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A REVIEW OF WIRELESS POWER TRANSFER SYSTEM USING INDUCTIVE AND RESONANT COUPLING

ABSTRACT: Wireless Power Transfer (WPT) using Magnetic Resonance Coupling (MRC) caught the significant attention from the researchers in academia and industries worldwide due to its higher power transfer efficiency especially at medium distances. In this regard, various circuit topologies have been proposed for further improving the efficiency. This review emphasizes the efficiency analysis of WPT system using circuit equations. This literature survey covers the two, three and four coils WPT system. In addition, review of multiple coils WPT structure is also presented. Frequency decrease analysis, impedance matching and frequency splitting phenomenon are also discussed. The two operating principles, maximum power transfer and maximum energy efficiency are described. This is followed by safety standard for WPT technology. Finally, a comparison of Inductive Wireless Power Transfer (IWPT) and Resonant Wireless Power Transfer (RWPT) is provided. This review will be helpful for the readers to understand the circuit structures and operating principles of the WPT technology.

Keywords: Wireless Power Transfer (WPT), Magnetic Resonance Coupling, Frequency Splitting, Efficiency Analysis, Maximum Power Transfer, Maximum Energy Efficiency.

INTRODUCTION

Wireless Power Transfer (WPT) is an old technology. It was first reported at the end of 19th century and the idea was demonstrated by Nikola Tesla (Tesla, 1914). WPT can be broadly segregated into radiative or non-radiative power transfer. Radiative power transfer can be explained as the power, transfers through air or vacuum in the shape of an electromagnetic wave via a transmitting antenna over a large distance which can be several times greater than the dimensions of the transmitting antenna (Hui and Zhong, *et al.*, 2014). This WPT technology finds its application in industrial, scientific, medical and defense purposes and it utilizes the frequency from 100 kHz to tens of megahertz (Tseng *et al.*, 2013; van Wageningen *et al.*, 2010). Although, notable research has been carried out in the late 1970s in this field of long distance radiative WPT, this approach does not offer high transfer efficiency because of its omni-directional nature (Barman *et al.*, 2015). Moreover, the radiative power transfer technique can be dangerous for human health because of its radiation pattern, so it is not a prevalent option for civilian use. Recent trends of ongoing research in non-radiative WPT technology indicates that this technology would be more effective and affordable for commercialization in the near future. The non-radiative wireless power transfer can be segregated into capacitive wireless power transfer, inductive wireless power transfer (IWPT) and resonant wireless power transfer (RWPT) as illustrated in Figure 1. The capacitive coupling mode works on the principle of electric induction is defined as the dispersal of surface charges on the body or object. In this method, a resonating transmitter is excited by high-frequency and high-voltage source to create an alternating electric field which couples with the resonating receiver, thus power can be transported to the load. The transfer efficiency of capacitive coupling is affected by the nearby bodies or objects (Liu *et al.*, 2011) and the amount of power transfer is comparatively less than IWPT or RWPT.

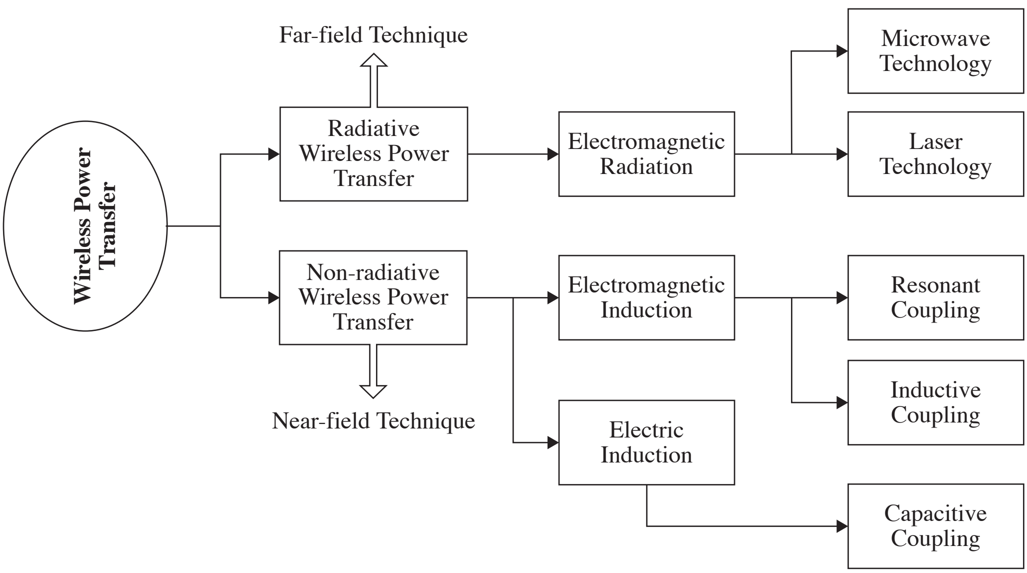

Figure 1. *Categorization of WPT technology*

Inductive and resonant WPT employ the electromagnetic induction method for transferring the power from source to load coil. IWPT is suitable for short-distance applications and RWPT can be a good choice for medium-distance applications (Hui and Wenxing, *et al.*, 2014). According to Hui and Zhong in 2014 (Hui and Zhong *et al.*, 2014), the medium distance WPT can be referred as the transmitting power distance between the source and the load coil which is greater than the dimensions of the coils. Although every WPT technology has its own advantages and disadvantages, RWPT technology possess certain advantages because of its high efficiency and reliability for medium distance applications.

WPT systems are complicated because many things need to be considered before designing the systems, such as: dimensions of the transmitter and receiver coils, operating voltage and current carrying capacity and compensation topology. Studies are presented to optimize the coil shapes by (H. Li *et al.*, 2015; Strauch *et al.*, 2015). Apart from the dimensions of coils, the studies on various compensation topologies are also carried out. There are four basic circuit topologies, which includes SS, SP, PS, PP, where first S or P referred as series (S) or parallel (P) compensation from primary side, while second S or P can be referred as series or parallel compensation from the secondary side. These basic circuit topologies are studied by (Moradewicz *et al.*, (2010); Sallán *et al.*, (2009); Villa *et al.*, (2009) and W. Zhang *et al.*, (2014). Comparative study between two-and three-coil structures were presented by J. Zhang, (J. Zhang *et al.*, 2017) and a simplified way of finding circuit parameters of WPT for electric vehicle charging was provided. It was found that three-coil structure is better in terms of efficiency and has better tolerance during misalignment between transmitter (Tx) and (Rx) receiver. Detailed study on four-coils structure was presented by Sample in 2011 (Sample *et al.*, 2011).

Furthermore, a circuit structure with series and parallel mixed compensation from primary and secondary side was proposed by Chen in 2013, (Chen *et al.*, 2013). It was proved that mixed compensation has capability of providing good efficiency even with non-symmetrical loads. The achieved efficiency was 85 % at 10 cm distance and 45 % at 20 cm distance. A new terminology was introduced i.e. relative distance, which was defined as a distance compared to the size of the coils. It is just not a distance between Tx and Rx, but defines how long the distance is, i.e. double of the coils etc. A Series/Capacitor-Inductor-Capacitor compensation topology was presented by Wang in 2017, (Wang *et al.*, 2017), which offers the advantage of constant output voltage with zero phase angle and zero voltage switching. The axial and angular misalignment between magnetically coupled coils in a WPT system significantly impairs the power transfer efficiency and limits the amount of power. Coil misalignment leads primary coil driver to operate in an unturned state, which causes non-optimum switching operation and results in an increase in switching losses as defined by Aldhaher in 2014, (Aldhaher *et al.*, 2014). Therefore, an investigation of the tuning mechanism would be useful to minimize the adverse effects of misalignment between the magnetically coupled coils. Furthermore, WPT based on Domino-Resonator Systems with Noncoaxial Axes and Circular Structures are discussed by Zhong in 2012, (Zhong *et al.*, 2012). The relay resonators for enhancing the transfer distance between source and load coil were employed by Zhang in 2012, (X. Zhang *et al.*, 2012).

This review will help the readers to understand the efficiency behavior of series-series topology and it provides literature survey of different circuit topologies. Several issues associated with the WPT technology, which includes the impact of impedance matching on overall efficiency of the WPT systems and the importance of the quality factors of the magnetically coupled coils and the operating frequency for getting maximum efficiency are also discussed.

EFFICIENCY AND FREQUENCY ANALYSIS OF WPT SYSTEM

In this section, the investigation regarding the issues of efficiency, splitting frequency, coil misalignment and frequency decrease analysis is carried out. There are two main theories for analyzing the WPT system. One is the coupled mode theory, which is suitable for physicist and another is the circuit theory, which is suitable and easily understandable for electrical engineers. Moreover, the two operating principles of WPT are suggested in the literature, i.e. maximum power transfer principle or maximum energy efficiency principle. Maximum power transfer theorem permits a flexible control of impedance matching in the model by adjusting two extra coupling coils to enhance the air gap, but in this case, efficiency will be compromised. If the relay resonators or domino resonators between the source and the load are deployed, a good compromise between efficiency and air gap can be achieved, by using the maximum energy efficiency principle (Hui Zhong *et al.*, 2014).

Power transfer efficiency analysis

In order to analyze the behaviour of efficiciency of WPT system, a basic SS topology is investigated here as depicted in Figure 2.

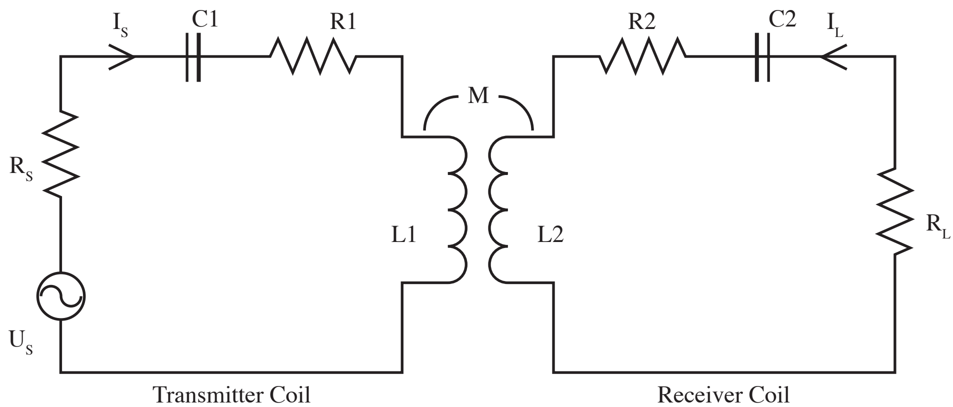

Figure 2. *Equivalent Circuit of Series-Series (SS) Topology*

Following equation can be derived by using Kirchhoff's Mesh rule.

$$\begin{pmatrix} U_s \\ 0 \end{pmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{pmatrix} I_s \\ I_L \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} U_s \\ 0 \end{pmatrix} = \begin{bmatrix} R_s + R_1 + j\omega L_1 + \frac{1}{j\omega C_1} & -j\omega M \\ -j\omega M & R_L + R_2 + j\omega L_r + \frac{1}{j\omega C_2} \end{bmatrix} \begin{pmatrix} I_s \\ I_L \end{pmatrix} \tag{2}$$

where, U_s is the source voltage of the transmitting coil at resonance frequency (ω), R_1 and R_2 are the resistances of transmitter and receiver coils respectively. $L_{1,2,}$ and $C_{1,2}$ are the inductances and capacitances of transmitter and receiver coils, respectively. The mutual inductance *(M)* between the transmitter coil and receiver coils is organized in terms of coupling factor (k) and self-inductances (L_1 and L_2) of the coils, which can be written as,

$$M = k\sqrt{L_1 L_2} \tag{3}$$

When the condition of resonance occurs, the capacitive and inductive reactance becomes equal, therefore the summation of these parameters would be equal to zero as described by the following equations (Vilathgamuwa *et al.*, 2015).

$$J\omega L_1 + \frac{1}{j\omega C_1} = j\omega L_2 + \frac{1}{j\omega C_2} = 0 \tag{4}$$

Now (4) can be rewritten as,

$$\binom{U_s}{0} = \begin{bmatrix} R_s + R_1 & -j\omega M \\ -j\omega M & R_L + R_2 \end{bmatrix} \binom{I_s}{I_L} \tag{5}$$

The currents passing through the transmitting coil and the load coil is expressed by (6) and (7),

$$I_s = \frac{(R_L+R_2)\, U_s+(\omega M)^2}{(R_s+R_1)(1+j\omega M)} \tag{6}$$

$$I_L = \frac{(R_L+R_2)\, U_s+ (\omega M)^2}{(R_s+R_1)\,(R_L+R_2)+\left(1+\frac{1}{j\omega M}\right)} \tag{7}$$

For simplification purpose, it is assumed that Rs is equal to R_L. Then the efficiency (η) is given by,

$$\eta = \frac{|I_L|^2 R_L}{|I_s|^2 R_1 + |I_L|^2 (R_L+R_2)} \tag{8}$$

According to (8), the efficiency is associated with the parameters including input and output current, load resistance (R_L), source resistance (R_S) and intrinsic resistance of the coils. According to (6) and (7), the source and load currents are related to mutual inductance *(M)* and resonance frequency *(ω)*. Therefore, by optimizing the related circuit parameters, efficiency can be improved.

