A Literature Survey of Wireless Power Transfer

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***Abstract*— Over 115 years ago Tesla invented the concept of wireless power transfer. Many industrial applications based on this technology have been developed ever since. This technology is of interest especially where the interconnecting wires are inconvenient, or even impossible. This paper provides a survey that describes the history of wireless power technology. Specifically two types of wireless power transfer, radiative and non- radiative, are studied. Additionally the formation of the first standard (Qi) and other standards are mentioned. Finally, the main challenges and future prediction of this technology are presented too.**

I. INTRODUCTION

Wireless Power Transfer (WPT) is a term that includes several technologies to transmit power without connecting wires. This technology is not only useful for application where interconnecting wire is not possible (such as charging cardiac pacemakers) but also will be useful for reducing toxic material resulted from disposing of 6 billion batteries each year used for battery operated electronic devices (e.g. laptops, mobile devices and toys) [1]. There is a need for significant research to mature the technology of wireless power.

Wireless power transfer is classified into non-radiative and radiative categories depending on the mechanism of energy transfer [2]. Non-radiative or near-field (short and medium range) power transfer operates at distance less than a wavelength of the transmitted signal [3]. For short-range charging the receiver distance is less than the diameter of the transmitting coil. Inductive and capacitive coupling are two types of this charging method. In mid-range the receiver distance varies from one to ten times the diameter of the transmitting coil [4], Resonant inductive or capacitive coupling power transfer method fall into this type. Radiative or far-field power transfer operate at distance more than twice of the wavelength of transmitted signal.

This literature survey begins with a brief description of wireless power transfer history, continued with a discussion on the research done on non-radiative and radiative power transfer, followed by an introduction of formation of the first international wireless power standard (Qi) and other standards. Finally the challenges and the future of wireless power transfer are discussed.

II. HISTORY OF WIRELESS POWER TRANSMISSION

In 1820 Han Oerested, during a lecture, noticed a needle deflection of compass when electric current flew in one wire cable which proved the magnetic effect of electricity. In 1826, Andrie-Marie Ampere, through his circuital law, formulated the relationship between electric current and the produced magnetic field. In 1831 Faraday's law described that the electromagnetic force could be induced in a conductor by varying magnetic flux. In 1888, Heirnrich Hertz confirmed that electromagnetic radiation exists. In 1891 Nicola Tesla improved Hertz's wireless transmitter and registered it in a patent [5].

In 1894 Hutin and Leblanc's patent on wireless power transmission at 3 kHz was issued [6]. In the same year, Tesla successfully energized a light lamp using a pair of coils [7], as shown in Fig. 1.

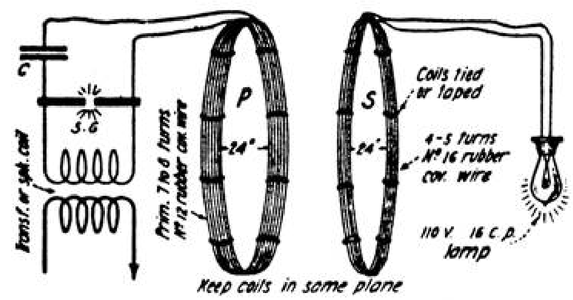

Fig. 1. Diagram of one of Tesla's wireless power experiment [8].

In 1895, Jagdish Bose was able to ring a bell remotely from 75 feet distance through a wall using electromagnetic wave [9]. Marconi successfully sent radio transmission over distance 1.5 miles in 1896. Tesla performed wireless power transmission to 48 km distance [10].

In 1904, a prize was offered for a successful attempt to drive a 0.1 horsepower (75W) airship motor by energy transmitted through space at a distance of least 100 feet [11]. In 1926 Yagi and Uda invented their high gain directional array antenna. Then William Brown published his article about possibilities of microwave power transfer and demonstrated a helicopter model that receives the microwave beam [12]. In 1968, Peter Glaser demonstrate the principle of solar power satellite through his proposal that the wireless energy transmitted from the Sun could be captured [13]. In 1973, the first passive system Radio Frequency Identification (RFID) receivers were energized by electrodynamic induction from a few feet distance in Los Alamos National Lab.

