A Comprehensive Review on Wireless Power Transmission

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Abstract*— The percentage of energy sent that reaches its destination is the efficiency of an energy transferring system. Energy transfer via wires is considerably more reliable and efficient because wires are a low-loss way of confining and guiding energy to where it is utilized. Still, wireless energy transfer works very well in general at short distances, and make sure to become more efficient over a long-distance transfer is possible if the size of transmitters / receivers are physically large, or if the energy can be synthesized into a tight beam. The efficiency of an energy transferring system is the percentage of energy sent that arrives at its destination. Because wires are a low-loss medium of confining and guiding energy, also sending it through wires is often more efficient. Mostly, in the distribution system, the wire resistivity of the electrical grid results in a loss of 26-30% of generated energy. Because of that loss implies to our current electrical distribution system is only 70-74% efficient. There are many hilly and even rural areas the world those facing shortage of energy in domestic as well as in commercial or industrial utilization in such evolutionary era. However, there is no way to deliver power up to their daily base needs. Even the people of south Asia and Africa requires electricity to power pumps that will require the electrical power required to bring them into the twenty-first century and equal opportunity to meet their needs in standing with Western nations. When conventional wires are unaffordable, inconvenient, costly, dangerous, unwanted, or impossible, wireless power transmission (WPT) can be employed in the place where energy delivery needs to be continuous or instantaneous. Microwaves, millimeter waves, and lasers can all be used to transmit power. WPT otherwise be impossible or impractical to reach. The goal of this work is to identify the challenges that arise during transmission of power wirelessly on the basis of comparative analysis of different techniques and to propose a suitable model for overcoming these challenges. It is a technology that can transport power to places that would otherwise be impossible or impractical to reach and gives appropriate solution of different concerned parameters.

Keywords—WPT, MPT, SPS,

I. INTRODUCTION

In the recent era, research in the field of WPT is exploring from theories into the practical implementation as well as in commercial base utilization of products from smart phones to high power solar satellites and wireless power products will meet upto 15 billion dollars market in near future. Power transmission grid losses can reach upto 30% of transmitting power is problem this can be solved with wireless power transmission [1]. The first theoretical basis of WPT was given by James C. Maxwell in 1864. He proposed an idea of the radio waves existence by means of mathematical modelling based on different laws and derived equations known as Maxwell equations. In 1884, John H. Poynting described in far-field region, those electric field and magnetic field vectors are right angled. These vectors constitute a Poynting vector which plays a vital role in the quantification of electromagnetic energy [2,3]. In the field of high frequencies at its peak by Nikola Tesla s' creating in 1898, when he starting working on those high frequencies wireless power transmission. He almost, immediately began to precise their test possibilities for wireless transmission of intelligible signals perhaps power and was the first one to introduce the concept of wireless power. He worked on practical development on his ideas during 1891to1893. In 1897, he designed an apparatus utilization WPT system. Tesla arrived in Colorado Spring Laboratory USA on18th May 1899 and started research in wireless telegraphy and properties of upper atmosphere [4]. At the end of 19th century, he acknowledged out the first WPT experiments by trying to transmit 300 kW power by radio wave at frequency of 150 kHz but unfortunately failed since the diffusion of wireless power due to dependency on antenna size and frequency of operation [5]. A valuable experimental research was carried out in 1926 by H. Yagi and S. Uda known as invertors of the Yagi-Udda antenna in Japan. For this purpose, wireless power transmission at frequency 68 MHz, they placed parasitic element between the transmitting and receiving antennas [6]. They successfully performed an experiment by transmitting 2-3 W of electrical power and received approximately 0.2 W in that manner. During the same period H.V Noble also described WPT in United States by using radio waves at frequency of 100 MHz keeping the distance about 5-12 m between transmitting and receiving antennas at Chicago World Fair 3 of 1933 [7]. Nearly a hundred years after Tesla, it was derived on the basis of research and commercial development, that WPT operation principles can be classified into two categories, electromagnetic coupling WPT and radiative WPT also known as uncoupling WPT. The first type of WPT uses high frequencies electric and magnetic fields known as near- field WPT. At higher frequency magnetic field, it is also called inductive coupling and explained by Faraday's law and Ampere's law. The second form radiative WPT is known as far-field based on radio waves explained by Maxwell's equations [7-8]. These equations and laws are elaborated in mathematical modelling section. In 2007,on the basis of resonance phenomenon, MIT research group proposed WPT resonance coupling system by which transmitter receiver distance can be increased than that of conventional inductive coupling system[9].

