Design and Optimization of Transmission Efficiency and Power Transfer Distance in a Wireless Power Transfer System: A Systematic Review

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Abstract

Wireless power transmission (WPT) is an emerging technology which is gaining a lot of attention in the field of electronics engineering, and it holds much promise in the area of commercialization. In 1898, for the first time, a model for transferring power wirelessly was designed and built by Nikola Tesla, and since then the idea of transferring electricity without the use of wires has been taught of as a possibility. The aim of this paper is to carry out a systematic review on the optimization of the power transmission Efficiency of the wireless power transfer system as well as the power transfer distance between its transmitter and receiver. To this effect, various literatures include journal articles, conference proceedings, etc. which cover the various aspects that determine the performances of the various performance metrics were reviewed. The performance metrics of concern as well as their relationship were found to be Power transfer efficiency (PTE), Coil size or geometry, and transfer distance. The inductive resonant coupling approach is applied to gain higher efficiency and flexibility than other approaches, by coupling both receiver and transmitter coils resonantly. From the various literature, observations were made based on comparisons and conclusions around various approaches including the coil design, the use of repeater resonators, the use of meta-materials, the selection of an optimum frequency of operation, as well as the rectifier design. Based on these investigations and observations from literature, recommendations are made which suggest a superior combination of the various findings from the various literatures covering various aspect of the wireless power transfer technology, towards an overall improved efficiency of the system while maintaining a small coil size and an increased distance of power transmission.

Keywords: Wireless Power Transfer, Optimization, Power Transfer Efficiency, Transfer Distance, Performance Metrics

1.0 INTRODUCTION

Since the discovery of electricity, the way electricity has been transmitted has continued to evolve.

Wireless power transfer (WPT), which is a concept that is beginning to gain attention in recent times is simply the transmission of electricity without the use of any physical connections. The concept of wireless power transfer was first explored by Nikola Tesla shortly before the beginning of the 20th century (Tesla, 1999). At the beginning of the twentieth century Nikola Tesla spent much time and effort to develop ways to transmit power without the use of wires or any physical conductor or connection. While his work didn't quite yield the desired results, due to advancements in semiconductor physics, his ideas are now becoming reality. This development in technology has become very attractive in recent decades as it holds several applications in various electrical and electronic systems (Cruciani et al., 2019).

Wireless power transfer (WPT), also fondly called witricity, or wireless energy transmission (WET), wireless power transmission or electromagnetic power transfer is the transmission of electricity without the connection of wires or conductors in a circuit. In this kind of system, a transmitter circuit is connected to a source of power. This circuit converts the power supplied from the source into an oscillating signal which generates an oscillating magnetic field. This field is linked to the receiver circuit or coil, which extracts the power supplied and supplies it to an electrical load. This is very similar to how the primary and secondary coils of a transformer interact in accordance to faradays law of electromagnetic induction, where voltage is induced by the primary coil (which has a time varying current flowing in it) to the secondary coil via a process called mutual induction. With the wireless power transfer technology, the use of batteries or wires, will gradually but sure become less relevant and consequently no more in use, thus leading to an increase in ease of use of various electronic devices, while offering better mobility and reducing safety concerns of the users (Sidiku et al., 2021). This therefore means that the wireless power transfer technology will hold much benefit when it comes to the powering of electronic devices, especially in cases where it is much better or desired and less hazardous for use when compared to its wired counterpart. It also holds much relevance in cases where powering a device with wires is impossible. The importance and application of WPT has continued to increase as the usage of home appliances, electric vehicles, Mobile devices etc. are increasing. This is largely due to the convenience it offers to customers. Thus, because of the need for performance upgrade, many devices such as the portable devices (Chunyu Wu, 2018; Jeong et al., 2019), household electronics (Jinwook Kim, 2012b; Seungyoung Ahn; Hyun Ho Park; Cheol-Seung Choi; Jonghoon Kim; Eakhwan Song; Hark Byung Park, 2012), electrical vehicles (Kim et al., 2016; Seungyoung Ahn, 2010; Song et al., 2016; Song et al., 2018), and integrated 3D IC chips (Campi et al., 2018) are beginning to adopt the WPT technology.

Wireless power transfer techniques largely fall under two broad categories- the near field or (non radiative technique) and far-field (or radiative technique). In near field technique also referred to as the non-radiative technique, power is transmitted over short distances through magnetic fields using the inductive coupling that exists between two coils of wire, or power is transmitted through electric fields using capacitive coupling that exists between two metal plates or electrodes (Reza Erfani, 2017). Inductive coupling is the wireless technology that has one of the widest ranges of application. Like earlier stated, they include applications such as charging of toothbrushes, medical implants, electric vehicles, mobile phones etc.

In far-field or radiative techniques, Electrical power is transferred either in the form of solar energy, or through the use of power beams like laser and microwaves (Reza Erfani, 2017). For these techniques to be used, there must be an established line of sight connection between the transmitter and receiver. This technology has the potential of being applied in wireless powered aircrafts or UAVs (Poveda-Garcia et al., 2019). The safety of humans and other devices has been an important concern that continues to require attention in every known technique of transmitting power wirelessly, due to the dangers associated with humans or other devices being exposed to electromagnetic (EM) waves. Because of this, research is still ongoing to determine the safety levels of radiations and exposure to radiations (Yan Lu 2018). Generally, a wireless power grid has a transmitter devices that feeds the power from the power source to its antenna. The antenna which is a metallic strip or plate converts this power to an oscillating EM wave and transmits it by radiation to the receiver. The receiver antenna now converts it back to a form usable by the load (Sun et al., 2013).

Inductive Resonant coupling works with a similar principle to the inductive coupling technique or approach. The difference is that the wireless transfer of power is done between two coils or circuits that are at resonance with each other. This is achieved by tuning both the receiver and transmitter coils to the same resonant frequency. The resonance between the coils can greatly increase coupling and thus increase power transfer efficiency and transfer range (Shinohara, 2014). This inductive resonant coupling technique still has very promising and rich potentials yet to be tapped and maximized as far as realizing the goal of transmitting power wirelessly with minimized loss and maximized efficiency remains cogent.

Very important indices used in checking and analyzing the performance of a wireless power transfer system are power transfer efficiency (PTE) and transferred power (TP), transmission range, load variation tolerance and the system's ability to tolerate misalignment. PTE refers to a comparison or a ratio of power output at the load or power received at the receiver to the input power transferred from the transmitter over the wireless connection, TP refers to the normalized output power at the load. In order to lessen system losses, a high power transfer efficiency (PTE) is needed, also the higher the transfer power (TP), the higher the power delivered to the load. Thus in the optimization of wireless power transfer systems, these two factors must be considered.

Both PTE and TP are called system performances, while indices such as transfer distance, misalignment tolerance and load variation tolerance are application specific performance requirements. System performance indices are very much affected by application specific performance indices. For instance the relationship between the PTE and the transfer distance is an inverse one, because as the transfer distance is increased the PTE decreases.

Over time in literature, various ideas and approaches have been suggested and explored towards the improvement of the overall system performance. Some of the methods or ideas implemented towards the optimization of the wireless power transfer technology include compensation network and circuit design (Cheon et al., 2011; Jegadeesan & Guo, 2012), coil design for high efficiency (Ali et al., 2019; Liu et al., 2018), repeaters (Ahn & Hong, 2013a; JinWook et al., 2011; Kiani et al., 2011; Lee et al., 2016; S.Y.R. Hui, 2014), tuning approaches (Kim et al., 2012; Sample et al., 2011) and control methods (Madawala et al., 2013; Wu et al., 2012). Even with the vast interest and work by researchers in this area, there are still so many challenges yet to be surmounted for this technology to be widely commercialized.

1.1 STATEMENT OF PROBLEM

The convenience offered by the wireless power transfer WPT technology, has resulted in the technology gaining a lot of attention from many applications. There are various wireless power transfer technologies currently which include far-field radiative techniques like the microwave, radio-wave and laser techniques, as well as near-field non-radiative techniques such as the capacitive coupling and the inductive coupling. The magnetic resonant coupling or the inductive resonant coupling approach has gained a lot of attention because of its improved efficiency characteristics and its wide range of application, however there is still room for improvement in the area of its transmission efficiency, since this is still nowhere close to the transmission efficiency offered by its wired counterpart. Also there is a problem of limited mobility as transmission distance especially for mobile devices is still very small, in the order of a few millimeters. There also exists the need to improve the tolerance in the case of misalignment as well as the load characteristics. This systematic review aims to address this gap by critically analyzing existing research to identify key factors influencing transmission efficiency and power transfer distance, exploring optimization techniques, and proposing pathways to design WPT systems that achieve optimal performance across varying distances. By doing so, this study seeks to contribute to the development of efficient and distance-optimized wireless power transfer solutions with implications for diverse applications, from consumer electronics to industrial systems.

2.0 AIM AND OBJECTIVES

The aim of this work is to carry out a systematic review on the design and optimization of transmission efficiency and power transfer distance for a wireless power transfer system.

The objectives to be achieved in reaching the aim are as follows:

1. To undertake a review of WPT technology and identify the areas and gaps for further research and investigation.
2. A review on some of the system architecture used in literature that focus on achieving high power transfer efficiency and longer transmission range with small coil area for an integrated WPT receiver.
3. Investigation and analysis of the various sources of losses and how to mitigate these losses

3.0 METHODOLOGY

To accomplish the outlined objectives, a systematic and comprehensive methodology is adopted for this research. First, an analysis of the literature on Wireless Power Transfer (WPT) technology is done. This includes evaluating research papers, publications, patents, and technical documents critically in order to gain insights into the current status of the topic. The goal is to identify existing advancements, problems, and gaps in the WPT technological environment, particularly those related to transmission efficiency, power transfer distance, and receiver integration of small coil regions.

An evaluation of various system architectures used in the literature is carried out. The emphasis is on architectures designed to provide great power transfer efficiency while expanding transmission range. Designs that incorporate small coil regions in integrated WPT receivers are given special consideration. This entails a comparison of various architectures, their merits, limits, and new ways used to maximize performance characteristics.

Potential study directions are identified based on the outcomes of the literature evaluation, system architecture analysis, and loss inquiry. These directions indicate interesting topics for future research and development in the field of wireless power transfer. The goal is to give assistance for researchers, engineers, and practitioners working on WPT system design and optimization.

Various WPT systems have been demonstrated in prior literature. WPT systems may be generally evaluated by 3 main metrics: efficiency, transmission distance, and receiver area. The tradeoffs between these metrics are shown in Fig. 3.1.

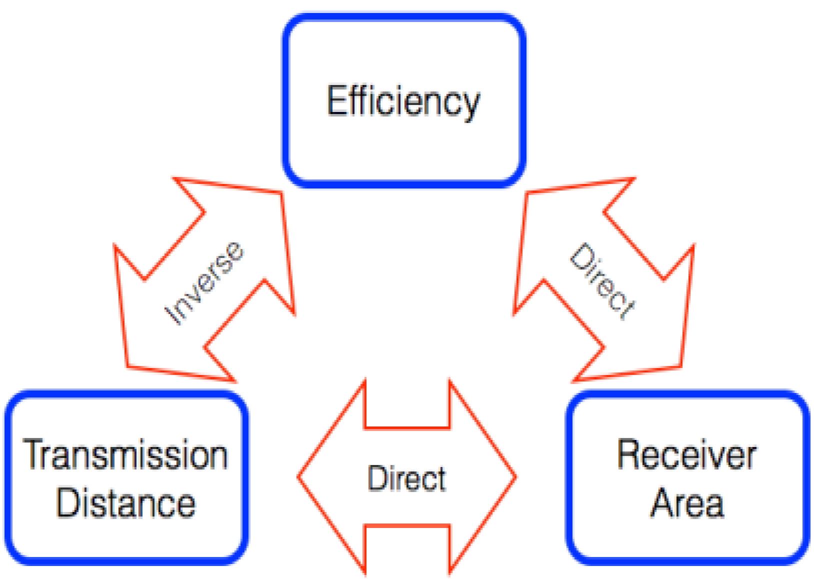

Figure 3.1 Relationships Between the Main Metrics for Inductive Resonant Coupling Wireless Power Transfer Systems

The literature included in this paper was limited to those which cover the main metrics for inductive resonant coupling wireless power transfer systems, which are transmission distance, receiver area, and efficiency. In these papers, simulations are carried out using various simulation software to design and test various aspects that border around the performance relationships of the main metrics of the inductive resonant coupling wireless power transfer systems. For optimization to be possible, various aspects of the wireless power transfer technology using the inductive resonant coupling must be evaluated and improved in such a way that the overall system is improved. There have been many optimization ideas and efforts implemented in various works and literature. The use of relay (or repeater) resonators (Ahn & Hong, 2013a; Arakawa et al., 2018; Cannon et al., 2009; Zhong et al., 2013), impedance matching techniques (Beh et al., 2013; Keisuke Kusaka, 2012), load transformation (Xue et al., 2013), frequency tuning approaches (Kim et al., 2012; Sample et al., 2011), meta-materials (Das et al., 2019; Wang et al., 2011) and optimized resonator designs (Budhia et al., 2011; Chen & Zhao, 2013) have been introduced in the literature to improve performance of WPT.

Articles were explored and searched by the keywords wireless power transfer, Witricity, WPT, power transfer efficiency of wireless power transfer systems, inductive resonant coupling WPT, and wireless charging. Searches on Studies on WPT technologies and wireless power transfer applications were limited to articles written in English and directed towards developing technologies and architectures for enhancing the implementation of WPT especially in the area of improved efficiency of the system. Apart from the searches conducted on various search engines like Google, Google patent, Google scholar, Bing search, digital databases used for the articles search included: EEE Explore, a scholarly database that supplies reliable articles in electronic technologies, electrical engineering, and computer science. These databases contained a large amount of studies on Wireless power transfer in large range of subjects. To identify WPT studies, a mix of keywords were used, including “WPT”, “WPT technologies”, “WPT applications”, these keywords were combined with logical terms such as OR and AND for example “ WPT and biomedical implants” ,wireless power transfer and EV charging” or “WPT and wireless charging.

The main inclusion and exclusion criteria used in selecting literature in the research space of wireless power transfer technology and for the aims and objectives of this research work, were those whose focus were defined by the following metrics as well as the reason for selecting those literature:

a. **Literature on Performance indices of WPT**

Articles on the optimization of power transfer efficiency and transfer power which represent the system level performances as well as the misalignment tolerance which represents an application specific requirement were explored. The power transfer efficiency and transfer power represent one of the very important indices used to measure the performance of wireless power transfer system applications.

The improvement of the PTE is very necessary in minimizing system losses, while the TP is an essential factor that determines the power delivered to the load. Maximum transfer power is obtained when maximum power is delivered from the source to the load, and this occurs when the load impedance is matched to the input impedance of the coil.

Both the Power transfer efficiency and transfer power show varying properties as it relates to the design parameters.

For instance, while the power transfer efficiency is maximized at the self-resonance frequency, maximum power is transferred at two frequencies away from self-resonance

Also, at a specific coupling value called the critical point, maximum power is transferred, however as the coupling is reduced, the PTE begins to rapidly decrease as well.

Apart from the system level performance indices, application specific indices such as transfer distance, misalignment tolerance and nature of the position or geometry of the receiver also has a significant effect on the WPT systems design performance. Generally, a sizeable number of optimizations presented in various literature focuses on the improvement of the system performance for a desired Receiver position as well as orientation, and as a result, the performance is analyzed in relation to the misalignment (Flynn & Fotopoulou, 2013; Fotopoulou & Flynn, 2011).

b. **Literature on WPT coil optimization**
The coil and its design play a very critical role in the WPT systems design. For WPT coils design, there are two important performance indices namely- quality factor and the EM coupling existing between transmitter and receiver. To improve the quality factor, the coil's AC resistance can be decreased while a high inductance is maintained. However, the improvement of the EM coupling between Rx and Tx coils faces serious limitations due to the factors of misalignment and range (distance between coils). EM coupling can however be optimized by making use of a suitable coil structure or geometry for a particular position displacement profile.

c. **Literature on Repeater resonators**
Also articles on numerical analysis on the design of wireless power transfer (WPT) systems with repeaters and segmented transmitter array were also studied. According to various literature, repeater resonators have been found to improve the system performance of WPT systems (Ahn & Hong, 2013a, 2013b; JinWook et al., 2011; Kiani et al., 2011; Zhang et al., 2011).
Repeater resonators placed between the transmitter and receiver coils have been observed to be useful in the improvement of the Power transmission efficiency, the power transferred as well as increasing the range of its transfer. Thus, papers which make use of this approach were also included as part of the research literature.

d. **Literature on Meta-materials for WPT**
Meta-materials (MMs) are artificial materials which possess extraordinary physical as well as electromagnetic characteristics that are not obtainable in natural materials. Meta-materials improve the evanescent near-field and subsequently enhance the power transfer efficiency in WPT applications (Rong et al., 2018; Xin et al., 2017; Zeng et al., 2021). Literature which explored the use of meta-meterials in the wireless power transfer application was consulted.

e. **Literature on Impedance matching and compensation networks**
Adaptive impedance matching (AIM) networks has been proposed in literature to maximize Transfer power where the input impedance of the wireless power transfer network is made to match with the impedance of the source (Beh et al., 2013; Lim et al., 2014). Contrary to Power-amplifier-based laboratory prototyping where impedance of the source is around 50 Ω, the source impedance in power-converter-based designs typically are by far smaller in value. Thus, it is imperative that the input impedance of the WPT system should be brought very near that of the source impedance by the matching network. Articles which explored the use of Impedance matching and compensation networks to improve the overall efficiency of the wireless power transfer system were studied and reviewed as literature.

f. **Literature on Selection of Operating frequency**
When choosing the frequency of Operation for a wireless power transfer system, a number of constraints, technicalities and regulations which vary from country to country must be considered. In order to optimize the efficiency of a wireless power transfer system, it is important to have a quality factor that is as high as possible. The quality factor shares a direct relationship with the coil inductance and operating frequency, but an inverse relationship with the coil resistance. So in order to increase quality factor both the inductance of the coil and the frequency of operation need to be increased, while the coil resistance is decreased. While the alternating current resistance is increased

when the frequency is increased, as a result of skin effect losses, the inductance of the coil is determined almost entirely by its shape with little dependence on its frequency of operation.

4.0 FINDINGS FROM LITERATURE

Various findings related to the various aspects of the topic under investigation are enumerated below.

a. WPT coil optimization

The optimization of the WPT coil is a very important aspect that affects the improvements of the performance of the WPT systems. There have been a number of studies reported in the literature which sought to improve the WPT coils. The focus of some literature is on the improvement of loss minimization, enhancement of coupling, improvement of quality factor leading to the improvement of efficiency (Jinwook Kim, 2012a; Waffenschmidt, 2015). For instance, it is suggested that when windings are concentrated towards the edge of coils, higher coupling is achieved (C.M. Zierhofer, 1996). Also a claim by Xun Liu (2008) suggests that a better performance for the application criteria can be achieved by a hybrid structure. Jinwook and Young-Jin (2015), in their study for the minimization of the coil AC resistance presented unequal pitch distribution. The improvement of quality factor which makes use of a double layered printed spiral coil is presented by Chen and Zhao (2013). While the improvement of the electromagnetic coupling, quality factor, and AC resistance are all important aspects of improving performance, it however may not be the best condition for a particular design scenario.

The various studies reviewed pay attention to particular design conditions, and differences between design limitations and geometries leading to various conclusions. Hence it is imperative to derive a generalized coil design model for WPT coil design. There have been a number of studies which addressed and look into the losses related to resonators. Many optimized designs of resonators have been proposed. For instance, a detailed process for optimizing the double layered printed spiral coil is presented by (Chen & Zhao, 2013). In this paper an illustration of procedures of design for the best choice of number of turns, track width, and turns separation is presented by the authors. Seung Lee (2013) presented a multi turn surface spiral for low AC resistance. However, the surface spiral is limited in utility in limited levels of power as their construction are in printed circuit boards (PCBs) and the role of substrate losses in AC resistance is substantial. The issue of deterioration of coupling with misalignment is addressed by insertion of a negative current loop as proposed by Lee et al. (2013). While this approach reduces the coupling variation it also reduces the overall coupling factor due to its negative magnetic flux.

An experimental study is carried out to compare the helical and spiral coils made from litz windings. At 1000 kHz and with all the resonance frequencies from the experiment close to 0.990 MHz, it was observed that the quality factor measurements of the spiral coil was about 800, while that of the helical coil was about a thousand (1000). Clearly from the experiment, it is seen that the helical shaped coils perform better than its spiral counterpart.