In 2007, a physics research group at the Massachusetts Institute of technology (MIT), led by Professor Marin Soljacic, presented a coupled magnetic resonance power transfer system and his success to wireless powering of a 60W light bulb with 40% efficiency at a 2m distance using two 60 cm-diameter coils, they called it "Witricity" [14]. Recently in 2008, Intel reproduced the MIT group's experiment and wirelessly powering a light bulb at 75% efficiency, but for a shorter distance [15].

In 2015, Dr. Rim, a professor of Nuclear and Quantum Engineering at KAIST University, and his team used inductive power transfer and transmitted it to a distance of 3-5m where efficiency is 29%, 16%, 8% for 3m, 4m and 5m, respectively [16]. They used 20kHz signals.

Wireless power transfer research between 2001-2013 is summarized in reference [17], with citation of over 50 papers. According to [17] the most productive author is Fu and Imura. Also the top four active countries in this field are mentioned as USA, South Korea, China and Japan.

III. Non-Radiative Power Transfer

Non-Radiative power transfer also called near-field transfer technique offers very good efficiency. The drawback is that it is very limited to small distance, where the receiver distance (*r*) is less than the wavelength of transmitted signal (λ).

A. Short Range

In short range the receiver distance r is less than the diameter of the coil d ($r < d$), the following two techniques are used to transfer power wirelessly.

1) Inductive Coupling

Inductive coupling is an old method based on a simple principle; a source driving the varying magnetic field is connected to a primary coil which will induce a voltage across the receiver secondary coil, and transfer the power transfer to load accordingly. Frequency varies between the range of 20-40kHz for a distance around of 10cm.

Inductive coupling can be classified into two groups depending on the direction of the flux flow relative to the charging surface: horizontal approach and vertical approach [18].

In commercial side, wirelessly charged waterproof products, such as electronic toothbrush and shavers, have already entered the consumer market, such power chargers adopted a fix positioning load receiver [19].

Usually inductive charging induce Eddy current in metal which causes sparking and arching hazard, to solve this problem researchers introduce very thin electromagnetic shield under the charging pad and over the receiving coil to solve this problem [20],[21]. Also in [22] authors applied this technology to eliminate an electronic device external metallic contact via designing a high efficiency wireless power transfer system using class-E transmitter efficiency, they used 134kHz frequency and provided 295W power at 75.7% efficiency, applying forced air cooling.

In [23] a system based on inductive charging has been proposed that has the ability to transfer 20W power to 1cm distance with efficiency of 80%. This system is suitable for medical applications. In the same paper the major differences between the low power and high power inductive link have been presented.

Recently, MIT scientists have announced the invention of wireless charging technology, called MagMIMO [24], which can charge a wireless device at distance as far as 30cm away. MagMIMO can detect and cast a cone of energy toward a phone, even when the phone is put inside the pocket

2) Capacitive Coupling

In capacitive coupling energy is transferred through electric field between two electrodes. The amount of transferred energy is increased with frequency increase. It has advantage of capability of transferring power through metal. This method has only been used for low power devices, due to hazardous issues when high voltage is applied to electrodes. Additionally, many materials are strongly affected by high power electric fields, including human body. This yields limitation in using this technology in biomedical applications.

The main two types of circuit that are used for capacitive coupling *are* (1) transverse of bipolar design, where the receiving plates should be always aligned to the charging plates, and (2) longitudinal or unipolar design.

B. Medium Range

There is great interest in mid-range power transfer, e.g. distances around 0.5m to 5m ($d < r < 10d$). The operating frequency usually ranges between 10kHz-200MHz. Two coil, three coil, and four coil systems have been used for this range [2]. This method can be used to energize and transfer power at home and offices. There are two techniques proposed to transfer power in this range: magnetic resonance coupling, and inductive power transfer system.

The use of resonant frequency principle has been favored because it reduces the leakage, and therefore, this allows to transfer the power to a farther distances. In [25], the relationship between the frequency between (11 MHz-17 MHz) and power efficiency was studied using electromagnetic field analysis for different air gap length for magnetic coupling resonance circuit. They also studied the relation between the maximum efficiency and air gap length. Their results shows that two resonant frequencies appeared for 49cm and 80cm airgap where one resonant frequency happens for 170cm and 357cm airgap. The result for peak efficiencies versus different air gap length is shown in Fig. 2.

In [14] MIT team explained in details the magnetic resonance coupling method to transfer power in this range. In the same paper they also implemented two identical helical copper coils (d=25cm) to transfer 60W light bulb for 2m (4 times the diameter of coil) with 40% efficiency, they used 9.9MHz resonant frequency. Colpitts oscillators have been used as the source coil, their schematic diagram is shown in Fig. 3. The availability of building a receiver device coil to fit in any portable device without decreasing the efficiency was discussed in [14]. They also suggested that the efficiency could be improved by using silver-plating coil and better geometries of the resonance object.

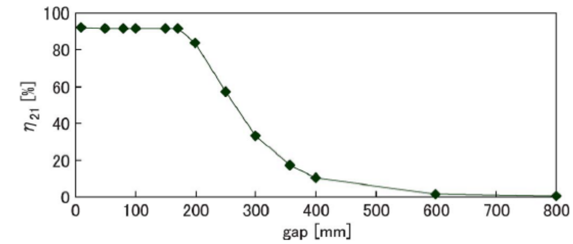

Fig. 2. Peak efficiency versus air gap length [48].

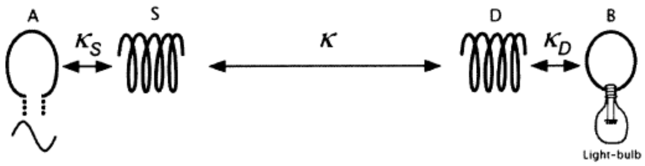

Fig. 3. Schematic diagram for MIT experiment [14].

Using magnetic resonant coupling to power multi receiver is reported by [26]. Authors built a magnetic resonant coupling experiment with one large source coil to generate a signal with frequency of 8.3MHz, and multiple resonant coil receivers were made using lumped capacitors at the terminal in order to match them to the resonant frequency. Their analysis showed that the efficiency was increased with increasing the quality factor of the resonant coupling factor. Authors stated that adjusting the lumped capacitance at the receiver coil with respect to the source and all other surrounding would be the main challenge for future work.

In [27] the experiment is explained where the laptop battery was removed and replaced by a battery that was charged via magnetic resonant coupling system. The system showed an efficiency of 50% for 70cm distance power transfer using 7.65MHz frequency.

Inductive power transfer technology is also proposed to transfer power in this range [16]. This system consists of capacitor, invertor, rectifier and load. It was shown by simulations, analysis and experiment that 20kHz and 105kHz are the most suitable frequency for this technique [16].

A team of researchers from KAIST University used 20kHz frequency inductive power transfer system [16]. They used dipole structure coil with ferrite core with long and narrow shape to be easily installed on the ceiling or the corner of a room, with overall configuration shown in Fig. 4. The maximum output power for 3m, 4m, and 5m, for frequency of 20 kHz were 1403W, 471W and 209W, respectively. The efficiency was 29%, 16%, 8% for each distance, respectively.

IV. Radiative Power Transfer

Radiative power transfer, or far-field power transfer technique, uses the propagation of electromagnetic waves in long distance (kilometers range) where $r > 2\lambda$. Two types of radiative power transfer are directive and non-directive. Microwaves with frequencies 300MHz – 300GHz and laser (ten of micrometer to nanometer wavelength) are used to transmit far-field power. For microwave propagation rectennas convert the received microwave signals to DC power. In [28], microwave with frequency 2.45GHz was suggested to be used to power solar satellites. In this study it was shown that the size of transmitter antenna should be 1km where the rectanna at receiver needs to 10km, which is impractical. It was stated that increasing frequency can minimize the antenna dimension but the drawback will be atmospheric absorption of the wave. Recently directive microwave was used to remotely power Electric Vehicles (EVs) [29]. A system that utilizes power transmitter on the side of the road directed to a rectenna receiver was suggested to rectify 10kW power with 80% efficiency conversion to energize EVs [30]. Commercializing these systems is expensive, depending on the design and infrastructure, also the electromagnetic compatibility for these systems should be considered during design. In [31]-[32] it has been advocated that mobile devices could be powered through high frequency microwave, for example 60GHz in the cellular networks. However, the practicability requires further experimental evaluation.

