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Wireless power Transmission: Applications and Components

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Abstract

Wireless power technology offer the assure of cutting the last cord, allowing users to faultlessly recharge mobile devices as simply as data is transmitted through the air. In this manuscript, we present the idea of transmitting power without using wires. Besides discussed the technical developments in Wireless Power Transmission (WPT) we also emphasis on reward, disadvantages, biological impacts and applications of WPT.

1. Introduction

Maxwell's equations, which were formulated in 1862, are basically the first theoretical basis of WPT [Figure 1]. The concept of the Poynting vector describes the radio wave as an energy flow. After Maxwell and Poynting, Nikola Tesla had a dream over a hundred years ago that all electricity would be provided wirelessly. He conceded out the first WPT experiments at the end of 19th century [1], [2] [Figure1(2)]. He tried to broadcast approximately 300 kW power via 150 kHz radio wave. Unfortunately, he failed because of diffusion of the wireless power, which depends on the frequency of operation and the size of the transmitting antenna. He used an operating frequency of 150 kHz. After Tesla's failure, the history of radio-wave development focused on wireless communication and remote sensing rather than WPT [Figure 1(3)]. However, the advancement of wireless communication and remote sensing technology helped the development of new WPT techniques.

The true history of WPT started with the use of microwaves: microwave power transmission (MPT). In the 1960s, William C. Brown restarted WPT experiments with high-efficiency microwave technologies [3], [4] based on the wireless communications and radar remote sensing [Figure 1(4)] technology developments during World War II. He carried out many kinds of MPT experiments with 2.45 GHz microwave tubes (for example, magnetrons, and klystrons) [Figure 1(5)]. He first developed a rectifying antenna, which he called a "rectenna," for receiving and rectifying microwaves. The efficiency of the first rectenna developed in 1963 and was 50% at an output power of 4 W dc and 40% at an output power of 7 W dc, respectively [3]. With the rectenna, Brown succeeded in transmission of power by microwaves to a tethered helicopter in 1964, and to free-flying helicopter in 1968. In 1975, the total dc-dc efficiency was up to 54% at 495 W dc, using a magnetron in the Raytheon Laboratory (Figure 2). In parallel, Brown and Richard Dickinson's team succeeded in the largest MPT demonstration in 1975 at the Venus Site of the Jet Propulsion Laboratory (JPL) Goldstone Facility (Figure 3) [6]. The distance between the 26 m diameter parabolic transmitting antenna and the 3.4× 37.2 m^2 size rectennas array was 1.6 km. The transmitted microwave power from the klystron source was 450 kW at a frequency of 2.388 GHz, and the achieved rectified dc power was 30 kW dc with 82.5% rectifying efficiency.

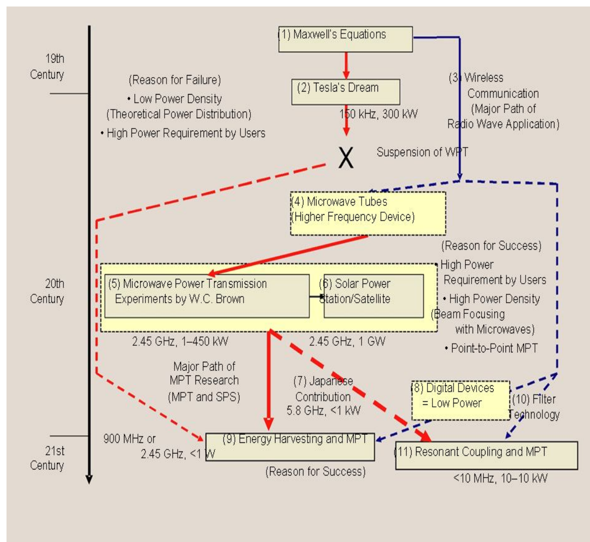

Figure 1 History of wireless power transmission and microwave power transmission. The main application areas and characteristics, such as frequency and power, are shown.