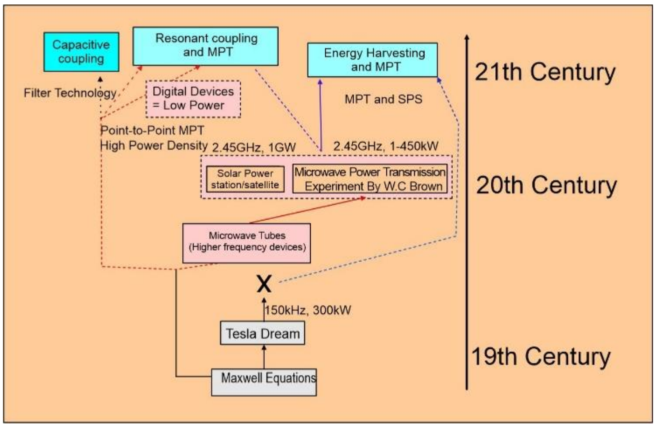

Fig.1Historical development in the field of WPT

II. MATHEMATICAL METHOD

First, electric field **E** and magnetic field **B** can be merge in Maxwell's equations into a single distinct physical quantity known as the electromagnetic field [7]. A system of linear partial differential equations is designed in this way by keeping the dielectric and magnetic medium linear. Although, sometimes it becomes essential to express these equations in integral forms to avoid discontinuity instead of differential equations [8]. Since every derivable function is continues but converse is not true [10-11] that's why differential equation does not suitable for every moment. For this purpose, integrate both sides the Gauss's law and divergence equation of magnetic density **B** in the absence of charge ($\vec{\nabla}\cdot\vec{D} = q_v$ and $\vec{\nabla}\cdot\vec{B} = 0$), over whole volume v and apply Gauss-Ostrogradsky's theorem for transformation from volume integral of the divergence to outgoing flux over surface S with limits v. Also in the case of Faraday's law and Ampare's law ($\vec{\nabla}\times\vec{E}+\partial_t\vec{B}=0$, $\vec{\nabla}\times\vec{H} = \vec{j}+\partial_t\vec{D}$), also, Stokes theorem is used to transform flux of curl into circulation over the curve which limits S, to calculate the flux of both sides. Hence, we get four equations in the form of

$$\iint d\vec{S}\cdot\vec{D} = Q^{in} \tag{1}$$

Gauss's law

where, $Q^{in} = \iiint_v dvq_v$

$$\iint_s dS\,\vec{n}\cdot\vec{B} = 0 \tag{2}$$

That is Faraday's law

$$\int_l d\vec{r}\cdot\vec{E}+\partial_t\iint_s dS\,\vec{n}\cdot\vec{B} = 0 \tag{3}$$

Nonentity of magnetic charge

$$\int_l d\vec{r}\cdot\vec{H}-\partial_t\iint_s dS\,\vec{n}\cdot\vec{D} = I^{in} \tag{4}$$

Ampere's law

Where as, $I^{in} = \iint_s dS\,\vec{n}\cdot\vec{j}$

This set of integral equations are uniformly applicable irrespective of fields discontinuities. On the other way, differential with respect to time of fluxes receive contributions both form of fields variation in time and displacement of the surfaces. Integral form of Maxwell's equations has more general validity compared to their differential form. Charges and currents are considered at same time in these integral type equations [8,12]. The flux of outgoing electric field from S becomes zero only if charge enters that closed surface and remains inside at that instant. However, some effects (such as propagation) are based on the local characteristics of the fields, they can be explained in sophisticated way by applying Maxwell's equations in local form.

III. MICROWAVEPOWER TRANSMISSION

One of the most reliable and efficient far-field power transmission technique is known as microwave power transmission MPT which can make it possible to transmit power up to several kilometer range[1]. In this method microwave frequencies are used in the range from 1GHz to 1000 GHz [13]. For MPT system, the reception areas can be shaped by using high directivity antennas that's why it becomes possible to transfer electrical power wirelessly over a long distance [5].Power transmission by means of using radio waves can be made more directional up to longer distance power beaming having shorter wavelengths of electromagnetic radiations specially the microwave range [14]. In 1960s during the World War 2, the real history of WPT started when William C. Brown started WPT experiments using high frequencies microwave technologies [15-16] radar remote sensing and wireless communications. He was the first one who used 2.45 GHz frequency microwave tubes like magnetrons and klystrons in his microwave power transmission (MPT) and designed rectifying antenna which named rectenna for the purpose of receiving and rectifying microwaves.

In 1963, the first designed rectenna had efficiency of 50% with output dc power of 4W and it became 40% at an output dc power of 7W [15]. By using rectenna, Brown successfully performed two experiments, the first in 1964 and the second one in 1968. He achieved goal in the field experiments of WPT however, the size and also cost of system was so high that cannot be realized in practical as well as on commercial basis. The basic circuit components of rectennas designed by Brown at 2.45 GHz is still taking as the reference of now a days rectenna shown in the figures. In 1977, Brown's aluminium "bar-type" measured efficiency at microwave frequency range was 91.4% that was the highest recorded than any other [17].