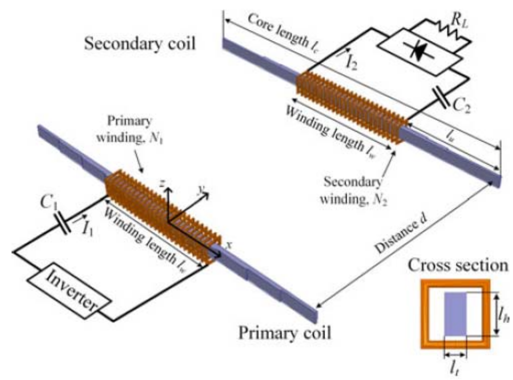

Fig. 4. Overall configuration the system proposed in [16].

For non-directive application, omnidirectional RF broadcast may also be used to transfer power to portable devices. In [33], [34], it is discussed if the energy is transmitted in the same way that radio signals are transmitted, it can be used for powering ultra high frequency RFID tags for 10m operating range. Usually low efficiency limits using multidirectional RF power transfer technology.

RF Beam with power densities between 20-200μW/cm^2 can be utilized to wirelessly charged sensor netwrosks, using non-directive RF charging., In [35] the authors implemented transmitter with 1.79mW power to 0.683mW receiver for an ultra-low power sensor platform powered by far-field method to achieve the data rate of 500kbps. Also similar work has been done for wirelessly charging sensors with batteries in [36]-[37].

Power could be also transferred through laser beam and stored it in photovoltaic cells. In 2003, NASA flew the first aircraft powered by laser [38].

RF energy harvesting also technology to convert RF radio wave from environment to DC, usually providing power at the level of milliwatts to microwatts. It is used to power low power sensors and electronic devices and calculators. Some of applications have been commercialized such as TX91501 power caster transmitter and P2210 power harvester, more detailed review for harvesting technology could be found in [39]-[40].

Ambient waves have many forms [41]. In [42] authors used TV broadcast to collect energy. In [43] amplitude modulated

(AM) radio broadcast have been used. In [44] 900MHz and 1800MHz bands of Global System for Mobile Communications (GSM) were used for energy harvesting. In [45] WiFi routers is used. In [46] cellular base stations is used, and finally, in [47], [48] satellites' electromagnetic waves are used for energy harvesting.

V. Standards

When designing the wireless power transfer system, safety standard should be taken into account, electromagnetic interference and human exposure to radiation should be studied. Lots of standards identify the safety of radiated emission [19], a few are: CISPR 11 or EN55011 class B group 2, CISPR 22 or EN55022 class B, FCC part 15 class B, CISPR 14.2 and EN62233:2008.

Over 130 companies formed a wireless power consortium and launched the first standard. "Q_i" was announced in 2010 for portable electronic devices up to 5W, and then part-1 of the standard was updated. This standard adopted the inductive wireless charging, vertical flux approach, guide for free positioning, communication between loads and charging pad and compatibility checks of load [19]. This standard is scoped for low power products such as mobile phones, and tablets.

Also another consortium has been established to develop the wireless power transfer standards: Power Matters Alliance (PMA) and Alliance for Wireless Power (A4WP). A4WP is focusing on how to generate larger electromagnetic fields with magnetic resonance coupling. This standard has three different power classes for a power transmitter unit (PTU) and a power receiver unit (PRU). PTUs are ranging from 10 W to 22W that can charge PRU devices of 3.5 W and 6.5 W output power. This standard proposes to achieve spatial freedom [40].

It is of interest to extend Qi standard to include effects of foreign objects, load detection, and ways to increase the transmission distance. In future extending the Qi standard to cover power capability to 120W instead of only 5W will be useful in order to apply it to large devices such as laptop [19].