Frequency decrease analysis

The high frequency in several MHz range is one of the reason behind higher coil to coil efficiency and higher transfer distance. However, it is difficult and costly to generate a very high frequency (HF) AC supply. So, it is of great importance to reduce the resonant frequency without changing resonance conditions, in order to reduce the losses due to HF power electronics inverters. In this regard, two-coil circuit of RWPT is analyzed as shown in Figure 2. The power transfer efficiency (PTE) in terms of mutual inductance and resonance frequency can be expressed as equation (9) (Y. Zhang *et al.*, 2014),

$$\eta = \frac{\left(\frac{\omega M}{R}\right)^2}{1+\left(\frac{\omega M}{R}\right)^2+\frac{R_L}{R}} \frac{\frac{R_L}{R}}{1+\frac{R_L}{R}} \quad (9)$$

In order to simplify the expression, suppose that, *Rt* = *Rr* = *R*. Then, the transfer quality factor *(Q)* and load matching factor *(Lm)* are given by,

$$Q = \frac{\omega M}{R} \quad (10)$$

$$Lm = \frac{R_L}{R} \quad (11)$$

Now (9) can be re-written as,

$$\eta = \frac{(Q)^2}{1+(Q)^2+Lm} \frac{Lm}{1+Lm} \quad (12)$$

The general formula for resonance frequency is given by,

$$\omega = \frac{1}{\sqrt{LC}} \quad (13)$$

From (12), it can be concluded that the quality factor *(Q)* is directly proportional to the transfer efficiency. Hence by increasing *Q*, higher efficiency can be achieved, but it is mandatory to select the optimized value of load matching factor Lm, in order to achieve the highest efficiency. Usually in RWPT system high frequency in MHz range is used in order to get high efficiency. It is worth noting that operating frequency of more than 10 MHz would significantly increase the costs and switching losses of the driving circuits (Hui and Zhong *et al.*, 2014). From equation (13), it is obvious that the resonance frequency can be decreased by increasing the inductance and increasing the capacitance. Therefore, the optimal selection of resonance frequency, inductance and capacitance is necessary to achieve better results. It is important to mention that equation (13) is valid for simple series of compensation topology. The equation of resonance frequency may vary according to the compensation topology.

Frequency splitting phenomenon

Frequency splitting phenomenon has the vital impact on output power of WPT system. It leads to the degradation of power transfer efficiency. This phenomenon occurs in single or multi-transmitter and multi-receiver coils when the adjacent two or more resonant coils are in the proximity that their coupling coefficient is large enough. The common approach to deal with this phenomenon is impedance matching or adaptive frequency shifting. However Nguyen in 2015 (Nguyen *et al.*, 2015) examined the splitting mode for transmission in single transmitter and multi receiver resonant system and have utilized the frequency splitting as an advantageous phenomenon to multiple receivers in straight domino-resonators. According to the authors, the variation of the distance between the transmitter and receiver within the range below the critical point is prerequisite for the multiplicity of the splitting frequencies.

In this situation, the frequency splits into two peak values as presented by Huang in 2014, (Huang *et al.*, 2014) and the input impedance changes into small amplitude with increased impedance angle according to Nguyen in 2015, (Nguyen *et al.*, 2015).

Additionally, it was observed that the splitting frequencies are not equal to the natural resonant frequency. These can be either higher or lower than natural resonance frequencies. Between these two splitting frequencies, the lower frequency corresponds to the odd mode, while the higher frequency defines the even mode. Therefore, the frequency control system was developed and investigated to select the best mode for achieving higher efficiency. Critical coupling is the coupling point at which the maximum power transfer efficiency can be achieved and beyond that point, efficiency decreases drastically. As shown in Figure 3, the highlighted red volume is over coupled regime, where frequency splitting occurs and transfer efficiency can be maintained independent of distance if the correct frequency is chosen by Sample in 2011, Sample *et al.*, (2011).

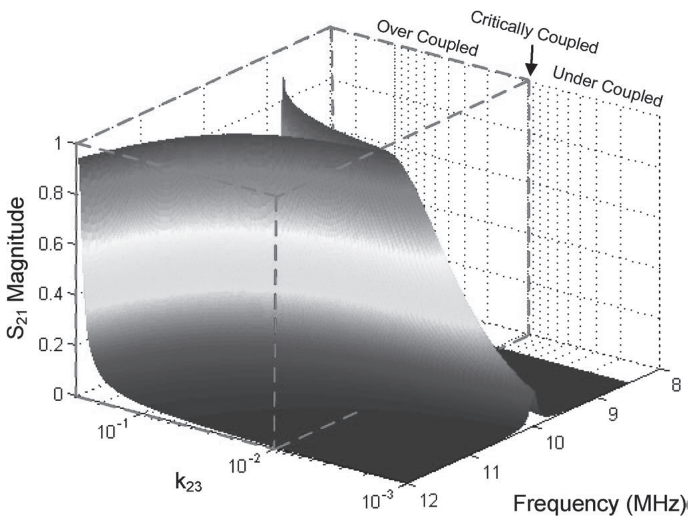

Figure 3. *S_{21} magnitude as a function of frequency and transmitter-to-receiver coupling k23 for the simplified circuit model (Sample et al., 2011).*

OPERATING PRINCIPLES OF WIRELESS POWER TRANSFER SYSTEM

This section comprises of the detailed explanation regarding the two main operating principles of WPT system.

Maximum power transfer principle

This principle can be defined as the transport of maximum average power to the load that can be attained when the impedances of the load are identical to the complex conjugate of the source impedances irrespective of the circuit structure (McLaughlin *et al.*, 2007). The example of this principle is depicted in Figure 4.

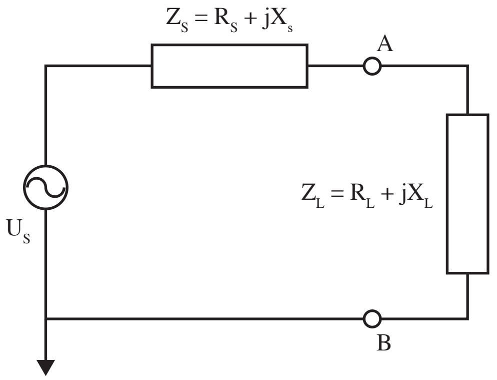

***Figure 4.** Equivalent circuit of the AC power source with equivalent load (Barman et al., 2015)*

In order to calculate the maximum power transfer, an equation from Figure 4 can be derived, which is given as (14). According to (14), the maximum efficiency of 50 % is achieveable, when $R_L = R_S$.

$$P_{L,max} = \left(\frac{U_S}{R_S+R_L}\right)^2 R_L = \left(\frac{U_S}{R_S+R_S}\right)^2 R_S = \frac{U^2{}_S}{4\,R_S} = \frac{U^2{}_S}{4\,R_L} \qquad (14)$$

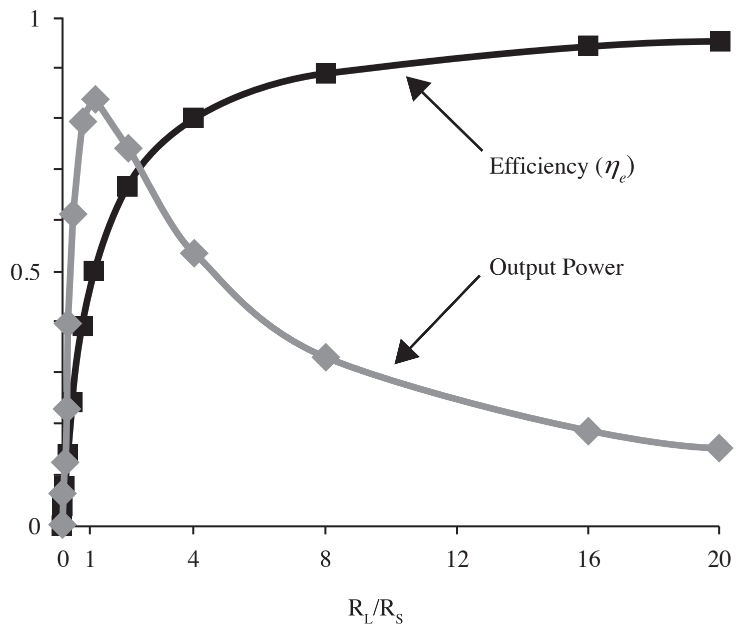

***Figure 5.** Difference between output power and efficiency as a function of RL/RS (Barman et al., 2015)*

Maximum energy efficiency principle

This principle provides good trade-off capacity between efficiency and air gap (Hui, Zhong, *et al.*, 2014). From Figure 4, if the source is open circuited, it will give the appearance of Thevenien equivalent circuit. Furthermore, with the increased load, the power transfer efficiency will increase and is given by (15).

$$Efficiency = \frac{\left(\frac{U_S}{R_S+R_L}\right)^2 R_L}{\left(\frac{U_S}{R_S+R_L}\right)^2 R_L + \left(\frac{U_S}{R_S+R_L}\right)^2 R_S} = \frac{R_L}{R_L + R_S} \tag{15}$$

If, RL >> RS, it shows an open circuit behavior, in that case the efficiency of 100 % can be achieved, but no power will be delivered to the load. When RL = 3 RS, the efficiency of 75 % is achievable and the power delivered to the load can be calculated by the following equation (McLaughlin *et al.*, 2007)

$$P_L = \left(\frac{U_S}{R_S+R_L}\right)^2 R_L = \left(\frac{U_S}{R_S+3R_S}\right)^2 R_S = \frac{3\,U^2{}_s}{16\,R_s} = \frac{3}{4}\,P_{L,max} \tag{16}$$

Equation (16) determines that 75 % of the power will be transferred to the load. It should be noted that in WPT system, both maximum efficiency and power transfer will be required according to the particular applications. For example, in high voltage applications, like charging of electric vehicle using WPT maximum efficiency principle is appropriate. When maximum power transfer principle is applied in high power applications then there is a possibility of huge power losses due to inherent lower efficiency of this principle. But, in some cases, maximum power transfer is of utmost importance, such as charging of cellphones, laptops and toothbrushes or other similar low power devices.

RECENT WORK ON RESONANT AND INDUCTIVE WPT SYSTEMS

This section is sub-divided into two sections. First section consists of the comparison between inductive and resonant coupling for WPT using near field coupling and second part presents the detailed literature survey on recent advancements on WPT technology.

Comparison between IWPT and RWPT technologies

The IWPT technique can be further elaborated based on simple transformer, in which, a primary coil is supplied by an AC power. When current is induced in the primary coil, it creates a varying magnetic field, which induces a voltage across the terminals of the secondary coil, and thus transfers power to the load. In a transformer, the magnetic field is typically confined to a high permeability core, but it also functions when the region between the primary and secondary coils is simply air (Cannon *et al.*, 2009). IWPT technology can be used for several kilowatt applications such as charging electric vehicle etc. A typical system energy efficiency of more than 80 % can be achieved using IWPT. IWPT is simple in structure and a promising technique of wireless power transfer for short-distances from few millimeters to few centimeters. However, it requires precise alignment for the charging path to achieve higher efficiency. Charging pads for laptops, cell phones, electrical tooth brush chargers and electrical vehicle charging are the examples of IWPT technology. It employs the frequencies between several kHz to few MHz (Barman *et al.*, 2015). The RWPT can also be described as an improved form IWPT technology. It utilizes the magnetic resonance coupling to transfer the energy from transmitter to receiver. Magnetic resonance coupling can be created with self-resonance coils, which resonates with its self-inductance and parasitic capacitance. But when the parasitic capacitance of coils is inadequate to make resonance at desired frequency, an external lumped capacitor can be added to build the resonance coils (Hui Zhong, *et al.*, 2014).

Additionally, in RWPT technology, the leakage inductance is compensated by combining the near-field magnetic coupling and resonance techniques together in the power flow path to ensure improved wireless transmission energy efficiency (Hui Zhong, *et al.*, 2014). If the RWPT design is seen from physics point of view, it depends upon the magnetic and electric field resonance, and if it is seen from electrical engineering point of view, the resonance in the LC circuit is mandatory for achieving higher efficiency. According to the previous research and experimental results provided in the literature, it can be concluded that RWPT technology presents certain benefits in terms of efficiency and transmission distance over IWPT. RWPT is appropriate for medium distance applications from few meters to several meters. The operating frequency of RWPT is usually much higher than IWPT, either in the order of few MHz to several MHz (Imura *et al.*, 2011; Kurschner *et al.*, 2013). Furthermore, the research reported in Ho *et al.*, (2011) presents a comparative study between RWPT and IWPT by creating a system model for charging the small battery of implantable devices. This model behaves like traditional IWPT, when the system frequency is not resonant. But when it operates on resonant frequency, it behaves like RWPT.

Furthermore, the quantitative comparative analysis has been performed by finite element analysis method by selecting the frequency range between 0.01 MHz to 10 MHz and the prototype model was built to verify the simulation results. The results of the study show that the efficiency of the proposed RWPT is much higher than that of traditional IWPT system. Moreover, in Sample *et al.*, (2011) it was proved that there is a "magic regime" in magnetically coupled resonators, where efficiency remains nearly constant over certain distance. This regime does not exist in conventional IWPT system. Additionally, it was reported in Wei *et al.*, (2014) that RWPT and IWPT will merge together in the future despite their current distinctions. High operating frequencies and high-quality factors are the basic reasons in RWPT behind the high-power transfer efficiency over long distances. It was observed that to realize impedance matching and system stability, a closed-loop control system with good performance is necessary. From the comparison, it can be concluded that both the IWPT and RWPT technologies are using the same technique of electromagnetic induction for transferring the power. Therefore, they will be merged together in one technique in near future.