In 1968, Peter Glaser proposed an idea by which MPT technologies of beam-type WPT applications were with a solar power satellite SPS. By which a new solar power station above 36,000 km distance above the space in geostationary orbit [18]..

Microwave vacuum tubes are used to generate microwaves and they have several types such as klystron, magnetron and travelling wave tube TWT. Mostly, magnetron is used to generate microwave [19] by passing electrons through the magnetic field. Its frequency though the magnetic field. Its frequency is not controllable precisely as compared to TWT and klystron although it is relatively cheap one. Due to limited power and high cost make unsuitable to use TWT in practical and commercial implementation of power transfer system [2]. On the other hand, klystron is also comparably expensive but suitable microwave generator for the purpose of WPT applications

The input microwave power density at frequencies such as 2.24[17], 5.8[20] and 35 GHz [21] versus highest conversion efficiencies are drawn in the graph. It is also shown the performance curves for 2.45 GHz rectenna which was scaled to 5.8 and 35 GHz for the sake of comparison. Nearly last half century, considerable research is taken place by selecting highest common proposed attainable efficiencies at 2.45 GHz. However, the main source of losses in well- matched rectenna is diode which takes part as critical component for attaining highest efficiency.

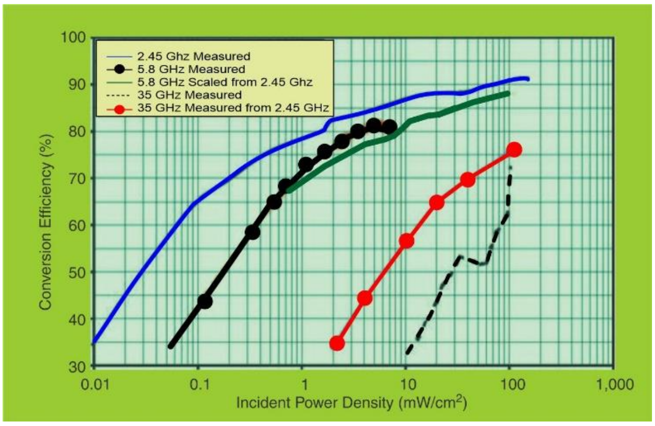

Fig.2. Rectenna efficiency

Si and GaAs Schottky barrier diodes have used making rectification efficiencies more than 80%. For the sake of better reliability Si has greater thermal conductivity because of electron of GaAs is six times more than that of Si for high efficiency [22]. A specific operating frequency for efficient rectifier in WPT applications, the selection of proper diode and its parameters are taken more attention since breakdown voltage is much critical to limit the diode's power handling capability and depends directly on junction by intrinsic properties of its material, structure and also the series resistance.

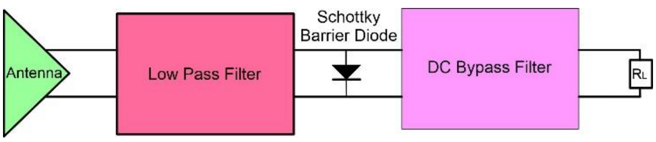

Fig. 3 Rectenna design

On the basis of experiments data base the selection of diode parameters are given in the table, with conversion efficiency. The cutoff frequency is given by following relation [23]. The cutoff frequency of schottky barrier diodes can be made possible upto several terahertz at which it must be nearly ten times of operating frequency for making process rectification efficient [24]. Harmonics generation by diode is main issue for losses in rectennas radiation due to highly non-linear circuit, they must be suppressed.

TABLE -I

IV. INDUCTIVE COUPLING

Different Parameters of Rectenna				
Frequency	2.45	***5.6***	***8.51***	***35***
Schottky Diode	GaAS-W	Si	GaAS	GaAS
R (Ohm)	0.66	8	11.2	3
C (pF)	3	0.12	0.26	0.03
V_{bi} (V)	0.6	0.4	0.714	0.8
V_{br} (V)	60	8.8	9.5	12
RFP	7	0.05	0.10	0.026
R (Ohm)	160	327	250	213
Calculated Effiency	90.5	78.3	66.2	63/6
Measured Efficiency	92.5	82	62.5	60

Before 1890s, the inductive power transmission concept was developed originally by Nikola Tesla. Due to limitation, at initial stage of research and also inefficient system products, this technique was not implemented in industrial and commercial applications till 1950s. In 1960s, fruitful research has been taken in this technique in biomedical applications. With the development in the field of power electronics and inductive power transmission go side by side in the period of 1980s.

On the basis of different schemes such as reflected load theory, resonance theory and circuit configurations, the behavior of inductive power transmission technique can be predicted on the basis of multidimensional approach of resonant coupling [25]. Under steady state conditions, these different types of resonant coupling theories are discussed in terms of power transfer efficiency. In the near-field types reflected load theory is mostly use to predict the behavior of the resonant inductive coupled scheme. The others two are lumped circuit theory and coupled mode theory also it is seen that at steady state the optimal load value becomes equivalent for all these [26-27].