VI. Challenges and Future Work

The main challenge that the near-field method is facing is the limitation on its transmission distance. The future work for this technology is focused on improving it to be used in the medical applications; integrating core link driver will be a way to increase the reliability.

Many challenges face the mid and long range technologies. Efficiency is very low for these methods, as shown in Fig. 5. It should be noted that the maximum efficiency that could be achieved for mid-range, which requires impedance matching, couldn't exceed 50% [2].

Future work in mid-range technology should consider maximizing the coil's quality factor; designing proper loading of the drive and load loop; and designing a system for impedance matching between the load and transmitter for variable distance, e.g. portable devices. Developing an adaptive rectifier that does not interfere with the of magnetically coupled resonant circuit is also desired [27]. Reducing the size of transmitter and receiver to be more suitable for commercial stage and reducing interference with foreign object surrounding the device are other challenges to be addressed [28].

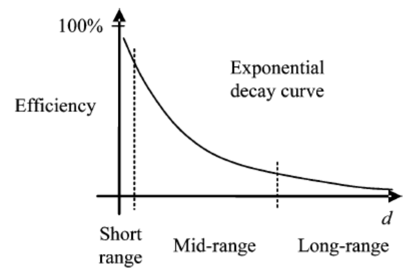

Fig. 5. Decay curve of efficiency [30].

For both short and mid ranges, the following factor should be considered during design stage. First the emitted magnetic flux shouldn't cause fire. It shouldn't corrupt data in smart card or credit cards. Also the surrounding metallic objects placed near the charging region shouldn't be heated up. The wireless charging system should be able to locate the position of the load or even make recommendations on how to locate it before starting energy transfer [19].

The main focuses for far-field systems are the improvement of directivity and efficiency. Although many systems have been built using microwave with high gain antennas to transfer power over kilometer distance with efficiency 90% [49][50], these systems still suffer from the need for Line of Sight (LOS) (point to point) connection. On one hand there is need to transfer power using omnidirectional antennas to cover more area, on the other hand there is a need for directive antennas to improve the efficiency. The received power density decreases by the factor of square distance from the transmitter to receiver. The transmitter needs to locate the load and direct the beam.

VII. Conclusion

Wireless power technology offers the chance to remove the cord connections required to connect electronic devices. Lots of research has been done in the past decade for this promising technology. In this paper a literature survey about wireless power transfer was presented. The paper first described the history of this technology, its two types of radiative and non-radiative ones, as well as the formation of the standards. These are summarized in Table I. Some of the main challenges and future predictions were mentioned too.

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TABLE I. COMPARISON OF DIFFERENT WIRELESS POWER TRANSMISSION METHODS.

	Categories	Range	Transferring Method	Frequency Range	Penetration	Efficiency	Drawbacks	Flexibility in Moving	Advantage
Wireless power Transfer	Non-Radiative (Near Field)	Short-Range	Inductive Coupling	10kHz-1MHz	Strong	High	Induce Eddy current through metal	Depending on design of charging pad	High efficiency up to 95% for few millimeter or few centimeters
			Capacitive Coupling	High Frequency	Strong	High	Strongly interact with materials and human body	Less flexibility for load location	Could be transferred through metal
				Low Frequency			Require large coupling area		
		Mid-Range	Resonant Inductive Coupling	10kHz-200MHz	Medium	Medium	Maximum efficiency when impedances are matching cannot exceed 50% also using operating frequency larger 10MHz will increase the cost and switching losses	Used for portable devices	High efficiency for few centimeters to few meters Charging multiple devices simultaneously
			Resonant Capacitive Coupling						
	Radiative (Far Field)	Long Range	RF/Microwave	300MHz-300GHz	Weak	Weak	Need directivity to transfer power (point – point) and in case of Omni-directional efficiency will be low	Less flexibility for load location in case of line of sight	Useful for mobile devices when using omnidirectional RF range
			Laser Photo Electricity	Millimeter to Micrometer wavelength (frequency up to ten of THz)	Weak	Weak	Harmful radiation	Require a direct line of sight with the receiver	Transmitted for large distance usually from several meters to several kilometers