Ze Zhou (2020) proposed a multi-objective optimization method (CAPSO) to find an optimal control target between the output power and efficiency. In this work, the loss power model of the WPT system is established, and the efficiency of the WPT system is analyzed in detail. Finally, simulation results illustrate that the output power is 10.4 kW and the efficiency is 92.97 % when the system is in the optimal solution state. The simulation results demonstrate that the DC–DC converter has the largest loss in the system, and the output power reaches 10.4 kW and the efficiency is 92.97 % when the DC–DC input voltage is at the optimal solution 417.37 V.

Liu et al. (2022) used genetic algorithm optimization technique for the planar circular coil optimization in a limited space in an S-S compensated network of an inductively coupled WPT system by determining the optimal number of turns and turn spacing to improve the transfer quality factor. A PTE of 98% was obtained at a resonant frequency of 85 kHz and a transfer distance of 30mm

A unique 4 coil network is examined by Pardue (2018)**.** In this design, the objective is to increase the transmission range and provide similar power output discontinuously without having to increase the source power or increase the coil area significantly. Therefore compared to the transmission range and coil area, power transfer efficiency is not as much a concern. The geometry of the 4 coil system is shown in Fig. 4.1. The coil1 gets its supply through a matching network from an RF source and coil 2 is on the opposite layer of the board, center aligned. Coil 3 is placed on the receiver board and it is made to faces coil 2. Coil 4 is on the other layer of the receiver board, center aligned, and is connected to a half-wave rectifier.

To minimize the amount of the HFSS simulations, coil 1 and coil 4 were chosen to have the same geometry, and coil 2 and coil 3 were selected to have the same geometry as well. Also, this system operates at 30 mm transmission distance with 14.5 dBm, 960 MHz source.

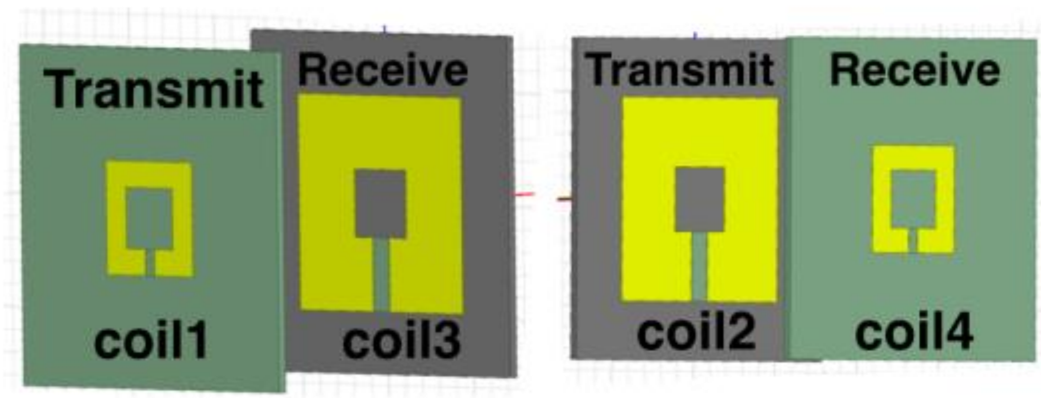

Figure 4.1: A 4 coil system (Pardue, 2018)

b. Repeaters for WPT

Repeater resonators have been found to be very useful in improving the overall system performance when placed between transmitter and receiver coils (Ahn & Hong, 2013b; Cheng et al., 2020; Lee et al., 2016; Tummala et al., 2021). They are seen to bring improvement of the power transfer efficiency, the transfer power as well as the transmission distance or range. In the improvement of transfer distance, it is seen that the repeater resonator achieves this through its relay effect (Zhang et al., 2011). However, the unimpeded distance between the transmitter and receiver is not increased because there is a need to place these resonators between the transmitter and receiver. The Efficiency of a wireless power transfer system with a single repeater placed near the Transmitter has been analyzed by Zhong et al. (2013). This study showed that the optimized three-coil wireless power transfer system offers a higher efficiency than the two coil wireless power transfer system. The frequency characteristics of power transfer efficiency and transfer power were analyzed and

explored by Ahn and Hong (2013b). However, these studies have not proposed a generalized design method for WPT repeaters.

c. The use of Meta-materials

Urzhumov and Smith (2011) put forward an intensive theoretical inquiry on improving the Power transfer efficiency by the use of meta-materials. Their inquiry also shows the improvement of mutual inductance that could be achieved by the use of these meta-materials. This phenomenon can be applied towards the improvement of the Power transfer efficiency in terms of both the power transfer range and the misalignment tolerance. This improvement in PTE is due to the material's ability to redirect leakage magnetic flux from the transmitter to the receiver, thereby minimizing the losses due to flux leakage.