Although Brown succeeded in the WPT field experiments, the system size and cost was too big for any realizable practical applications. Therefore, commercial MPT systems did not become part of our daily life. MPT technologies were also developed with a solar power satellite (SPS), as presented in [Figure 1(6)], and the approach was proposed by Peter Glaser in 1968 [7]. The SPS overcame some of the drawbacks of MPT, for example, the low overall system efficiency, which depends on microwave/dc conversion, and the large size of the antennas. The SPS supplied approximately ten times more electric power than solar cells on the ground because it was in geostationary orbit in space. There is no night in the geostationary orbit, so power generation is 24/7, and the microwaves do not get absorbed by the clouds and rain as sunlight does. MPT was required for the SPS, and consequently, MPT techniques have been developed with the development of the SPS [8]. After the 1980s, many experiments on the MPT development were carried out in Japan [Figure 1(7)]. Hiroshi Matsumoto of Kyoto University and his group carried out MPT rocket experiments in 1983 (Figure 4). This included the microwave ionosphere nonlinear interaction experiment (MINIX) for the SPS. His group carried out a several MPT field experiments [8], which were based on new microwave technologies for wireless communication and radar sensing.

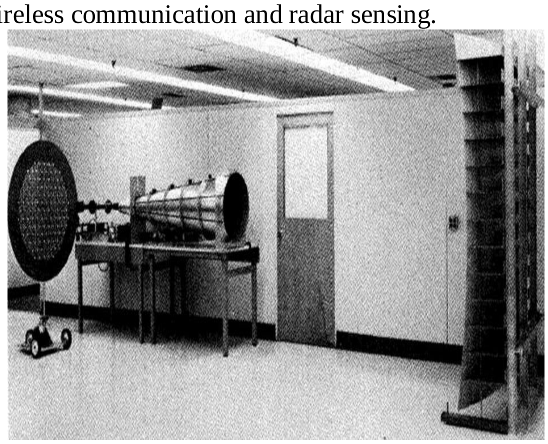

Figure 2 Microwave power transmission laboratory experiment in 1975 by W. Brown [5].

An MPT experiment with a phased array was carried out in 1992 [9], [10], the first trial to apply the phased array technique for this purpose. Kyoto University, Kobe University, and their team flew a fuel-free airplane powered only with 2.411 GHz microwave energy using a phased array with 96 GaAs semiconductor amplifiers and 288 antennas in three sub arrays (Figure 5). A Canadian group also flew a fuel-free airplane in 1987. They adopted a parabolic antenna system [11]. In the United States, some research groups maintained the MPT and SPS research through the 1980s. Then in 1995, NASA launched a project to take a fresh look at solar powered satellites. U.S. research in MPT reenergized with this project [12].

The phased array is an important feature in the development of a practical MPT system. In Japan, two MPT experiments with phased arrays were carried out at the end of the 2000s. One was a field MPT experiment from an airship to ground with two phased-controlled magnetrons by Kyoto University's group in 2009 (Figure 6) [13]. The first phase-controlled magnetron was developed by W. C. Brown in 1960s [14]. The Kyoto University group revised the phase-controlled magnetron in the 1990s [15] and applied it to an airship experiment. The other field experiment with a phased array was carried out by a team from Kobe University, Japan, and John Mankins, from Hawaii in the United States in 2008. They transmitted approximately 20 W of microwave power towards a target 150 km away with a phased array. microwave power, which depended on distance and antenna aperture, the transmission scheme formed the basis for follow-on work.

In the 2000s, advances in microwave technologies pushed WPT back into consideration for commercial applications. With the development of mobile communications technologies, the required power decreases for WPT [Figure 1(8)]. This means that we can receive enough power via microwaves, just as with a wireless communication [Figure 1(9)]. This was termed "ubiquitous power source," meaning that the source of the microwave power is everywhere and always on with WPT [16]. Wireless power can be received through broadcast service radio waves also [Figure 1(9)].

Figure 3 first and largest ground-to-ground MPT experiment conducted in 1975 at the Venus [6].

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Figure 4 MINIX rocket experiment in 1983.
Figure 5 MINIX rocket experiment in 1983.

Energy harvesting systems can be developed based on this approach [17], [18]. The definition of “energy harvesting” or “energy scavenging” is the process by which energy is derived, captured, and stored from external sources, for example, solar power, thermal energy, wind energy, salinity gradients, kinetic energy, or broadcast radio waves.

Figure 6 Microwave power transmission experiment with two phase-controlled magnetrons by Kyoto University, whose microwave power was transmitted from the airship in 2009.

One of the more famous energy harvesters is the power microelectromechanical systems (MEMS), which can generate electric power from the fluctuation in a MEMS semiconductor. The energy harvester from broadcast radio waves is a rectenna, used for both MPT and WPT. The other recent trend in WPT started from the use of resonant coupling by MIT [19] in 2006. The resonant coupler is well known as a microwave filter. The team at Massachusetts Institute of Technology (MIT) applied it to WPT. With this technique, a large amount of power (from watts to kilowatts) can be transmitted without any radiation over mid-length distances (more than a few meters) at low frequencies (less than 10 MHz) using simple resonant circuits. It became evident that, the resonant coupling of WPT is more suitable for commercial needs. The IEEE MTT-S International Microwave Symposium (IMS) Workshop on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMSWIWPT2011) was held in May, 2011 [20], where much new research on the resonant coupling WPT was presented.

2. WPT system Components

The Primary components of Wireless Power Transmission are Microwave Generator, Transmitting antenna and Receiving antenna (Rectenna). The components are described in this chapter.

2.3.1Microwave Generator

The microwave transmitting devices are classified as Microwave Vacuum Tubes (magnetron, klystron, Travelling Wave Tube (TWT), and Microwave Power Module (MPM)) and Semiconductor Microwave transmitters (GaAs MESFET, GaN pHEMT, SiC MESFET, AlGaN/GaN HFET, and InGaAS). Magnetron is widely used for experimentation of WPT. The microwave transmission often uses 2.45GHz or 5.8GHz of ISMband. The other choices of frequencies are 8.5 GHz [13], 10 GHz [14] and 35 GHz [15]. The highest efficiency over 90% is achieved at 2.45 GHz among all the frequencies [15].

2.1 Transmitting Antenna

The slotted wave guide antenna, microstrip patch antenna, and parabolic dish antenna are the most popular type of transmitting antenna. The slotted waveguide antenna is ideal for power transmission because of its high aperture efficiency (> 95%) and high power handling capability.

2.2 Rectenna

The concept, the name ‘rectenna’ and the rectenna was conceived by W.C. Brown of Raytheon Company in the early of 1960s [16]. The rectenna is a passive element consists of antenna, rectifying circuit with a low pass filter between the antennas and rectifying diode. The antenna used in rectenna may be dipole, Yagi – Uda, microstrip or parabolic dish antenna. The patch dipole antenna achieved the highest efficiency among the all. Schottky barrier diodes (GaAs-W, Si, and GaAs) are usually used in the rectifying circuit due to the faster reverse recovery time and much lower forward voltage drop and good RF characteristics.

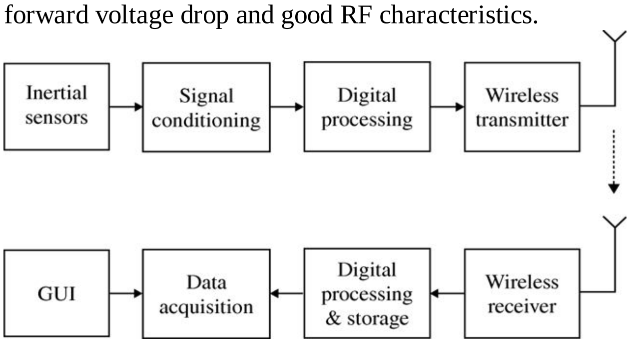

Figure 7 Flow and components of Wireless power System

Various Technologies of WPT

3. Merits

1. Various methods of transmitting power wirelessly have been known for centuries. Perhaps the best known example is electromagnetic radiation, such as radio waves. While such radiation is excellent for wireless transmission of information, it is not feasible to use it for power transmission. Since radiation spreads in all directions, a vast majority of power would end up being wasted into free space.
2. Wireless Power Transmission system would completely eliminates the existing high-tension power transmission line cables, towers and sub stations between the generating station and consumers and facilitates the interconnection of electrical generation plants on a global scale.
3. It has more freedom of choice of both receiver and transmitters. Even mobile transmitters and receivers can be chosen for the WPT system.
4. The power could be transmitted to the places where the wired transmission is not possible. Loss of transmission is negligible level in the Wireless Power Transmission; therefore, the efficiency of this method is very much higher than the wired transmission.
5. Power is available at the rectenna as long as the WPT is operating. The power failure due to short circuit and fault on cables would never exist in the transmission and power theft would be not possible at all.

3.1 **Demerits**

1. Capital Cost for practical implementation of WPT to be very high.
2. The other disadvantage of the concept is interference of microwave with present communication systems.
3. Common belief fears the effect of microwave radiation.
4. But the studies in this domain repeatedly proves that the microwave radiation level would be never higher than the dose received while opening the microwave oven door, meaning it is slightly higher than the emissions created by cellular telephones [6].

