



Integrating Magnetic Resonance Coupling with Radio Frequency Energy to
Wirelessly Charge Mobile Device Batteries

By

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DECLARATION

I, Neetu Ramsaroop, declare that this dissertation represents my work and has not been previously submitted in any form for another degree at any university or institution of higher learning. All information cited from published and unpublished works has been acknowledged.

01 August 2025

Student

Date

Approved for final submission

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09/12/2025

Date

DEDICATION

To

My family and my supportive colleagues

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I am thankful to God for covering me with strength and encouragement through this research path.

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LIST OF ABBREVIATIONS

4G	Fourth Generation (Network)
5G	Fifth Generation (Network)
A4WP	Alliance for Wireless Power
ABS	Acrylonitrile Butadiene Styrene
AC	Alternate Current
AM	Angular Misalignment
BPF	Bandpass Filter
BS	Base Station
C-IWPT	Resonant Capacitors-Impedance Wireless Power Transfer
CMRS	Coupled Magnetic Resonance System
CMT	Coupled Model Theory
Cu	Copper
DC	Direct Current
DH	Double Helix
EMF	Electromagnetic Frequency
EMI	Electromagnetic Interference
EVs	Electric Vehicles
EX	Enhancing Coil
EMR	Electro-Magnetic Radiation
GHz	Giga Hertz
GSM	Global System of Mobile Communication

HD	High Definition
HFM	Higher Frequency Mode
IEEE	Institute of Electrical and Electronics Engineers
IM	Impedance Matching
IMN-C-IWPT	Resonant Capacitors and Impedance Matching Networks
IoT	Internet of Things
IPTS	Induction Power Transfer System
ISM	Industrial Scientific Media
IWPT	Impedance Wireless Power Transfer
kHz	Kilo Hertz
km	Kilometre
LED	Light Emitting Diode
LFM	Lower Frequency Mode
LM	Lateral Misalignment
MANET	Mobile Ad Hoc Network
M&S	Modelling and Simulation
MHz	Mega Hertz
MRC	Magnetic Resonance Coupling
MR	Magnetic Resonance
MRWPT	Magnetic Resonance Wireless Power Transfer
NASA	National Aeronautics and Space Administration
NLoS	Non-Line-of-Sight
PA	Power Amplifier

PPPs	Poisson Point Processes
PTE	Power Transfer Efficiency
RF	Radio Frequency
RFID	Radio Frequency Identification
Rx	Receiver
SCMR	Strongly Coupled Magnetic Resonance
SPMR	Series-Parallel Mixed Resonance
SRF	Self-Resonance Frequency
SS	Series-Series
SWIPT	Simultaneous Wireless Information and Power Transfer
Tx	Transmitter
V	Volts
W	Watts
WBAN	Wireless Body Area Network
WCE	Wireless Capsule Endoscope
WET	Wireless Energy Transfer
WiFi	Wireless Fidelity (Wireless Network)
WPC	Wireless Power Consortium
WPT	Wireless Power Transfer
WSN	Wireless Sensor Network

ABSTRACT

Mobile devices are rapidly evolving, with new features being continuously integrated into smartphones and an increasing number of apps being developed to enhance user convenience. The convenience of these mobile devices is constrained only by the lifespan of their batteries. The reliance on mobile devices like smartphones necessitates frequent battery charging, which can be inconvenient for users since the device becomes unusable during charging. Additionally, unnecessary charging leads to wasted electricity, a significant concern given the ongoing electricity crisis.

Wireless Power Transfer (WPT) offers an efficient solution for charging mobile device batteries without the need for wires. This research aimed to present the results of a WPT prototype circuit that combines magnetic resonance coupling with harvested Radio Frequency (RF) energy to enable wireless power transmission for recharging mobile devices. Initial work on the RF energy harvesting circuit has been conducted, yielding promising results.

WPT enables the transmission of energy or power from a transmitting component to a receiving component through a pulsating magnetic field. This process enables electricity to travel wirelessly from a power source, such as harvested RF energy, to an electrical load, like a mobile device battery, without the need for physical connectors, bridging the gap through non-contact transmission.