Normally, Meta-materials are structures which are periodically placed. The experimentation carried out by Wang et al. (2011) shows the improvement of power transfer efficiency by making use of a double sided spiral as the composing unit cell. It has also been found that the planar meta structure has a better performance than the 3D counterpart, and has shown to be very useful for the design of a compacted system. Another study by Yingchun Fan (2013) presents how the efficiency improves from an experiment using a design with two layers, with planar spiral on one side and a Meande Line with narrow metallic strips on the other side, at 14.8 MHz. The above study shows that the Meta-materials can be situated at the ends of the transmitter and receiver, instead of at the middle, which will consequently have the effect of increasing the unobstructed distance. Examples of systems with this arrangement can be seen in (Bui et al., 2017; Ranaweera et al., 2014; Ranaweera et al., 2016; Song et al., 2019).

Rong et al. (2020) constructed two types of MMs, and the key parameters for achieving the peculiar properties were formulated. A new method of using an equivalent circuit model to analyze the MM in the WPT system is proposed. The MM unit cell is regarded as RLC resonance circuit and then the whole MM is regarded as the compound resonator. In addition, the Electromagnetic force (EMF) simulations of the WPT system in the diverse situation are evaluated to achieve excellent transfer performance. Moreover, the tuning scheme to achieve high PTE by changing the mutual inductance is applied in the WPT system with mu-negative meta-material MNM-MM. The shielding effect of the mu-near zero meta-material MNZ-MM is deduced and expounded in terms of equivalent circuit model. Both the ADS simulation and the experiments are performed to validate the proposed method, the results of which agree with the results of the calculation. In this work, the WPT system is a 4 coil system. The MM slab is a 3 x 3 cell array and resonant frequency is 13.56MHz. The fabricated WPT system with the combined MM exhibits a 15.7% improvement in the PTE and 15.17% reduction in EMF leakage.

d. Impedance Matching

The specific application determines the equivalent load impedance. For instance, for a battery charging application, the equivalent load resistance is determined by the state of charge (SOC) of the battery. In such situations of varying load, an advanced impedance matching network can be employed between the receiver coil and the battery charger in order to optimize the equivalent load impedance. These matching networks are expected to be able to adapt by changing the impedance of the network. At the source, when there are dynamic changes in a wireless power transfer system, the input impedance should be held at a constant matched condition. Normally, an inductor with a switched capacitor bank is utilized in making changes to the impedance (Beh et al., 2013; Lim et al., 2014). For the matching network, a current controlled inductor that has been employed as a control for a micro-inverter can be utilized as a variable inductor. According to the arrangement of component of the matching network impedance, matching networks have been grouped into the L, inverted L, T and Π types.

However to make the choice of the most efficient matching network, certain constraints of design must be considered, and they include, variations in coupling, as well as the number of switching devices.

e. Operating frequency selection

In order to achieve the maximum efficiency for a wireless power transfer system, the quality factor should be increased to the highest possible value. This can be achieved in three ways; by increasing the coil inductance, decreasing coil resistance, and increasing the operating frequency. But due to skin effect losses, as the frequency increases, the AC resistance is also increased. Inductance of the coil however is defined by its shape, and the operating frequency has very little or no effect on it. Thus, for a certain optimal quality factor, there is an optimized frequency for a particular type of design. Typically, for most designs, this optimized frequency is in the MHz range. Frequency ranges from about 0.01 MHz to about 0.15 MHz have been employed successfully to power high power applications such as Electric Vehicles (Poveda-Garcia et al., 2019), meanwhile, operating frequencies as high as 20 MHz have been employed in low power applications such as biomedical applications (Na et al., 2015). Advances in semiconductor technologies and research activities (José Millán, 2014) brings to light that in commercial space in the near future high frequency high power devices will be available. Therefore, high power and high frequency wireless power transfer in the order of MHz is closer than we think for high power applications.

f. Rectifier design

(Pardue, 2018) carried out a comparison of a half-wave rectifier and bridge rectifier. The measurement was completed at 1mm transmission distance with 14.5 dBm, 868 MHz source. The half wave rectifier was found to have a higher efficiency across all loads. Also, at lower load resistance and consequently lower voltage output, the difference in efficiency was seen to largest. It was observed that the forward voltage had more effects on the bridge rectifier. And conversely at higher output voltage, that is large load resistance, the difference in efficiency was decreased. Also the effect of the input power on the efficiency of the rectifier was studied. The measurement was carried out at 0.1cm transmission range with 1 kΩ load resistance and 780 MHz source frequency. It was found that, as the input power increases, the efficiency also improves. With constant resistance load, the coil efficiency and the source efficiency were mostly unaffected as the input power increased.

5.0 CONCLUSION

It is seen that the helical coils have a higher quality factor than the spiral coils and therefore outperform the spiral coils when used as transmitter and receiver of the wireless power transfer system. In a WPT system where efficiency is not the focus, a four coil system is used in such an arrangement that makes for an increased transmission distance. This further shows the tradeoff relationship between optimizing the power transfer Efficiency and the power transfer distance.

Repeaters are found to be a good solution for optimization of power transfer efficiency and improved transmission distance when placed between transmitter and receiver. A double spiral repeater which was placed at the receiver coil was seen to improve the power transfer efficiency as well as increase the transmission distance and ensure an increased misalignment tolerance. A novel tri-spiral repeater has also been introduced which has the capacity to improve the overall system performance and offers a higher power transfer efficiency than the two coil system.

The use of Meta-materials has been seen to offer more power transfer efficiency than the usual metallic materials commonly used due to the ability to redirect leakage magnetic flux, hence minimizing the losses resulting from the leakage. It is shown also that when these meta structures are planar, they outperform their 3D counterparts.

To get the best possible quality factor, there is an operating frequency which is optimum for use. With the coming of wideband gap semiconductor devices like the SiC and GaN devices, the MHz frequency range is now a possible operating frequency range for the WPT systems, since higher frequency of operation will improve the quality factor of coils and thus the overall performance of the system.

It is seen that in the design of a rectifier for this wireless power transfer system, since power transfer efficiency is a goal to be achieved, a half wave rectifier is seen to have a higher efficiency across all load resistance conditions as compare to the full wave bridge rectifier. This is because the full wave bridge rectifier is more affected by the forward voltage. Also at low load resistance which results in low voltage output, it is observed that the efficiency difference between the half wave rectifier and full wave bridge rectifier is largest. At high load resistance which results in high voltage output, it is observed that the efficiency difference between the half wave rectifier and full wave bridge rectifier is lowest. In any case, the efficiency of the half-wave rectifier is still higher than that of the full-wave bridge rectifier. It is observed that as the input power of the system is increased, the efficiency of the rectifier also increases, although with this increase in input power with load resistance constant, the coil efficiency as well as the source efficiency hardly experiences any changes.

5.1 RECOMMENDATIONS

From the findings above, the following recommendations can be implemented on various aspects of a single wireless power transfer system.

1. The coil system of a wireless power transfer system can be built using helical coils for both transmitter and receiver
2. Repeater resonators can be incorporated into the design in order to improve the system power transfer efficiency and the power transfer distance and the overall system performance.
3. Quad-spiral planar repeater resonators should be placed in-between the transmitter and receiver, since it is observed that the tri spiral repeater performed better than the double-spiral repeater in its function to improve power transfer efficiency, the power transfer distance, and increased misalignment tolerance.
4. For the design of the resonators, meta-materials can be used.
5. Due to the recent advances in semiconductor devices, frequency of 10 MHz can be used as the systems frequency of operation in order to have a higher and better qualify factor in the coils or inductor system
6. For the rectifier design, a half wave rectifier should be used over a full wave bridge rectifier, since it is less affected by the forward voltage. This is to further ensure an increased power transfer efficiency at the output of the rectifier delivering power to the load.
7. Because of the various variables and indices which have stakes in determining the overall efficiency and range of transmission of the wireless power transmission system as well as the nature of relationships existing between these indices, the metaheuristic optimization technique like the particle swarm optimization (PSO) or the moth swarm optimization algorithm (MSA) can be used to optimize the efficiency and range performance of this system.

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