4 Environmental Issues

4.1 Interferences to Existent Wireless System

Most MPT system adopted 2.45 GHz or 5.8 GHz band which are allocated in the ITU-R Radio Regulations to a number of radio services and are also designated for ISM (Industry, Science and Medical) applications. Conversely speaking, there is no allowed frequency band for the MPT; therefore, we used the ISM band. The bandwidth of the microwave for the MPT do not need wide band and it is enough quite narrow since an essentially monochromatic wave is used without modulation because we use only carrier of the microwave as energy. Power density for the MPT is a few orders higher than that for the wireless communication. We have to consider and dissolve interferences between the MPT to the wireless communication systems.

4.2 Safety on Ground

One of the characteristics of the MPT is to use more intense microwave than that in wireless communication systems. Therefore, we have to consider MPT safety for human. In recent years there have been considerable discussions and concerns about the possible effect for human health by RF and MW radiation. Especially, there have been many research and discussions about effects at 50/60 Hz and over GHz (microwave). These two effects are different. There is long history concerning the safety of the microwave. The corresponding limits for IEEE standards for maximum permissible human exposure to microwave radiation, at 2.45 or 5.8 GHz, are 81.6 or 100 W/m2 as averaged over six min, and 16.3 or 38.7 W/m2 as averaged over 30 min, respectively, for controlled and uncontrolled environments [37]. The controlled and uncontrolled situations are distinguished by whether the exposure takes place with or without knowledge of the exposed individual, and is normally interpreted to mean individuals who are occupationally exposed to the microwave radiation, as contrasted with the general public. In future MPT system, we have to keep the safety guideline outside of a rectenna site. Inside the rectenna site, there remains discussion concerning the keep out area, controlled or uncontrolled area.

4.3 Interaction with Atmosphere

In general, effect of atmosphere to microwave is quite small. There are absorption and scatter by air, rain, and irregularity of air refraction ratio. In 2.45 GHz and 5.8 GHz, the absorption by water vapor and oxygen dominate the effect in the air. Especially, it is enough to consider only absorption by the oxygen in the microwave frequency. It is approximately 0.007 dB/km [38]. In the SPS case, the amount of total absorption through the air from space is approximately 0.035 dB[39].

4.4 Interaction with Space Plasmas

When microwave from the SPS propagates through ionospheric plasmas, some interaction between the microwave and the ionospheric plasmas occurs. It is well known that refraction, Faraday rotation, scintillation, and absorption occur between weak microwave used for satellite communication and the plasmas. However, influence to the MPT system is negligible. For example, reflection through the ionosphere at 2.45 GHz and 5.8 GHz is only 0.67 m and 0.12 m, respectively, when they calculated theoretically with the Snell's law and total electron contents in the ionosphere [40]. However, there is no inference because diameter of rectenna site will be over km. These interactions will not occur in existent satellite communication systems because the microwave power is very weak.

5. Applications of WPT

5.1 Wireless Power Transmission for Electric Vehicles

One exciting application of WPT is wireless charging of an electric vehicle. We can apply various WPT techniques including inductive coupling, resonant coupling, or MPT, for use in charging electric vehicles. Inductive coupling WPT has been applied to the wireless charging of an electric bus by Hino Motors [22], Ltd. and Showa Aircraft Industry [23]. They called it ‘inductive power transfer’ and demonstrated an inductive power transfer hybrid system, operating over the period from April 13 to 27, 2009. In Korea, a resonant coupling technique for a wireless power supply has been used for an online electric vehicle [24]. Power from the 60 Hz supply is converted to a frequency of 20 kHz by an inverter stage. 60 kW of power may be transferred wirelessly from power lines with 80% efficiency. Some companies in the world, for example, HaloIPT Co., Evatran Co., and UniServices Co., showed the inductive coupling.

WPT system for an electric vehicle as commercial products. There have been some research studies of the application of resonant coupling WPT for electric vehicles [25]–[27]. Toyota Central R&C Lab., Inc. and Toyohashi University of Technology proposed a new concept of power transfer through a capacitor composed of a steel belt in a tire and a metal plate attached to the road [27]. Toyota Motor Co. invested in WiTricity Co., which is the first inventor of resonant coupling for WPT in 2011. IHI Co. was given a license from WiTricity Co. in 2011.

