Aerial Vehicles (UAV), and Autonomous Underwater Vehicles (AUV) etc. With Space Solar Power System, satellites collectenergy from sunlight and sends power back to earth through MPT, which is a potential renewable energy solution for the planet.Furthermore, WPT can be used in the design of solar-powered cooling system for vehicle cabin, so as to reduce the resultant greenhouse emissions that could occur if using the cabin engine [31].

6. Challenges

Wireless transfer of powerto electronic devices at maximum efficiency while considering the safety concerns can be quite challenging [32]. Microwave power transfer uses more intense microwaves when compared to wireless communication system, these microwaves can be harmful to humans. Specific absorption rate (SAR) is the benchmark used in determining if the microwave is harmful for humans [6].

Another problem is power density which is difficult to estimate. Due to refraction and reflection of signal originating from the source, there is minimal control. Electromagnetic radiations have erratic movement so therefore there is going to be level safety concern associated with it when used for wearable devices. WPT shares the same frequency (2.45 GHz or 5.8GHz) with a number of radio services, so WPT can possible interfere with these services [6].

Another challenge of employing wireless power transfer technology can be highlighted in applying WPT to communications systems as the system is likely to suffer from possible information interception considering the nature of the wireless channels which may increase the vulnerability of the system to eavesdropping [31]. This is also emphasized in applying WPT in clinical applications as the limitations include safety and security issues due to jamming, monitoring and spoofing; which further emphasizes the point that Wireless Power Transfer is vulnerable to attacks [28].

7. Conclusion

WPT is a revolutionizing technology that has inherent applications in different sectors as highlighted in this paper. However, there exists several limitations in achieving the widespread use of this technology. Hence, these limitations serve as opportunities for further investigations into these centuries-old questions. The solutions in terms of new technologies and methods that will be provided by these researches will potentially go a long way in actualizing electrical power systems with minimal use of wires, which in turn will lead to better cost savings. The eliminations of such cables also have resultant effects in allowing for more portability and better performance of mobile devices that require continuous operations.

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