The received power P_r, transmitted power P_t, and effective aperture area A_r at a distance d between transmitting and receiving antenna with gains of antennas G_t,, G_r are related by mathematical relation

$$P_r = \frac{G_t G_r}{(\frac{4\pi d}{\lambda})^2} P_t \qquad (5)$$

This relation is known as Friis transmission equation, however, theoretically efficiency is given by $\eta = \frac{P_r}{P_t}$. It is assumed, plane wave in Friis equation [7,28]

V. CAPACITIVE COUPLING

This method is also known as electrostatics induction. For the purpose of power transfer wirelessly, Tesla used first time by capacitive coupling. This method is generally used in high electric field intensity applications such cathode ray tubes [32].

VI. LASER POWER TRANSMISSION

Considerable research has been conducting in the field of WPT through laser since 1950s. The idea of laser power transmission has been evolved from photoelectric effect since 1965[30]. A NASA scientist, Peter Glaser was the first one who proposed a concept to collect solar energy for space station and in the form of beam it reaches to earth by means of laser in 1968[18]. Due to low efficiency and short coverage were main hurdles for its commercial implementation at that age. WPT by means of laser has keeping the ability to transfer several kilowatts power upto some kilometers. A major contribution in this research goes to Japanese Space Agency JAXA by which their aim to transfer power of 1GW via lasers using mirrors placed in the orbit of the Earth [33]. NASA research team proposed and designed laser power air craft in 2003[22]. Because of efficient atmospheric propagation of laser opens the door to enabling its exposure over a long-distance transmission. High intensity laser power beaming HILPB system now a day, having the capability to deliver energy orbiting satellites, reboots and unmanned vehicles. So, for the overall efficiency of this technique is near about 50%, which quit little bittle low as compared to any others [13]. A characteristic comparison of different techniques is explained in the table.

TABLE -II

Comparison of WPT Techniques

No	Characteristics	Microwave	Inductive	Capacitive	Laser
1	Distance	Upto 100km	Millimeter to meter	Millimeter to meter	Few meter to km
2	Transmitter Power	Hundred of megawatt	kW	kW	Hundred of mega Watt
3	Cost	Costly	Economical	Economical	Costly
4	Safety	Dangerous	Safe	Safe	Injurious
5	Efficiency	High	High		Low

CONCLUSION

Based on the divergence analysis of this research, we were able to make multiple decisions about the quality and performance of power transfer wirelessly. The main issue with wireless power transfer is its limited range and efficiency. A fruitful discussion has been made on different aspects of microwave power transmission. A good solution to this problem is strongly coupled magnetic resonance technique and also up to some extent MPT. In coupled resonance systems, there is frequently a general "strongly coupled" mode of operation. If that regime can be operated in each system, transfer of power is to be expected very efficient. Some factors must be considered for efficient power transfer. As for as quality factor, coupling co-efficient, and decay constant are become more relevant considerations in this way. They all are on frequency dependent. We must choose a frequency where coupling co-efficient is more than that of decay constant and quality factor is also better because increasing frequency which improves the quality factor, coupling co-efficient, but it also increases decay constant. Solid conductor provides a solution to this issue because as the number of turns increases, radiation resistance decreases due to an increase in decay constant, which also lowers quality factor. Greater cross sectional area of coil element and high conductivity is a solution to this problem because the coil's Ohmic resistance is proportional to its length. All the elements can contribute to effective wireless power transfer between two coils A comprehensive analysis on the basis of review is elaborated in this paper. The practical outcome was identical to the theoretical one. The practical outcome was identical to the theoretical one. Due to the equipment's limited availability, the entire proposed model could not be practically implemented. However, based on the theoretical analysis and straightforward experimental findings, it may be concluded that effective wireless power transfer between two coils is feasible when all the aforementioned factors are considered, and the right equipment parameters are chosen. In the near future MPT technique becomes more relevant in commercial and industrial utilization. The main issue with wireless power transfer is its limited range and efficiency. As the number of turns increases, so does the decay constant, lowering the quality factor; solid conductors provide a solution to this problem. The Ohmic resistance of coils is proportional to its length; a high conductivity and large cross sectional area coil element is a solution to this problem. When all the above factors are considered, efficient wireless power transfer between two coils is possible. We had successfully designed and implemented a model. The practical outcome was identical to the theoretical outcome.

Due to equipment availability constraints, that was not possible for implementation the entire proposed model practically. However, based on the theoretical analysis and simple experimental results, it may be stated that considering all the above mentioned factors and selecting appropriate parameters of used equipment, made more efficient wireless power transfer between two coils is possible

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