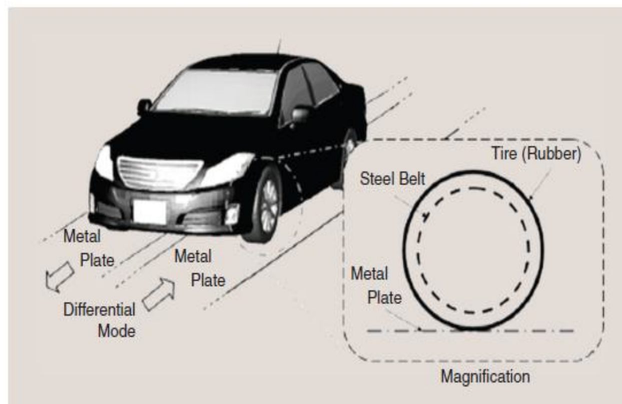

Figure 4.3 Diagram of the power transfer system proposed by Toyota Central R&C Lab., Inc. and Toyohashi Univ. of Tech., Japan [27].

MPT can also be applied to the wireless charging of an electric vehicle. Kyoto University proposed and developed a MPT technique for an electric vehicle in 2000. The battery on the electric vehicle can be charged using only microwave transmission with a theoretical beam efficiency of 83.7% and an experimental beam efficiency of 76.0% [28]. This efficiency is high enough to transmit wireless power with the microwave. We have developed a new GaN Schottky diode for this application, to increase the rectified power and to reduce the charging time [29].

5.2 Wireless Power Transmission for Mobile Phones

A wireless charging pad for mobile phones, based on the Qi standard defined by the Wireless Power

Consortium (WPC), is released in 2011 [30]. The Qi standard is based on an inductive coupling WPT technology. The WPC has been active in popularizing the Qi standard and multipurpose inductive coupling WPT. At the Mobile World Congress in 2009, Qualcomm demonstrated a wireless charging technology for a mobile phone with resonant coupling WPT technology. Qualcomm called it "eZone" [31] and used 13.56 MHz as the coupling frequency.

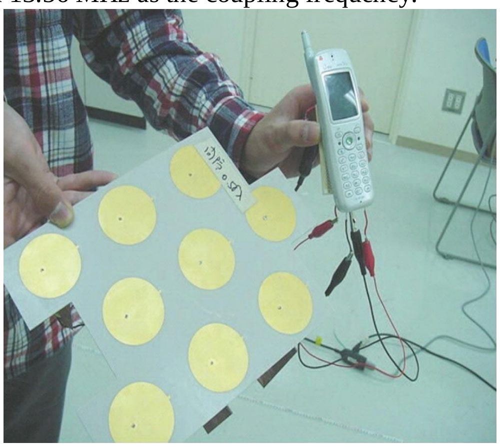

Figure 4.5 Wireless charging of a mobile phone via 2.45 GHz microwaves [16].

In Kyoto University, wireless charging for a mobile phone via 2.45 GHz microwave link (Figure 15) has been proposed [16]. The advantage of MPT based wireless charging is that it can be a multiuser and multipurpose system. We can transmit both power and information via the microwave connection [32].

5.3 Wireless Power Transmission for Other Applications

WPT can also be applied to various other applications and systems. RF identification (RFID) is probably the most well-known commercial application of MPT. This technology mainly uses the 900 MHz band. As already mentioned, energy harvesting from broadcast radio waves is one of the important technologies for WPT. A team from Intel used channel 48, 674– 680 MHz, and harvested 60 mW, 0.7 V with a Yagi-Udaantenna [17]. PowerCast Co. released an energy harvesting receiver for operation at 850–950 MHz, using 26 dBm and 211 dBm input power, respectively.

Kashima Co., Japanese building company, proposed a wireless building using microwave power technology with Kyoto University [34]. They used the building structure itself as a waveguide for the microwave power to reduce the number of electric wires. Another Japanese building company, Takenaka Co., is developing a noncontact outlet with a resonant coupling technology. A German company, EnOcean has released a codeless switch that uses an energy harvesting technology [35]. The codeless switch is composed of an energy harvester from light, vibration, and other sources, and an RF device to send on/off information to the lights. This presents a kind of wireless building since there is no wire between the switches and lights. A battery-less sensor is another innovative WPT application. Kyoto University's team has driven a Zigbee device using only 2.45 GHz microwave power [32]. Several medical applications also can utilize WPT. A wireless powered drug release system with a resonant coupling technology is being studied in the United Kingdom [36].

Conclusion

In this Paper, we lay a hand on the history behind wireless power technology while also explaining in fact how the diverse methods of wireless power transmission work. In particular, we spend a significant amount of time unfolding the models and functionality of circuitry found in devices that spawn wireless power.

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