Recent research on WPT technology

Nikola Tesla has conducted experiments about a century ago, afollowed by a slight research on WPT technology. Figure 6 shows the diagram of an old Tesla coil structure also known as a resonant transformer. Tesla coil was patented as "Apparatus for transmitting electrical energy" in 1914 (Tesla, 1914). As illustrated in Figure 6, the high voltage tranformer is supplying current through the spark gap (S.G) to the capacitor (C). Innitially, spark gap is open circuited, and current flows to the capacitor and the capacitor is fully charged. Once the voltage of capacitor becomes too high, the breakdown occurs at spark gap and spark gap acts as a conductor. This forms a shunt resonant circuit and capacitor discharges its energy into a primary coil (P) in the form of a damped high frequency oscillation. When this high frequency current is oscillating in primary coil, a voltage gain is achieved from secondary through the resonance. The natural resonance frequency is determined by the primary coil inductance and capacitor value (Burnett and Gerekos, 2012).

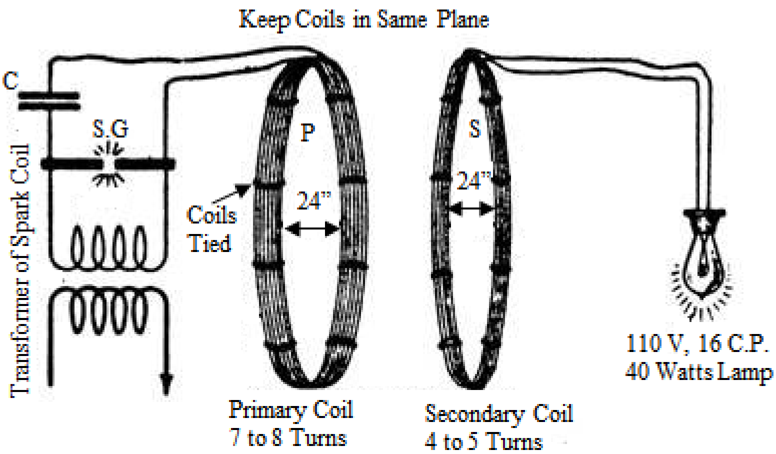

Figure 6. *Tesla Apparatus and Experiments by H. Winfield Secor, Practical Electrics, Nov. 1921*

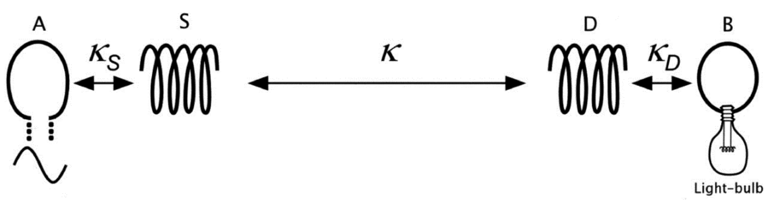

Figure 7. *Schematic diagram of the experimental setup by MIT (Kurs et al., 2007)*

In the year 1966, A WPT system based on microwave beams was proposed by William C. Brown (Brown, 1966). In 1968, Peter Glaser proposed an idea of a construction of solar power station in space so that the solar energy can be converted to electrical energy and then can be sent to the earth via microwave technology (Glaser, 1968).

In the late 20th century, the IWPT technique was commercialized for the wireless charging of portable electronic devices like tooth brushes, cell phones (Greene *et al.*, 2007) and other similar low power devices. Thereafter, IWPT method for high power applications up to few kilowatts like charging of electric vehicles was researched widely. Currently, at kilowatts power level, a grid to load efficiency above 90 % was achievable for short distance applications (S. Li *et al.*, 2015). Moreover, RWPT technology was proposed in 2007 by a team of researchers at Massachusetts Institute of Technology (MIT). Their proposed technique is illustrated in Figure 7, to enhance the transmission efficiency at medium distance. They were able to light a 60 W bulb at 2 m air gap with efficiency of 40 % to 60 % (Kurs *et al.*, 2007; Kurs *et al.*, 2010). They employed coupled mode theory to solve the equations. The circuit theory was explained by Sample *et al.*, (2011) for four coil structure. Presently, the wireless charging pads are commercially available. In the year 2015, more than 140 million wireless charging receivers were sold, and more than 50 million wireless chargers were sold, ("https://www.wirelesspowerconsortium.com/tradeshows/20160616_taipei/," June, 2016). It is expected that this quantity is going to be doubled in the coming years.

Presently, many researchers in academia and industry are working on the improvement of RWPT technology in terms of power transfer efficiency (PTE) and enhancement of distance between Tx and Rx. Misalignment between the Tx and Rx is also the subject of interest for the researchers. As presented by Fotopoulou *et al.*, (2011); Junhua *et al.*, (2011), the misalignment between Tx and Rx can significantly impair the power transfer efficiency. The detailed discussion has been presented for multi-dimensional WPT structure by (Agbinya *et al.*, 2014). Furthermore, the frequency splitting phenomenon often occurs in the system architecture with multi-relay, multi-transmitter and multi-receiver coils, when two adjacent or more resonant coils are in close proximity that their magnetic fields are relatively strongly coupled, which was discussed in the literature (Nguyen *et al.*, 2015). An innovative WPT circuit driven by an inverter of 20 kHz switching frequency with magnetic dipoles with optimum-stepped core structures has been proposed by Changbyung *et al.*, (2015) as depicted in Figure 8 and the results are shown in Figure 9. At 3, 4 and 5m distance, the achieved efficiencies were 29 %, 16 %, 8 %, with output powers of 1403, 471, 209 W, respectively. The proposed coil might be efficient as a transmitter coil, but it is quite difficult to use this type of coil core as a receiver coil because of its bulkiness and lengthy shape.

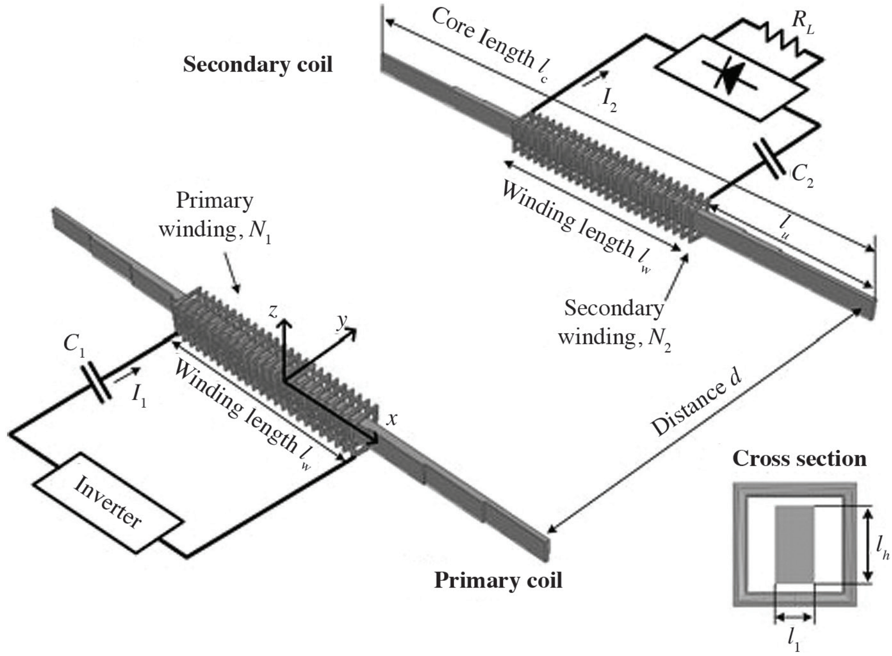

Figure 8. *Proposed Inductive Power Transfer System in (Changbyung et al., 2015))*

Moreover, Imura *et al.*, (2011) has concluded that the maximum distance between Tx and Rx is related to the radius and number of turns of the coils. Cheon has developed a circuit model and the optimum distances of the coils are derived analytically to achieve higher transfer efficiency using frequency ranges from 100 kHz to 20.1 MHz, and maximum power transfer efficiency achieved at 14.6 MHz frequency (Cheon *et al.*, 2011). Moreover, the idea of adding an additional resonator with traditional source resonator was proposed by Ahn and Kiani *et al.*, (2014), as shown in Figure 10. The authors suggested that the resonance frequency of additional resonator should be higher than the magnetic field excitation frequency to create the strong paramagnetic response, which results in the enhancement of magnetic dipole moment and the effective permeability of the transmitter. Moreover, it was found that the effective permeability can be controlled by adjusting the resonance frequency of the added resonator and the higher effective permeability yields higher resonant coupling at the same excitation amplitude. By this method, the transfer efficiency was improved from 57.8 % to 64.2 % at 15 cm distance and the power delivered to load was also improved from 0.38 W to 5.26 W using the same excitation voltage of 10 V.

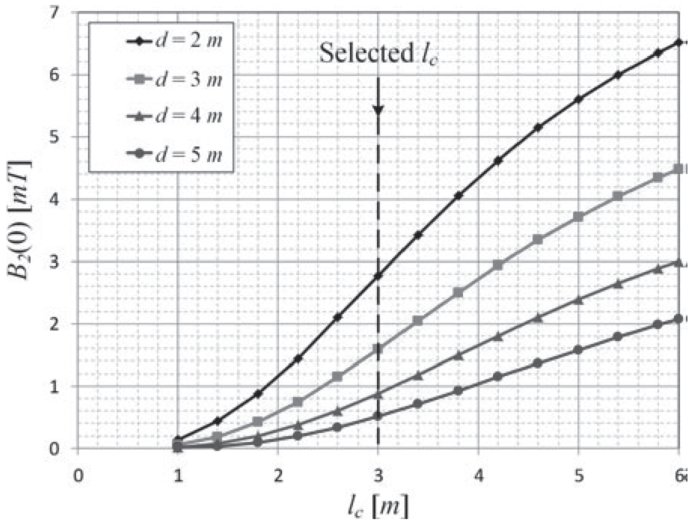

Figure 9. *Simulation results of the magnetic flux density at the center of the secondary coil for the primary and secondary core length lc (1–6 m) and various distance d (2–5 m). lc = 3 m was selected as the baseline design (Changbyung et al., 2015)*

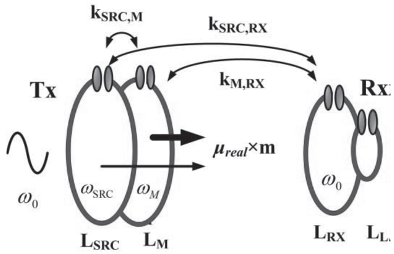

Figure 10. *Conventional four coils structure with additional resonator (LM) (Ahn, Kiani, et al., 2014)*

Furthermore, a novel model of two strongly coupled resonators was proposed by Ahn and Hong, as shown in Figure 11 (Ahn and Hong, 2014). It was different from four-coil conventional model in a way that, the first and fourth coil also participate in strong cross coupling with high Q. It was demonstrated that the proposed model gives 65.2 % efficiency with 17.2 W power transfer at 13 cm distance, whereas those values with conventional four coils technique were only 37.3 % and 6.2 W at the same distance. Kim *et al.* presented an efficiency analysis of a RWPT system with an intermediate resonant coil along with conventional four coils as illustrated in Figure 12 (Kim *et al.*, 2011). A spiral coil was employed as an intermediate coil to decrease its volume, while two single turn coils were used as source and load coils and helical coils were utilized for Tx and Rx coils. This structure was able to improve efficiency and enhance distance between Tx and Rx, however the overall cost of the system increased because of intermediate coil and its control. Intermediate coil was arranged coaxially and perpendicularly and the efficiency of former arrangement was much better than latter. However, from a practical point of view, the perpendicularly arranged intermediate system can be of better choice, since it can be implemented in the available space for wall-mounted TVs and furniture embedded systems.

In addition, the frequency splitting phenomenon of the two-coil and three-coil RWPT systems was analyzed in detail by circuit theory using 10 MHz frequency by Huang *et al.*, (2014). It was concluded that when the coupling coefficient is large enough, two splitting frequencies occurs, i.e. 9.5 MHz and 10.5 MHz. Furthermore, the magnetic field distribution of the two splitting frequencies was simulated and analyzed to select the better frequency for maximum power transfer. The critical coupling coefficient, which determines the over coupled region, of two coils and three coils WPT was also derived. Finally, a tuned frequency method according to the numerical results was proposed.