A wireless power system fundamentally relies on a pair of coils: one for transmitting energy and the other for receiving it. The transmitting coil is energized by an alternating current (AC), generating a magnetic field that induces a current in the receiving coil. Harvested RF energy is converted into high-frequency AC through precisely designed electronics embedded within the transmitter. The AC is supplied to a copper wire coil in the transmitter, generating a magnetic field. When the receiving coil is placed near the magnetic field, it induces an alternating current (AC) within the coil. The integrated electronic components in the receiving device then convert the AC into direct current (DC), delivering useful power. The experimental design of the WPT charging circuit, incorporating an RF harvesting circuit and magnetic resonance coupling, has shown promising performance.

A mathematical modelling and simulation research approach was employed to integrate magnetic resonance coupling with harvested RF energy in the wireless charging system. The developed model included constructing a WPT charging circuit prototype that incorporated RF-harvested energy and magnetic resonance coupling (magnetic coils).

The LTSpice simulation software was utilised to evaluate the feasibility of integrating capacitors into the circuit layout. The study's findings validate the successful development of a WPT charging circuit capable of wirelessly charging a mobile device battery. Furthermore, the research explores an alternative energy storage solution by substituting a capacitor for the mobile device battery.

CHAPTER 1

INTRODUCTION

Wireless power transfer (WPT) is a method used to charge mobile device batteries without wires, and this method has numerous appealing features related to traditional wired contact charging (Wang, Zhang, and Liu, 2013) (Zhang, Pang, Georgiadis, and Cecati, 2019). This research aims to charge mobile device batteries wirelessly by combining magnetic resonance coupling (MRC) with radio frequency (RF) energy.

The method of transmitting power wirelessly was first proposed by Nikola Tesla in the year 1891. Tesla's discovery, named the Tesla coil, is a resonant transformer (operation is at a precise frequency). The Tesla coil generated increased voltage, minimal current, and high-frequency alternating electricity. Tesla further made a major discovery in 1899, when he transmitted one hundred million volts of electric power without wires or any connectors over a distance of twenty-six miles to power a collection of two hundred light bulbs and to operate one electric motor (Tesla, 1904).

By using magnetic resonance coupling, power can be transferred without wires up to a specific distance using coils for transmitting and receiving within a magnetic field. The WPT method using magnetic resonance (MR) has been researched and implemented for charging electric vehicles, medical equipment, and underwater power supply equipment, to name a few, because of its appropriate and adaptable nature. Researchers and scientists are actively looking for ways to enhance the efficient transfer over larger distances by implementing new materials and new coil structures in the MR design (Xu, Yang, Yang, Zhao, and Li, 2016) (Zhou, Sandeep, Wu, Yang, Yu, and Huang, 2018) (Song, Jayathurathnage, Zanganeh, Krasikova, Smirnov, Belov, Kapitanova, Simovski, Tretyakov, and Krasnok, 2021).

Magnetic resonance coupling would be able to eliminate the use of wired charging methods, different cables, connectors, power cords, etc., which are utilised to transfer the power covering large distances. This approach can be used for different applications, such as charging a mobile device battery, laptop battery, iPod, etc. (Kumar, Anand, Chaubey, and Ambekar, 2017). This

wireless power transfer method can also be used to charge pacemaker batteries, which are placed inside the body of a heart patient, thereby eliminating the need to replace the batteries periodically.

When WPT is attained, charging devices will become considerably more convenient, as they eliminate the need to plug a cord into an electrical wall outlet. Furthermore, continuous power transfer to mobile device batteries allows for a reduction in battery size. WPT charging methods eliminate the risk of electrocution caused by the wear and tear of old cords, as they remove the need for handling power cables, thereby enhancing charging safety. To enable wireless charging, the wireless power transfer system must meet three key conditions: high efficiency, large air gaps, and high power (Beh, Kato, Imura, and Hori, 2010).

The benefits of wireless power according to Power by Proxi (2013), are as follows: reduces costs associated with maintaining direct connectors (like those in the traditional industrial slip ring); offers greater convenience for charging everyday electronic devices; provides safe transfer of power to applications that need to remain sterile or hermetically sealed; reduces the risk of corrosion due to elements such as oxygen and water as electronics can be fully enclosed; delivers robust and consistent power transfer to rotating, highly mobile industrial equipment; and delivers reliable power transfer to mission-critical systems in wet, dirty and moving environments (Detka and Górecki, 2022).

The majority of researchers have looked at WPT with magnetic resonance coupling to transfer power wirelessly from either batteries or wall sockets. This research focuses on combining Radio Frequency (RF) energy (free energy) with magnetic resonance coupling to transfer power wirelessly to a mobile device battery for charging. Limited research is available in this area of study, thus making this research unique and much needed.

According to an article by Coughlin (2015), an advanced mobile energy source can be any technology that does not require a direct connection or proximity to a fixed power source. This includes plugging the mobile device into wall outlets for charging or inductive charging of the mobile device, which requires the device to be kept close to a fixed-location inductive charging source. Other possible technologies that could be used are longer-life, higher-energy batteries (power-storage devices); other energy-storage devices such as supercapacitors, nano flywheels, etc.; energy-generating technologies such as fuel cells; energy harvesting from the local

environment, such as solar energy, RF harvesting, or user-generated energy; wireless power that does not require keeping the mobile device close to the power source; any other means for providing energy needed by the mobile device that does not require attachment or proximity to a fixed-location energy source (Coughlin, 2015).

RF energy is another name for radio waves and is considered free energy when harvested and converted. It is a type of electromagnetic energy made up of waves of electric and magnetic energy that travel together through space (radiating). The region where RF waves exist is known as an electromagnetic field.

A promising solution for mobile and compact electronic devices is the capability to capture and accumulate energy from external surrounding sources, a process known as energy harvesting. Alternate names for this type of technology are power harvesting, energy scavenging, and free energy, which are derived from renewable energy (Sivaramakrishnan and Jegadishkumar, 2011). RF energy harvesting is seen as an alternative to the current electrical energy supplied to the public at a fee. The various RF energy sources include WiFi, Wireless Local Area Network (WLAN), Digital TV, amplitude modulation (AM), frequency modulation (FM), and Bluetooth. Due to its ubiquitous nature, RF can be used to power wireless sensor nodes, wireless body area networks, wireless charging systems, and RFID tags. The loss in signal strength is characterised by free space path loss. It depends on the frequency of the transmitting wave, antenna gain, and distance between transmitter and receiver (Divakaran, Krishna, and Nasimuddin, 2019).

This research dissertation reports on a quantitative study based on mathematical modelling and simulation that demonstrates the use of WPT to wirelessly charge mobile device batteries using a combination of RF energy harvesting and magnetic resonance coupling.

The unrelenting increase in the use of wireless devices, such as mobile phones, wireless computing, and remote sensing, has given rise to a greater need for and dependence on batteries, both alkaline and lithium-ion (Taylor, 2012). This has resulted in the development of a WPT charging system that includes magnetic resonance coupling and harvested RF energy to charge mobile device batteries, such as the smartphone battery, wirelessly.

Henceforth, this chapter outlines the concept of energy harvesting and expands on the energy harvesting approaches to power mobile devices. The idea of using an alternative energy storage

method instead of the mobile device battery is also explored. The exploration of methods for wirelessly powering mobile devices sets the foundation for defining the research problem at the core of this study. This is followed by the formulation of the study's aim and objectives, along with its rationale and scope. The chapter concludes with an overview of the remaining sections of the dissertation.

1.1 RESEARCH PROBLEM

Currently, the use of wireless devices such as mobile phones is limited by their battery life. These devices require constant charging in the form of wired charging cables or contact wireless charging that requires the device to be placed on a charging platform. Contact wireless charging, although convenient and requiring no cable to be connected directly to the device, does result in the device not being used by the person owning it while it is charging. This does pose an inconvenience to the user (Taylor, 2012).

Electronic product designers and engineers have, in the past, experienced the following challenges involving power: the continuity of supplied power, recharging batteries, optimising the location of sensors, and dealing with rotating or moving joints. Although these challenges remain, new demands that arise from the increased use of mobile devices and operation in dirty or wet environments mean that designers require new approaches to supply power to equipment (Singh, Hasarmani, and Holmukhe, 2012).

The fourth industrial revolution is the future, and the requirement for charging electronic devices has motivated power electronic engineers to find innovative solutions to future charging infrastructure problems. Contact charging models are being explored extensively currently, based on existing Qi charging standards for AC (alternating current), where the current changes direction periodically, and DC (direct current), where the electric charge or current only flows in one direction. Meanwhile, previously, power supply and charger manufacturing industries began to consider wireless charging to be a viable solution to avoid the physical inadequacies of wired or plugged versions of charging mobile device batteries (Williamson, 2016).

The applications, features, and network connectivity that mobile technologies currently offer consumers were not thought of a decade ago. High-resolution, superior screens deliver high-definition (HD) videos and three-dimensional (3D) graphics. High-speed fourth-generation (4G),

fifth-generation (5G) Wi-Fi wireless chipsets, and high-capacity flash memory enable a high-quality mobile experience with streaming, caching, downloading, and storage of video, music, and games. Mobile technology is speeding into the future, while lithium-ion (Li-ion) battery technology is wedged in the past (Juzkow, 2011). Therefore, charging equipment plays a very important role in the popularisation of mobile devices.

1.1.1 Individual challenges

Mobile devices such as smartphones have drastically transformed the way people work, socialise, organise, and play. From existing as colossal car phones in the 1980s, mobile phones went on to become multimedia communication devices with a level of computing power seen in desktops only a short number of years before. The convenience offered by mobile devices such as smartphones is limited to the power offered by the device's battery (Sarwar and Soomro, 2013).

A mobile device battery requires regular charging, which becomes a significant issue when there is no access to an electrical outlet or charging cables. The charging process itself is inconvenient for the user, as the device cannot be utilised during that time. Given the ongoing energy crisis and unreliable electricity supply in some areas, the need for frequent charging is particularly problematic. (Sarwar and Soomro, 2013).

Other challenges, according to Border (2019), include frayed charging cables resulting in electrocution when touched and batteries draining more quickly than normal as a result of software bugs, unintended changes in system preferences, or malfunctioning hardware. Phones do not recognise when the charging cable is connected to the device, due to cheaper cables being used, and phones heat up more than normal, resulting in the phone battery needing to be replaced.

1.1.2 Environmental challenges

An article by Kattenburg (2019) states that the exact combination and number of chemicals inside a battery vary with the type of battery, but the list includes cadmium, lead, mercury, nickel, lithium, and electrolytes. When thrown away in the household trash, batteries end up in landfills. As the battery casing corrodes, chemicals leach into the soil and make their way into the water supply. Eventually, they reach the ocean. In addition, lithium-ion batteries react in a volatile way when exposed. According to Battery University, lithium can cause landfill fires that can burn

underground for years. This releases toxic chemicals into the air, which increases the potential for human exposure.

1.2 RESEARCH OBJECTIVES

This research work involves developing a charging circuit that integrates magnetic resonance coupling with Radio Frequency (RF) energy to wirelessly charge mobile device batteries. It is rational to suggest that specific known limitations related to harvesting RF energy and magnetic resonance coupling for charging a mobile device were resolved during the design of the wireless power transfer charging system and considered throughout the testing stages. Therefore, this study aimed to power a mobile device battery without wires through RF energy harvesting and magnetic resonance coupling. This aim is expanded in the research objectives that follow:

- to increase the voltage gained on the Radio Frequency harvesting circuit for wireless charging of mobile device batteries;
- to construct a wireless mobile device battery charging system derived from radio frequency harvesting using magnetic resonance coupling;
- to assess the outcomes of the constructed wireless charging system with different mobile devices based on device distance and battery size of mobile devices.

The research objectives outlined above can be reformulated into the following research questions:

- a) How can the voltage gained on the radio frequency harvesting circuit for wireless charging of mobile device batteries be increased?
- b) How would the wireless mobile device battery charging system be constructed based on radio frequency harvesting with magnetic resonance coupling?
- c) How would the results of the constructed wireless charging system be implemented with different mobile devices based on device distance and battery size of mobile devices?

The section below outlines the approach used to accomplish the objectives stated above, along with the factors and tools employed to understand the aim of this research.

1.2.1 Methodology

RF harvesting and magnetic resonance coupling are not new technologies, and research on various approaches related to the fields of RF harvesting and magnetic resonance coupling is still ongoing.

The concept of integrating RF harvesting with magnetic resonance coupling is a new concept and will be beneficial to most fields since this technology is based on free energy. This thesis is built upon previous studies, related work, and technical documents.

To establish the required background for this work, a preliminary study of the RF harvesting concept and related research on magnetic resonance coupling was conducted. This study offered valuable insights into alternative approaches to the concept, including its benefits, challenges, trends, and the models applied in this work.

This follows the specific literature study and analysis of the research problem. The literature study provides valuable insight into the anticipated input and output. Following this, a discussion is provided on the modelling method employed, the prototype developed, and the simulation tool selected to assess the effectiveness of the WPT charging system. Next, the various components are compared using the simulation application, and the circuit layouts are examined until reasonable results are obtained.

1.2.2 Simulation Tool

The research methodology was centred around mathematical modelling and simulation. A prototype model of the WPT charging circuit was developed, with the initial prototype revealing key findings and limitations to be addressed in future designs. The LTSpice simulation application was utilised for dimensioning and accurately interpreting the individual components of the circuit (Mikkelsen, 2005).

Several mathematical formulas were applied to determine the power output of both the prototype and the simulated circuit. The simulation software visualised the behaviour of different components and circuit layouts, ensuring efficient WPT transfer.

1.3 CONTRIBUTIONS

The input of related research toward combining RF energy harvesting with magnetic resonance coupling is limited. Therefore, this is seen as a novel concept.

The key contribution of this research is the development of a WPT charging circuit designed to power a mobile device battery, with the core principles of this innovative concept comprehensively explained. A prototype validates the feasibility of the WPT charging circuit theory. Simulation

software showcases the effectiveness of the circuit components and highlights key considerations for the circuit layout. This research's contributions are outlined below:

- Firstly, stage one of the research comprised proving the theory of magnetic resonance coupling to transfer power wirelessly using a prototype circuit.
- Secondly, stage two of the research looked at increasing the voltage in the RF energy harvesting circuit using the Yagi-Uda (rooftop) television antenna.
- Thirdly, the capacitor was considered as an alternative to the mobile device battery for storing the harvested energy, due to its longer lifespan and absence of battery chemicals.
- Fourthly, the test results of the WPT circuit were evaluated.
- Additionally, the circuit layout was analysed using various mathematical formulas to calculate voltage loss, antenna type, and full-wave rectifier circuits to optimize voltage harvesting. The type of capacitor for storing the harvested RF energy was also considered, and a voltage regulator circuit was incorporated to manage the amount of charge.
- Lastly, RF-harvested energy is seen as an alternative energy type and is considered free energy.

1.3.1 Performance Targets and Contribution to Advancing the Field

To guide and assess the feasibility of this research, a set of clear performance targets was established at the outset. These include:

- Achieving a minimum output voltage of 5V from the integrated WPT charging system, the threshold voltage required to initiate the charging of most mobile device batteries.
- Demonstrating that harvested RF energy, without reliance on wall-powered sources or batteries, can serve as a standalone energy input for wireless power transmission using magnetic resonance coupling.
- Validating the successful integration of RF energy harvesting and magnetic resonance coupling in a compact, functional circuit prototype.

These targets not only provided practical benchmarks for evaluating system functionality but also served as a basis for measuring the research's contribution to advancing the field. While previous studies employed batteries or wall power as input sources for WPT systems, this study advances

the state of the art by eliminating those dependencies and validating RF energy as a viable, sustainable alternative, a novel contribution with implications for future autonomous, low-maintenance wireless charging applications.

1.4 MOTIVATION

Research in integrating RF energy harvesting with magnetic resonance coupling is very limited. The following are summarised as motivations for the WPT charging system: it increases the device mobility, avoids wiring hazards, improves the electric vehicle's reliability, saves wiring costs, is immune to chemicals, dirt, and water, enhances the research of biomedical applications, and is maintenance-free and needs no electrical plugs.

The implementation of power harvesting technologies, devices, and equipment can enable self-sustainability in energy supply, ensuring continuous operation with an unlimited lifespan and minimising the need for power maintenance.

Battery waste disposal is a significant environmental issue, with the majority of these batteries ending up in landfills, contaminating both the land and the underlying water. The most effective way to address this problem is to minimise battery usage. By applying the RF harvesting concept, we can reduce reliance on batteries, leading to a positive environmental impact. Furthermore, harnessing electromagnetic energy produces no waste, as it is a clean and sustainable energy source.

1.5 OUTLINE OF THE DISSERTATION

The research is focused on developing a WPT charging circuit that is an integration of RF harvesting and magnetic resonance coupling, to wirelessly charge a mobile device battery. A solid understanding of the technological concepts and standards is essential for conducting a comprehensive study. Understanding the specifications and performance requirements of the WPT charging prototype is equally crucial to determine whether the technology meets the conditions necessary for charging a mobile device battery. This dissertation offers a comprehensive overview of RF harvesting and magnetic resonance coupling concepts, followed by an exploration of the theory, mathematical simulations, and prototype testing.

The layout of this dissertation is as follows. Chapter 2 reviews the literature in the field, as well as existing implementations, and ends with the research questions. Chapter 3 includes the theoretical foundation comprising the components required for the circuit model. Chapter 4 describes the research methodology used in computer engineering, testing, the study approach, and the analysis used. Chapter 5 reviews the experimental results of the three stages included in this research study. Chapter 6 presents the discussion and explanation of the findings of the research, including the design and any modifications to the prototype as a result of the testing feedback and limitations of the research. Finally, Chapter 7 presents the study's conclusion and explores potential directions for future research.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a synopsis of magnetic resonance coupling (MRC), RF energy harvesting, and methods that can be used to provide charging to mobile device batteries wirelessly. Wireless Power Transfer (WPT) is presented, and related research is explained. Limited by the detailed content of the thesis, this chapter presents a concise overview of WPT, wireless charging techniques, magnetic resonance coupling, and RF energy harvesting, with a focus on vital aspects relating to the charging of mobile device batteries.

2.1 WIRELESS POWER TRANSFER (WPT)

The concept of WPT was started or thought of at the beginning of the 19th century. WPT technology is the efficient transfer of electric power from one point to another, without the use of wires or any other conductive material (Raman, 2012).

The theory of electromagnetism, proven by J. Clerk Maxwell and published in 1865, states that electromagnetic waves move at the speed of light, and therefore Maxwell concluded that light itself is a wave (Maxwell, 1865).

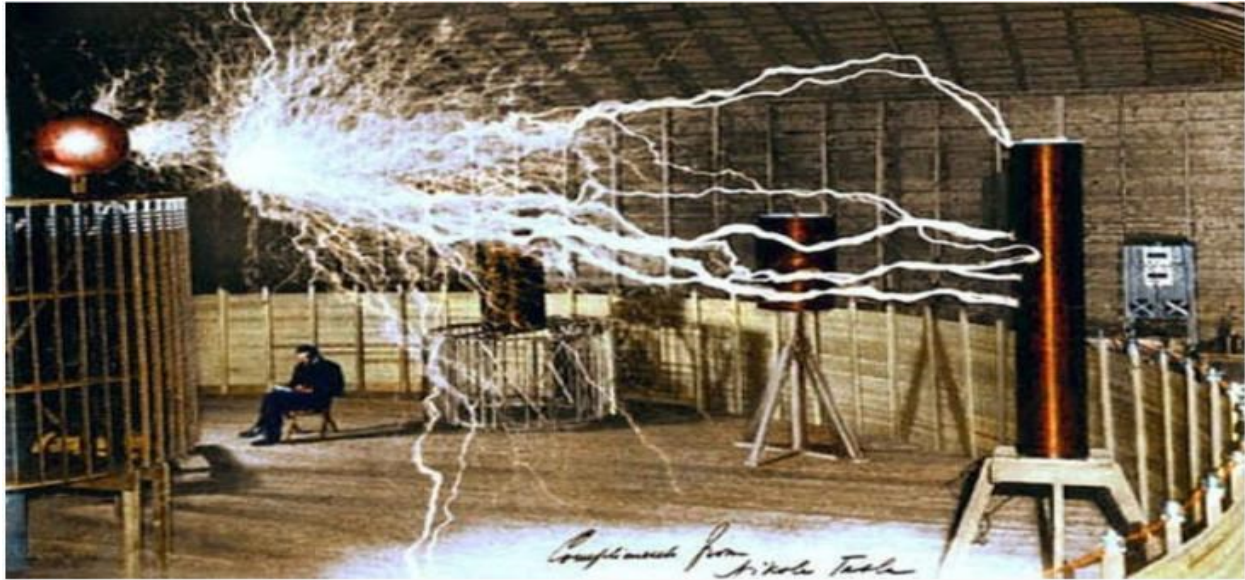
Hertz referred to Maxwell's theory of electromagnetism and, in 1886, conducted a successful experiment involving pulsed wireless energy transfer. He created the spark-gap transmitter (Figure 2.1), which created and detected microwaves in the UHF region (Doc, 2015).



1: Figure 2.1: Hertz's spark-gap transmitter (Doc, 2015)

Tesla conducted experiments in the area of pulsed wireless energy transfer in 1899. His 'Magnifying Transmitter', an initial form of Tesla Coil, was 16 m in diameter and was able to convey tens of thousands of watts without using wires (Raman, 2012). In 1897, Tesla filed his first

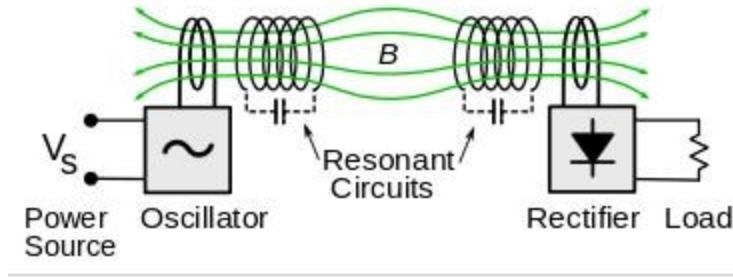
patents for the ‘Wardenclyffe Tower’ (Figure 2.2), which was to be the start of his ‘World Wireless System’ to transmit energy around the world. The tower was by no means completely functional and was incomplete owing to financial difficulties (Raman, 2012).



2: Figure 2.2: Nikola Tesla in his Colorado Laboratory with magnifying transmitter (Raman, 2012)

Preceding Tesla’s work, in 1863, the Raytheon Company conducted the initial effective WPT experiment in which energy was transmitted with a DC-to-DC efficiency of 13 percent. The Jet Propulsion Lab at NASA experimented in 1975 that displayed the transmission of 30kW over a distance of 1 mile using an antenna array set up at the Goldstone facility, thereby proving that wireless power outside the domain of the laboratory was possible. In 1991, Rockwell International and David Sarnoff Laboratory experimented using a microwave-powered rover at 5.86 GHz, in which 3 kW of power was transferred and 500 W was received (Raman, 2012).

An extremely competent mid-range wireless power transfer technology based on magnetic resonant coupling, called WiTricity, was proposed in 2007 by a group of MIT researchers led by Marin Soljačić. The WiTricity structure transfers power between two resonating antennas utilising magnetic coupling (Figure 2.3). This technology adheres to all three conditions, namely, maximum efficiency, huge air gaps, and maximum power, which makes wireless charging conceivable by having a high efficiency at mid-range (Kurs, Karalis, Moffatt, Joannopoulos, Fisher, and Soljadic, 2007). WiTricity is currently being used to charge electric vehicles (Shamon, 2018).



3: Figure 2.3: WiTricity (Kurs et al., 2007)

According to an article by Beh, Kato, Imura, and Hori (2010), the most common wireless transmission technologies are electromagnetic induction and microwave power transfer. The research study conducted by Beh et al. (2010) included a wireless power transfer system based on magnetic resonance coupling as a proposed method to charge electric vehicles (EVs); however, the actual demonstrated circuit was lacking.

Research conducted by Wang, Zhang, and Lui (2013) also focused on the efficiency of magnetic resonance coupling as a method to wirelessly charge electric vehicles. The limitation of this research was the failure to maintain the balance between maximum power and maximum efficiency. The results were one-sided, with the method producing minimum power and maximum efficiency.

A three-phase wireless power transfer system was proposed by Tanikawa, Kato, Imura, and Hori (2013). The proposed system had three times the capacity of a single WPT system and was therefore intended to have a higher transfer efficiency within a larger air gap. The limitations seen with this experiment were that the three-phase system was only suitable for rotating equipment, and the power source to the system was a multi-channel function generator.

Shin, Shin, Kim, Ahn, Lee, Jung, Jeon, and Cho (2014) conducted research in a magnetic resonance-based WPT system for powering a roadway to charge moving electric vehicles. The results of this research experiment produced 100 kW power with 80 percent power transfer efficiency within a 26 cm air gap. The limitation of this experiment was the small air gap of 26 cm.

Rahman, Ahmed, Islam, Awal, and Islam (2014), to achieve power-transfer efficiency, experimented with a WPT system. The system was successful in transferring power; however,

some components for the initial design were not available to the researchers, therefore, little power was available on the load coil.

The majority of the experiments conducted from 2007 until 2014 involved electric vehicles. Munir and Ranum (2015) conducted research involving WPT charging for a mobile device based on resonance coupling. The following components were used in the system: a transmitter circuit (generates the AC signal to be transmitted), transmitting and receiving radiators (transfer the power of the AC signal wirelessly), and a receiver circuit (converts the AC into DC voltage for charging). The researchers noted limitations with this system, such that each part of the system needed improvement, and the transmission efficiency of the radiator was improved.

Another research study focused on the efficiencies of a WPT system with five different obstacles, namely copper (Cu), