UNIVERSITI PUTRA MALAYSIA

HIGHLY EFFICIENT MAGNETIC RESONANCE COUPLING WIRELESS POWER TRANSFER FOR 5G APPLICATIONS

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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June 2021

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Faculty : Engineering

This thesis reviewed the existing technology of the WPT system. Most Magnetic Resonance Coupling Wireless Power Transfer (MRC WPT) applications have been designed in kHz and MHz frequency spectrum. The International telecommunication Union has declared the following spectrum for 5G communication, and the spectrum range is; 3.4-3.6 GHz, 5-6 GHz, 24.25-27.5 GHz, 37-40.5 GHz, and 66-76 GHz frequency bands.

The proposed design is first analyzed theoretically in MATLAB to realize the highly efficient MRC WPT at GHz frequency band. The Planar Spiral Coil Magnetic Resonance Coupling (PSC MRC) Antennas are designed at 3.4-3.5 GHz, and 5-6 GHz frequency band for the Circular and Square shapes with one, two and three turns. The PSC MRC Antennas circumference is designed to the one-wavelength loop λ. The Antenna will resonate when C is slightly larger than λ. The mutual coupling M has been calculated as the mutual coupling is crucial in determining the efficiency of the MRC WPT system,. and the From the results, the PSC MRC Circular one-turn of 3.4-3.5 GHz has the best mutual coupling, M at the distance of 0 to 20 mm. while the PSC MRC of square two-turns is the highest mutual coupling, M when the distance is more than 20 mm amongst the other PSC MRC designs. Also, the theoretical efficiency of the proposed PSC MRC Antennas is also calculated in MATLAB. For the 3.4-3.5 GHz designed, theoretically, the PSCMRC Circular's efficiency is better than the PSC MRC Square design's efficiency. For the 5-6 GHz PSC MRC design, the Square-one-turn has the highest efficiency than the Circular one-turn designs.

Next, all the designs have been simulated in the CST software to compare with the theoretical results. The PSC MRC Antennas are modelled on the FR4 substrate with thickness and copper thickness of 0.6 mm and 0.035 mm, respectively, in the CST Software. The parametric evaluation has been done in CST software to find the best

performance of S11 (dB) and SRF (GHz) of the proposed PSC MRC Antenna designs to be working at a 5G frequency band. The return loss S11 of each design needs to be below -10 dB to improve the efficiency of the MRC WPT system. In conclusion, all the PSC MRC Antenna for the circular and square designs at 3.4-3.5 GHz and 5-6 GHz are designed to be operated below -10 dB of return loss S11.

Finally, the Circular PSC MRC Antenna one-turn, two-turns, three-turns at 3.4-3.5 GHz and Circular one-turn PSC MRC Antenna 5-6 GHz are fabricated because they gave the best results when comparing with the theoretical and simulation results. The measurements results are compared with the simulated and the theoretical results to analyzed the efficiency performance with the distance,d.

From the measurement results, the highest efficiency for the proposed PSC MRC Antenna design is the Circular one-turn PSC MRC Antenna at 3.4-3.5 GHz. The PSC MRC antenna's efficiency is 31.58 % when the distance is 2 mm, 31.26% and 31.02% when the distance is 3 mm and 4 mm, respectively. It can be concluded that, previously, most PSC MRC Antenna designs are only used for short-distance low frequency and CMOS applications. Strong near-field PSC MRC antenna structures are designed at a 5G frequency band has been obtained, which offers overall efficiency higher than 20%, close to 7 mm distance by generating an intense magnetic field around the loop coil antenna. The efficiency in CMOS applications is also lower than 20%.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMINDAHAN KUASA TANPA WAYAR MENGGUNAKAN IKATAN MAGNETIK SALUNAN YANG SANGAT CEKAP UNTUK APLIKASI 5G

Oleh

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Tesis ini mengkaji teknologi sedia ada, iaitu sistem Pemindahan Kuasa Wayarles. Sebilangan besar aplikasi Gandingan Gelombang Magnet Salunan untuk sistem Pemindahan Kuasa Wayarles telah di gunakan dalam spektrum frekuensi kHz dan MHz. Kesatuan telekomunikasi Antarabangsa telah menyatakan spektrum berikut untuk komunikasi 5G. Julat spektrumnya adalah; 3.4-3.6 GHz, 5-6 GHz, 24.25-27.5 GHz, 37-40.5 GHz, dan juga jalur frekuensi 66-76 GHz.

Reka bentuk yang dicadangkan pertama kali dianalisis secara teori dalam MATLAB untuk mewujudkan Gandingan Gelombang Magnet Salunan untuk sistem Pemindahan Kuasa Wayarles yang sangat cekap pada jalur frekuensi GHz. Antena Satah Pilin Gandingan Gelombang Magnet Salunan untuk sistem Pemindahan Kuasa Wayarles direkabentuk pada jalur frekuensi 3.4-3.5 GHz dan 5-6 GHz untuk bentuk Bulat dan Persegi dengan satu, dua dan tiga putaran. Lingkaran Antena Satah Pilin Gandingan Gelombang Magnet Salunan dirancang untuk gelung panjang satu gelombang λ. Antena akan bergema apabila C sedikit lebih besar daripada λ. Gandingan bersama M telah dikira, dan PSC MRC Edaran satu-putaran 3.4-3.5 GHz mempunyai gandingan bersama terbaik, M pada jarak 0 hingga 20 mm. sementara PSC MRC dengan dua putaran persegi adalah gandingan bersama tertinggi, M apabila jaraknya lebih dari 20 mm di antara reka bentuk Antena Satah Pilin Gandingan Gelombang Magnet Salunan yang lain. Juga, kecekapan teoritis Antena Satah Pilin Gandingan Gelombang Magnet Salunan yang dicadangkan juga dikira dalam MATLAB. Untuk 3.4-3.5 GHz yang dirancang, secara teorinya, kecekapan Antena Satah Pilin Gandingan Gelombang Magnet Salunan berbentu bulat lebih baik daripada kecekapan reka bentuk Antena Satah Pilin Gandingan Gelombang Magnet Salunan berbentuk segi-empat. Untuk reka bentuk Antena Satah Pilin Gandingan Gelombang Magnet Salunan 5-6 GHz, satu lingkaran segi-empat mempunyai kecekapan tertinggi berbanding dengan reka bentuk satu lingkaran berbentuk bulat.

Seterusnya, semua reka bentuk telah disimulasikan dalam perisian CST untuk dibandingkan dengan hasil teori. Antena Satah Pilin Gandingan Gelombang Magnet Salunan dimodelkan dalam Perisian CST pada substrat FR4 dengan ketebalan dan ketebalan tembaga masing-masing 0.6 mm dan 0.035 mm. Penilaian parametrik telah dilakukan dalam perisian CST untuk mencari prestasi S11 (dB) terbaik dan frekuensi salunan sendiri, SRF (GHz) dari cadangan Antena Satah Pilin Gandingan Gelombang Magnet Salunan yang dirancang untuk berfungsi pada jalur frekuensi 5G. Kehilangan pulangan S11 setiap reka bentuk perlu berada di bawah -10 dB untuk meningkatkan kecekapan sistem Gandingan Gelombang Magnet Salunan untuk sistem Pemindahan Kuasa Wayarles. Kesimpulannya, semua Antena Satah Pilin Gandingan Gelombang Magnet Salunan untuk reka bentuk bulat dan segi-empat pada 3.4-3.5 GHz dan 5-6 GHz dirancang untuk beroperasi di bawah -10 dB kehilangan pulangan S11. Akhirnya, Antena Satah Pilin Gandingan Gelombang Magnet Salunan satu putaran, dua putaran, tiga putaran pada 3,4-3,5 GHz dan Satu putaran Antena Satah Pilin Gandingan Gelombang Magnet Salunan 5-6 GHz di modelkan kerana mereka memberikan hasil terbaik ketika membandingkan dengan hasil teori dan hasil simulasi.Hasil pengukuran dibandingkan dengan hasil simulasi dan teori untuk menganalisis prestasi kecekapan dengan jarak, *d*.

Dari hasil pengukuran, kecekapan tertinggi untuk reka bentuk Antena Satah Pilin Gandingan Gelombang Magnet Salunan yang dicadangkan adalah Antena Satah Pilin Gandingan Gelombang Magnet Salunan satu putaran pada 3.4-3.5 GHz. Kecekapan antenanya adalah 31.58% apabila jaraknya 2 mm, 31.26% dan 31.02% apabila jarak masing-masing berada pada 3 mm dan 4 mm.

Dapat disimpulkan bahawa, sebelumnya, kebanyakan reka bentuk Antena PSC MRC hanya digunakan untuk aplikasi frekuensi rendah dalam jarak yang pendek dan CMOS. Struktur antena Gandingan Gelombang Magnet Salunan untuk sistem Pemindahan Kuasa Wayarles medan dekat yang kuat dirancang pada jalur frekuensi 5G telah diperoleh, yang menawarkan kecekapan keseluruhan lebih tinggi daripada 20%, dengan jarak hampir 7 mm dan menghasilkan medan magnet yang kuat di sekitar antena gegelung. Kecekapan dalam aplikasi CMOS juga lebih rendah daripada 20%.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

WPT	Wireless Power Transfer
EM	Electromagnetic Wave
ICs	Integrated Circuits
MPT	Microwave Power Transfer
EMC	Electro Magnetic coupling
MIT	Massachusetts Institute of Technology
PTE	Power Transfer Efficiency
LF	Low Frequency
HF	High Frequency
RFID	Radio Frequency Identification
SRF	Self Resonance Frequency
VNA	Vector Network Analyser
RF	Radio Frequency
CST	Computer Simulation Technology
KHz	Kilo Hertz
MHz	Mega Hertz
GHz	Giga Hertz
2G	Second Generations
3G	Third Generations
4G	Fourth Generations
5G	Fifth Generations
IoT/IoE	Internet of Things/Internet of Everything
TX	Transmitter

RX	Receiver
PSC	Planar Spiral Coil
CMOS	Complementary metal–oxide–semiconductor
SS	Series-Series
SP	Series-Parallel
PS	Parallel-Series
PP	Parallel-Parallel
WPC	Foundation of Wireless Power Consortium
PMA	Foundation of Power Matters Alliance
A4WP	Foundation of Alliance for WPT
WET	Wireless Energy Transfer
WREL	Wireless Resonant Energy Links
WiTricity	Wireless Electricity

LIST OF SYMBOLS

H(X)	Path Field Strength
R	Radius
x	Distance From The Centre Of The Coil In The x-Direction
Φ	Magnetic Flux
B	Magnetic Flux Density
A	Area Of Loop
μ_o	Magnetic Conductivity (Permeability) In Vacuum
μ_r	Relative Permeability Of A Material
N	Number Of Turns
W	Width Of The Planar Coil
S	Space Between The Turns Of The Planar Coil
D_{in}	Inner Diameter Of The Planar Coil
D_{out}	Outer Diameter Of The Planar Coil
D_{avg}	Average Diameter
Ψ	The Total Flux
L	Inductance Of The Coil
I	Current
M	Mutual Coupling
k	Coupling Of The Coils
f	Resonance Frequency
Ω	Angular Frequency
R_S	Source Resistance
R_L	Load Resistance

I_S	Source Current
I_L	Load Current
Cp	Parasitic Capacitance
$\boldsymbol{\rho}$	Fill Ration
V_o	Voltage Output
Z	Impedance Of The Coil
S_{21}	Scattering Parameters

CHAPTER 1

INTRODUCTION

1.1 Background

Wireless power transfer (WPT) is a means of transferring electric power without any physical connections, and it provides a safe, mobile, and convenient solution to recharge the battery of any electrical devices (Jolani *et al.*, 2014; Farid, 2015; Jolani, Yu and Chen, 2015). The traditional power supply, which uses cords, is so messy compared to the wireless power supply, and they do not allow large-s cale utilization and mobility. However, using the battery as a replacement for the power cord power supply is not a great solution. The batteries have a lifetime shortage, increasing the hardware implementation's weight, cost, and surface area(Agiwal, Roy and Saxena, 2016)(Newsletter, 2021).

Furthermore, to replace or recharge the batteries inside the hardware seems to be unfeasible, and its high operational costs (Noohani and Magsi, 2020)(Ponnimbaduge Perera *et al.*, 2018). Thus, the development of WPT techniques has allowed electromagnetic wave energy to be transferred from the transmitter, which is the power source, to the receiver destination wirelessly (Jawad *et al.*, 2017). A century ago, Tesla investigated the WPT based on magnetic resonance and near-field coupling using two-loop resonators (Zhong, Lee and Ron Hui, 2013).

According to Tesla, depending on the energy transfer mechanism, WPT can be radiative or nonradiative. As for radiative power, the antenna can propagate electromagnetic waves over long distances through a medium, for instance, air or vacuum (Barman *et al.*, 2015)(Hui, 2013). However, the power transmission efficiency is very low due to the radiative power emissions' Omni-directional nature (Wei, Wang, and Dai, 2014)(Kim, Won, and Jang, 2010). Omni-directional antennas work very well for information transfer, and they not suitable for a high energy transfer because a vast majority of energy is wasted into free space (Karalis, Joannopoulos, and Soljačić, 2008). For this solution, to transfer energy with high efficiency, nonradiative WPT is used (Kim, Won and Jang, 2010). Nonradiative WPT depends on the near-field magnetic coupling using the conductive loops, and it can be categorized as short-range and mid-range WPT (Hui, Zhong and Lee, 2014)(Biswas *et al.*, 2018). It has also become an active area for standardization, such as Qi and A4WP specification (Galinina *et al.*, 2016). Nonradiative WPT mainly operates at the range frequency of 20 kilohertz (kHz) to a few megahertz (MHz) (Hui, Zhong and Lee, 2014). Nevertheless, it has been reported that recently WPT is also being used at sub-gigahertz(GHz) where miniature self-resonant antennas are designed to realize the transcutaneous WPT (Nukala *et al.*, 2016; YC Lie, 2017)(YC Lie, 2017)(Costanzo and Masotti, 2017).

WPT technique is also rapidly growing in research due to the rising of mobile electronics usage. There is a dramatic growth in the level of interest in near-field WPT and information technologies because the WPT technique has been used in mobile phones, electric vehicles, medical implants, wireless sensor networks, and others (Jawad *et al.*, 2017)(Vijayakumaran Nair and Choi, 2016)(Carvalho *et al.*, 2017)(Issue, 2013).

The Fifth Generation (5G) technology is the next evolution technology that can provide connectivity for any electrical device, increasing data rate, and has higher energy efficiency. The most important reasons for this rise in interest in higher frequency and are the larger available bandwidth, compact size, higher spatial resolution for a given antenna size, better temporal resolution, and the reusability of frequencies (M. Alonso-del Pino, Jan 2020)(Yifei and Longming, 2020)(Agiwal, Roy and Saxena, 2016). Varieties of 5G enabling technologies have been developed, including extending the wireless communication to the higher frequency band, the advances development of multi-band antenna, and the wireless power transfer system (Jones, 2018)(Bonati, Gambin and Rossi, 2017).5G technology can realize the vision of the Internet of Things/Internet of Everything (IoT/IoE). It supports the significant number of devices connected with a reduced cost per information transfer(Barman *et al.*, 2015). According to Costanzo and Masotti (2017), mobile traffic is expected to increase by more than 60% per year. The mobile traffic is due to the spread of electronic devices usage. The history of RF identification (RFID) Near-Field Wireless Power Transfer from few decades has applications that operate at low-frequency (LF) ranging from 30 ~ 300 kHz and high frequency (HF) ranging from 3 ~ 30 MHz bands. The LF and HF RFID systems' commercial applications have already been used since the 1990s (Chen *et al.*, 2008). Thus, the next 5G generation wireless networks' critical essence is to explore and exploit this new, high-frequency mm-wave band, which ranges from 3~300 GHz frequency band (Neil *et al.*, 2017)(Communications and Commission, 2019)(Galinina *et al.*, 2016)(Newsletter, 2021).

1.2 Problem Statement

1. Nearfield Inductive Coupling provides high efficiency only at a short distance. The transfer efficiency drops faster when the distance is expending and the axial's misalignment between the transmitter and receiver coil.

Wireless Power Transfer (WPT) provides a safe, convenient, and portable solution to transfer electric power without any physical connection and recharge any electrical devices' batteries. For the past few decades, most WPT system has been using inductive coupling to transfer electrical power, consisting of a transmitter from the power source and a receiver to the load coil over the air medium. The systems are e to be implemented. However, it can only provide high efficiency only at a very short distance. The transfer efficiency drops faster when the distance is expending and the axial's misalignment between the transmitter and receiver coil. Thus, in 2007, Magnetic Resonance Coupling (MRC) has been introduced from MIT (Massachusetts Institute of Technology), which can achieve power transmission over a significant distance (Raju *et al.*, 2014). Although magnetic resonance has an advantage in terms of distance compared to electromagnetic induction, the system has a limitation as the load absorption power is sensitive to the variations on the operating parameters. The transmission performance will significantly reduce due to a slight difference in resonance and operation frequency.

2. Most reported MRC WPT systems uses the coils that are often bulky in geometry, such as helical antenna, spiral loops, and dimensional wire loops. Thus, the techniques are challenging to apply to small electronics designs, such as in 5G designs applications.

Thus, this thesis utilizes the printed spiral coils (PSCs) MRC WPT methods to design the MRC WPT system for 5G Applications. This method is more suitable for low-design profiles, small footprints, and easy fabricating MRC WPT Antenna (Jolani *et al.*, 2014). Furthermore, this thesis also targets to analyze the design's critical parameters to achieve a highly efficient MRC WPT system for 5G Applications. The five key factors are the operation frequency, the coupling distance parameters, the power level, the coils' Q-factor, and the coil geometry, including size and weight (Yeoh *et al.*, no date)

3. According to Costanzo and Masotti (2017) , Ezhilarasan and E. (2017), and Bonati, Gambin, and Rossi (2017), mobile traffic is expected to increase by more than 60% per year. The traffic is congested due to the spreading of electronic devices. Furthermore, the circuit model equations are mainly designed for low frequency (kHz and MHz) MRC WPT systems.

The history of RF identification (RFID) Near-Field Wireless Power Transfer for few decades has applications that operate at low-frequency (LF) ranging from 30 ~ 300 kHz and high frequency (HF) ranging from 3 ~ 30 MHz bands. The LF and HF RFID systems' commercial applications have already been used since the 1990s (Chen *et al.*, 2008). Thus, the next 5G generation wireless networks' critical essence is exploring and exploiting this new, high-frequency mm-wave band, ranging from 3~300 GHz frequency band (Neil et al.). The transformation of the low frequency (kHz and MHz) circuit model equations to high frequency (GHz) circuit model equations is crucial to achieving high efficient planar coils antenna MRC WPT designs structure. This method is essential because no available circuit model equations have been designed at high frequency (GHz) for the MRC WPT system.