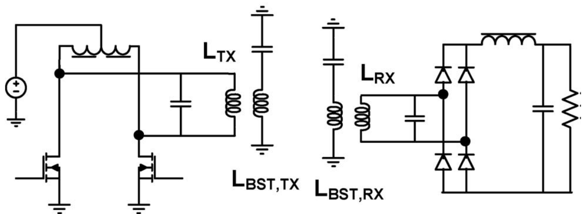

Figure 11. *Schematic diagram of four coil resonators using MOSFET (Ahn and Hong, 2014)*

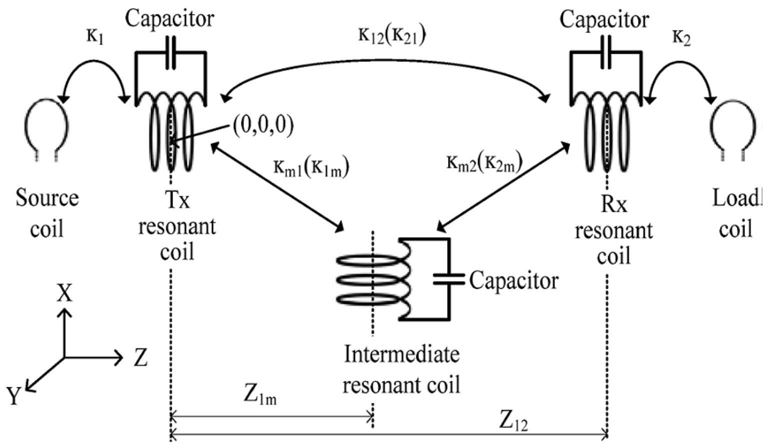

Figure 12. *Structure of four coil resonators using intermediate coil (Kim et al., 2011)*

Additonally, Waffenschmidt in 2015 has introduced a new method named as "frozen resonance state" for dynamically matching the resonant frequency without manupulating the values of the components (Waffenschmidt, 2015). The basic idea was to freeze the state of the resonant circuit for a fractionional duration of the resonant period, for example, by freewheeling the current of the resonant inductor or by upholding the voltage of the resonant capacitor. This additional time of frozen state extends virtually the resonant period, which leads to an effective decrease in resonant frequency. By adjusting this additional time, the effective resonant frequency was made identical to the operational resonant frequency separately for each receiver. Furthermore, Ahn *et al.* have studied the enhancement of air gap by repeaters and the aspects of frequency splitting were analyzed individually by using even and odd number of repeaters (Ahn *et al.*, 2013b). In each repeater configuration, the transfer efficiency, out power and impedance were evaluated. It was concluded that the optimum number of repeaters and their corresponding positions can be achieved by this analysis. Ahn also proposed the frequency conditions for getting highest efficiency and maximum amount of power transfer under multiple couplings between multiple transmitters (Txs) and receivers (Rxs) (Ahn *et al.*, 2013a). It was examined that due to multiple couplings, the effective resonant frequency of the Txs or the Rxs is changed. Hence, the amount and type of the necessary adjustments for those changed frequencies were provided. Experiments have been conducted with couplings between Txs or between Rxs. Based on proposed frequency adjustments, 51 to 65 W power was transferred with efficiency of 45 % to 57 %, respectively, using coupling coefficients of 0.025 to 0.063 from Tx to Rx.

Duong *et al.*, (2015) presented an impedance matching method, which consists of three steps: system calibration, coarse search and fine search. The method was applied to axial and angular misaligned coils with distance variations. The proposed method significantly reduced impedance searching time from a few minutes to approximately one second. At 6.78 MHz, the efficiency of greater than 80 % up to a distance of 50 cm was achieved. Furthermore, Choi *et al.* proposed RWPT with three major couplings, which included source–Tx, Tx-Rx, and Rx-load. In this proposed scheme only the Tx-Rx coupling directly contributes to the wireless power transfer, which was replaced with a lumped transformer with ferrite core to make the model compact in size and robust to ambient changes. Experiments have been conducted for 1 W and 10 W prototypes of RWPT using a class-E inverter at the switching frequency of 500 kHz, with less than 100 quality factors and the maximum Tx coil to load efficiency around 80 % was realized (Choi *et al.*, 2015). Additionally, an adjustable impedance matching technique for adjustable distribution of power among multiple receivers was investigated to achieve better power transfer efficiency for all receivers (Lee *et al.*, 2015). The effective soft switching technique to improve the performance of IPT was proposed by Peschiera (Peschiera *et al.*, 2014). Three control strategies were compared: phase-shift (PS) control, asymmetrical duty cycle (ADC) control and optimal asymmetrical voltage cancellation (o_AVC) control. The o_AVC control was found to be more efficient for this application. Mendes Duarte analyzed the coupling coefficient between two coplanar and coaxial coils as a function of the separation distance (Mendes Duarte *et al.*, 2014). It was investigated that despite the variations in the relative position of the source and load, a simple mechanism capable of locking the system efficiency at a desired level is possible.

A parallel 100 kW IPT power supply topology that can achieve high output power levels in a cost-effective manner was proposed by Hao (Hao *et al.*, 2014). Usually, the high inductive power transfer systems are equipped with costly high-power electronic components and their power level is fixed at one level. In order to reduce the cost of high-power electronic devices, the parallel topology can minimize uneven power sharing due to component tolerance, and does not require any additional reactive components for parallelization. The maximum efficiency of the power supply and track was obtained around 94 %. The parallel topology was experimentally verified using a 6-kW prototype system realized by parallelly adding three 2 kW single power supplies. This paper also introduced a synchronous clamped mode control technique for controlling the parallel power supply. Ju proposed a switch-mode operation to enrich the transfer characteristics of large quality factor IWPT at a short distance (Ju *et al.*, 2015). The proposed technique used the transient process of energy exchange between the resonators, which decouples the load with the transmitter circuit and maximizes the transferred power without the need of reducing efficiency of the system. Thus, by using the resonators as an energy storage element instead of a loosely coupled transformer, it was realized that the proposed switch-mode achieved the simultaneous increase in the maximum transferred power and the transfer efficiency within strongly coupled region. The power transfer capability of the high-quality factor IWPT system was enhanced and the upper limit of 50 % efficiency under the condition of maximum power transfer was eradicated.

Wireless power transfer using relay coil system having single source and multiple loads was presented (Stevens, 2015). The efficiency of such single source and multiple load systems at different points on the structure can vary widely. When these systems were excited with a frequency in their band pass, they carry signals in the form of magneto-inductive waves (MIW) and often called as magneto-inductive waveguides. To propose an optimum receiver load, the variations of matching conditions was defined by the effects of reflections and standing waves on single dimensional system. An experimental model was developed and power transfer efficiency of 58 % to single load at any point in the system is realized. The article by Lin in 2015 emphasized on the wireless charging pads for electric vehicles (Lin *et al.*, 2015). It was revealed that the solenoid pads are not appropriate as primary pads because of their high leakage fluxes, low native quality factors and their inability to operate over the entire range of usage. In contrast, the bipolar pads offer high quality factors and they can be coupled to any secondary pad over the entire desired distance. Moreover, an automatic impedance matching network was proposed by Beh *et. al.* using L-type matching and inverted L-type matching circuit (Beh *et al.*, 2013). It was found out that the inverted L-type IM circuit improves the efficiency by creating a sharper peak at the resonance frequency as depicted in Figure 13.

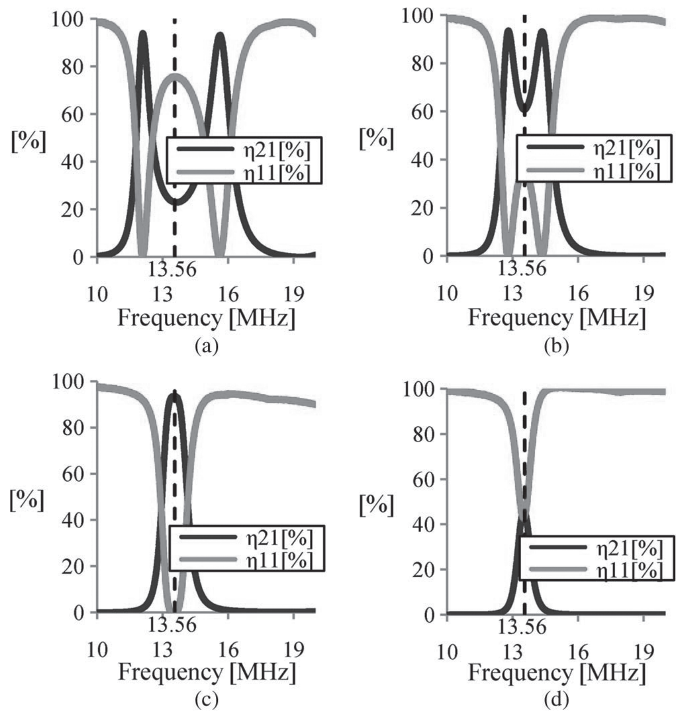

Figure 13. *Simulation results of frequency characteristics of the system, (a) and (b) before matching, (c) and (d) after matching (Beh et al., 2013)*

Shi has studied the effects of coil shapes on the performance of WPT system (Shi *et al.*, 2014). Three types of coils, which includes helix coils, planar spiral coils, and square helix coils were studied. It was verified that the helix coils exhibit the top performance and it offers a great efficiency having wider band-width, and the higher transfer distance especially under optimized load conditions; whereas the planar spiral coils gives the poor performance among these three types of coils. It was observed that the helix coils performance degrades more quickly with increasing distance between the transmitter and receiver coils as compared to other two types of coils. In addition, Mc Donough has conducted the analysis of Series-Series (SS) and Series-Parallel (SP) topologies using circular and square coil geometries (McDonough *et al.*, 2014). The mutual coupling and maximum capacity of transferrring the power transfer was compared between both geometries. It was found that during exact alignment, the circular coils are capable of providing better coupling. On the other hand, the square coils were better under misalignment conditions.

Table 1 gives the summary of recent work in WPT technology. The table is summarized in terms of resonance frequency, efficiency, distance and power level in order to understand the overall performance of various WPT models.

Table 1. Summary of Recent Work in WPT Technology

Reference	Year	Frequency	Power Level	Distance	Efficiency	Comments
(Kurs *et al*., 2007)	2007	10 MHz	60W	2m	40%	The frequency is very high and very high-quality factor wires used
(Sample *et al*., 2011)	2011	10 MHz	NA	0-70c	70%	Coefficient of determination (R2) of 0.9875.
(Chen *et al*., 2013)	2013	Not Available	NA	10cm 20cm	85% 45%	Diameter of the coil and transmission distance is same, that is the reason behind high efficiency
(Ahn *et al*., 2013a)	2013	500 kHz	51W to 65W	NA	45% to 57%	Operating distance is not given but coupling factor is very low.
(Fu *et al*., 2013)	2013	13.56 MHz	Not Available	Not Available	73% with resistive load and 66% with battery or super capacitor	Good efficiency but very high frequency
(Ahn and Hong, 2014)	2014	Not Available	17.2W	13cm	65.2%	Good efficiency but large dimensional coils were used
(Ahn, Kiani, *et al*., 2014)	2014	6.78 MHz	5.26W	15cm	64.2%	Good for low power applications
(Duong *et al*., 2015)	2015	MHz Range	NA	40 cm	74%	The model tested for 60 % angular misalignment and efficiency is good, but coil quality factor is very high.
(Changbyung *et al*., 2015)	2015	20 KHz	209W 471W	5m 3m	8% 29%	Efficiency is very low, but the frequency is also low in kHz range
(Choi *et al*., 2015)	2015	Not Available	1W to 10W	NA	80%	Very less power transfer up to 10W and coupling factor is also very low

Safety standards for WPT technology

The exposure of high frequencies to the human body is the main concern of the WPT technology. In telecommunication technology radio frequency is used along with very low power signals. However, the case is different in WPT technology, because it utilizes high power and the high frequencies. Therefore, several regulations have been implemented to limit the amount of electromagnetic fields (EMF) for the commercialization of WPT technology. Different standards have been employed according to power levels and frequency levels. Wireless Power Consortium (WPC) has defined the QI standards at power ratings up to 5 Watts and frequency band of 100-200 kHz. They are further planning to define the standards for power level of 120 Watts (Bululukova *et al.*, 2014) . Safety standards of the EMF exposure to human body in the range of 100 kHz to 10 MHz are determined by International Commision on Non-Ionizing Radiation Protection (ICNIRP) (Ahlbom *et al.*, 1998; Protection, 2010). The Alliance for Wireless Power Transfer (A4WP) has defined some regulations from 10 Watts to 22 Watts WPT systems at frequency of 6.78 MHz (67, BSS, A4WP, 2014). The International Committee on Electromagnetic Safety (ICES) under Institute of Electrical and Electronic Engineers (IEEE) has also defined EMF exposure limits to human body. They defined limits for WPT from 100 kHz to 5 MHz frequency band (68, I. S. C96.1, IEEE Standards, 2005). In addition, the detailed discussion regarding the safety standards and performace characteristics of WPT has been provided by Bulululukova and Jiang (Bulululukova *et al.*, 2014; Jiang *et al.*, 2012). Although several guidelines and regulations have been defined for WPT, a lot of work is required regarding the standarization of power and frequency levels for further commercialization of WPT technology.

CONCLUSION

An introduction of the existing WPT technologies is presented in this paper. The comparison between inductive wireless power transfer (IWPT) and resonant wireless power transfer (RWPT) is carried out. The review outlines the recent research in IWPT and RWPT. It highlights the efficiency analysis, frequency splitting phenomenon and effects of misalignment on the efficiency of the WPT system. It also summarizes the two operating principles namely 1) maximum power transfer principle 2) maximum energy efficiency principle. In addition, the review provides the literature survey on the two-coil, four-coil systems, and structure of four-coil resonators using intermediate coil. The frequency decrease analysis is presented to reduce the resonant frequency of RWPT to make it cost effective. The effects of degrading the resonance frequency on the functioning of the WPT system are also presented.

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