Furthermore, the GHz frequency efficiency, which is mainly in CMOS, is lower than 20% (Jia *et al.*, 2015). This thesis aims to find Near-field Wireless Power Transfer configurations using Strongly Magnetic Resonance Coupling at a 5G frequency band to achieve an efficiency higher than 20%. The frequency of operations focuses on the lower frequency band, ranging from 3.4~3.5 GHz and 5~6 GHz bands. The planar loops antenna is used to generate the alternating magnetic field for the system as the magnetic flux will be developed around any conductor loop of any shape and particularly intense in the form of loop coil antenna (Klaus Finkenzeller, 2010)

1.3 Research Aim and Objectives

This study aims to configure the MRC WPT with high efficiency at the high-frequency band. The targeting frequency operation is at the 5G frequency band (sub-6 GHz), ranging from 3.4~3.5 ad 5~6 GHz frequency band. This study designs apply the commonly used MRC WPT method by transforming the lower frequency band (KHz and MHz) to high-frequency bands (GHz).

The objectives of this thesis are to:

1. Design planar coils antenna configuration based on the MRC WPT method that is feasible for 5G applications.
2. Transform the low frequency (kHz and MHz) circuit model equations to high frequency (GHz) circuit model equations to achieve high efficient planar coils antenna MRC WPT designs structure.
3. Simulate and evaluate the proposed design of the planar coil antenna MRC WPT in terms of efficiency performance.
4. Validate the proposed design by fabrication and experimentation in terms of efficiency and distance effects.

1.4 Scope of Research

The scope of this study is to find configurations, develop and analyze the high-efficiency MCR-WPT using the planar loop antenna. According to the Bio-Savart law, currents can generate a magnetic field, and the magnetic field are active in the near-field of the loop antenna (Bevelacqua, 2019)(Yi and Kevin, 2008). The planar loops antenna is used to generate the alternating magnetic field for the system as the magnetic flux will be developed around any conductor loop of any shape and particularly intense in the form of a loop coil antenna (Klaus Finkenzeller, 2010). The scope of this study is to find configurations for Near-field Wireless Power Transfer using Strongly Magnetic Resonance Coupling at 5G frequency band. The operation frequency focuses on the lower frequency band, ranging from 3.4~3.5 and GHz and 5~6 GHz bands. The big challenge for Wireless Power Transfer for 5G is to improve the system's power transfer efficiency, as we know that the antenna size is proportional to its operating wavelength for optimum efficiency. Therefore, the antenna size should be reduced to increase the system's performance and design system to be operated at the high-frequency band (5G).

Furthermore, as the antenna design gets smaller, it would be impossible to use any passive components for the equivalent matching circuit to resonate with the operating frequency system. Thus, the operating frequency is achieved by adjusting the parasitic Capacitance Cp, which depends on the antenna pattern's geometry, the dielectric constant, thickness of the substrate layer, and the shielding layer pattern below the antenna layer. The antenna's geometry also includes the coil's length, number of turns, trace width, the gap between the two adjacent traces, inductance value, and Q-factor of the antenna coil (Chen *et al*., 2008). Figure 1.1 shows the type of WPT technologies.

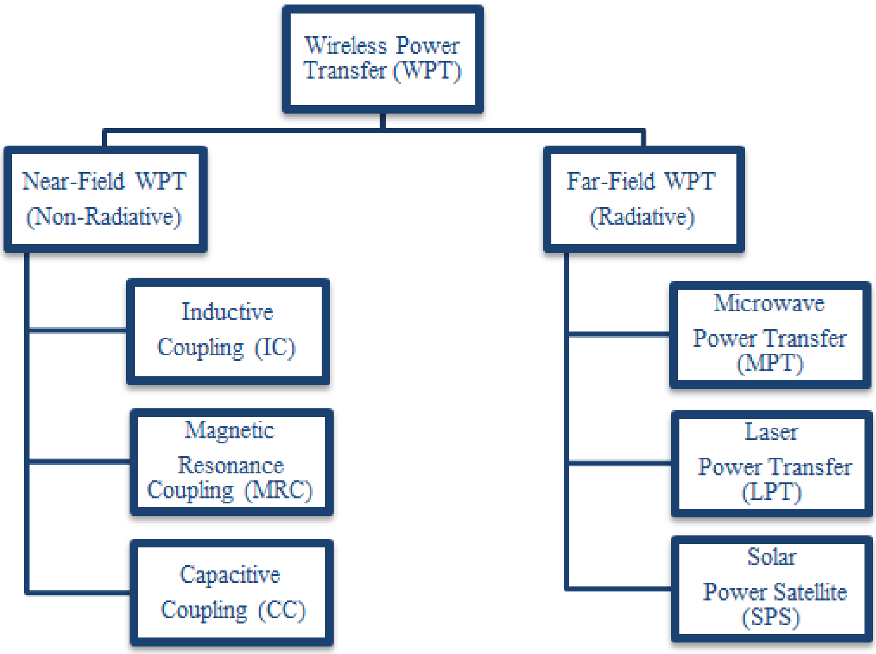

Figure 1.1 : Type of WPT Technologies

Based on Figure 1.1, this study's scope is illustrated in Figure 1.2. The continuous lines show the direction to follow in this study to achieve the objective, while the dashed line shows the research area that is not discussed in this study.

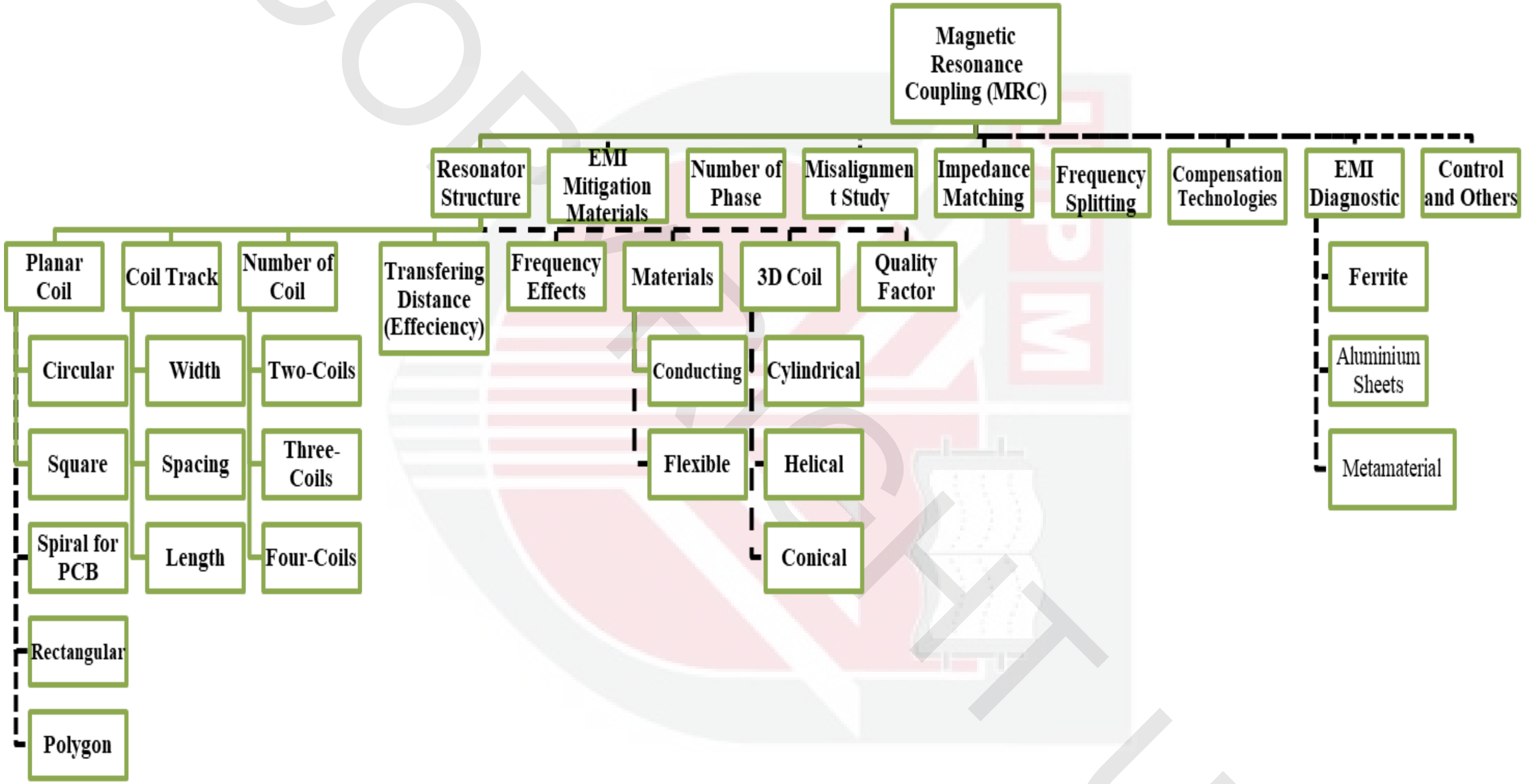

Figure 1.2 : Scope of Study

1.5 Research Methodology

Firstly, to achieve these study objectives, thorough research has been done to understand MRC WPT's fundamentals and the system design, resonating at the intended 5G application frequency. The theoretical analysis and parametric evaluation have been carried out in MATLAB software to find the highest efficiency needed for the system. The low-frequency circuit equations (kHz and MHz) is first transformed to the high-frequency circuit equations (GHz). The transform equations are used to calculate the theoretical efficiency performances of the proposed design. Then, the 3D full-wave electromagnetic simulator (CST Microwave Studio, Version 2016) is used to design the planar coil antenna, and the results between theoretical and simulation are compared. Then, the MRC WPT antennas are fabricated on the FR4 substrate. Finally, the MRC WPT antenna measurement is done to validate the design methods. The flow and development methodologies are explained in the flow chart shown in Figure 1.3.

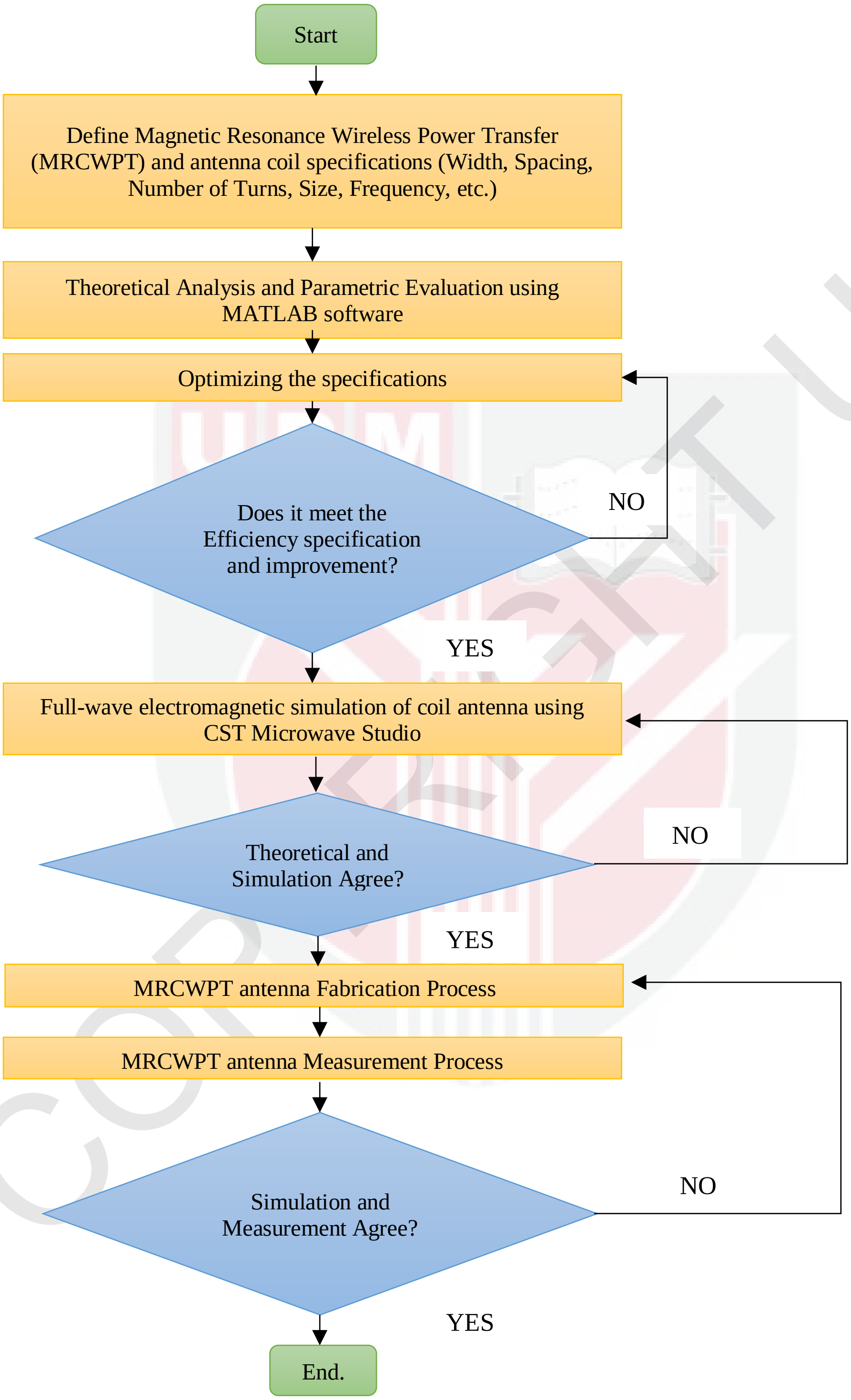

Figure 1.3 : Methodology of Design PSC MRC WPT

1.6 List of Contribution

The main contributions of this thesis can be summarized as follows:

- Nearfield Inductive Coupling provides high efficiency. However, the high efficiency is only at a short distance because the transfer efficiency drops faster when the distance is expending and the axial's misalignment between the transmitter and receiver coil. Thus, in 2007, the technology of magnetic resonant coupling wireless power transfer (MRC WPT) has been introduced by a research group from the Massachusetts Institute of Technology (MIT). This method takes advantage of two electromagnetic systems with the same resonance coil frequency to transfer energy at a certain distance. Generally, when two electromagnetic systems are weak coupling at a certain distance, the system can excite strong magnetic resonance if the natural resonance frequency is the same and improves the efficiency and the distance of the power transfer. Furthermore, from the reported literature review, most Low Frequencies MRC WPT designs use bulky resoanance coil, such as helix coil and litz wire to design the transmitter (TX) Reciever(RX) of the MRC WPT system. For this reason, the Nearfield Inductive Coupling configuration based on the MRC WPT for extended distance to cover 5G Applications had been introduced using the Planar Spiral Coil (PSC) designs for the system's simplicity.

- Most reported Near-Field Wireless Power Transfer for few decades has applications, for instance, RF identification (RFID), which operates at low-frequency (LF) ranging from 30 ~ 300 kHz and high frequency (HF) ranging from 3 ~ 30 MHz bands. Today, unfortunately, we observe a plethora of registered RFID applications. Thus, the next 5G bands' critical essence is exploring and exploiting this new, high-frequency mm-wave band, ranging from 3~300 GHz frequency band. The transformation of the low frequency (kHz and MHz) circuit model equations to high frequency (GHz) circuit model equations is crucial to achieving high efficient planar coils antenna MRC WPT designs structure. This method is essential because no available circuit model equations have been designed at high frequency (GHz) for the MRC WPT system. For this reason, the transformation technique of the low frequency (kHz and MHz) magnetic resonance circuit model equations to high frequency (GHz) circuit model equations to achieve a high-efficiency PSC MRC WPT designs structure is introduced. This technique can be applied to design PSC MRC Antenna WPT for 5G applications effectively.

- A possible solution to improve the antenna performance and efficiency of a higher frequency system (in this case, GHz), is to reduce the size of the antenna and the circumference of a free space wavelength of the antenna should be designed. Furthermore, most of the applications in the GHz frequency bands are mainly CMOS, yet the efficiency of the reported system is lower than 20% . For this reason, the strong magnetic resonance coupling at a 5G frequency band has been designed, which was previously only used for short distance low frequency and CMOS applications. The planar loops antenna, a loop shape coil, is used to generate the intense alternating magnetic field for the MRC WPT system as the magnetic flux will be developed around any conductor loop. The high efficient PSC MRC Antenna structures are designed, offering overall efficiency higher than 20%, close to 7 mm distance by generating an intense magnetic field around the loop coil antenna.

1.7 Thesis Organization

This thesis contains five chapters. Chapter 1 introduces the study background, research motivations, and current problem to design the MRC WPT of high frequency for 5G applications. The research objectives, scope, and methodology of the study have also been discussed in this chapter.

Chapter 2 explained the literature review of the traditional WPT system and the concept of using MRC WPT. The equivalent circuit model of the conventional MCR WPT, which utilized the low-frequency coil antenna and analytical equations, is also explained in this chapter. The study of the previous work for low frequency (kHz and MHz) and high frequency (GHz) in MRC WPT designs are also discussed in this chapter. The contents are summarized at the end of the chapter.

Chapter 3 presents the design of a high-frequency MRC WPT for 5G applications. Firstly, the analytical calculation of the coil antenna is validated using MATLAB software, and the mutual coupling and maximum coil antenna efficiency for high-frequency (GHz) design are also calculated. Next, the configurations of high-frequency (GHz) MRC WPT are designed in CST Microwave Studio 2016. The design is utilizing the Planar Spiral Coil (PSC) antenna. The PSC MRC Antenna is designed with a Circular and Square shape to be operated at 3.4-3.5 GHz and 5-6 GHz frequency band. The system consists of two coils; each of them is designed on the FR4 substrate. The first PSC MRC antenna is at the transmitter side (TX), and the second PSC MRC antenna is at the receiver side (RX). The chapter is summarized at the end.

Chapter 4 discussed the theoretical results in MATLAB and the simulation results in CST software. The proposed designs are fabricated and then are measured to validate the performance. Next, the results are discussed and compared with the theoretical and simulation results. The chapter is summarized at the end.

Chapter 5 concludes the thesis, followed by the significant contributions of the research. Future work in the proposed research area is also discussed and included in this chapter.

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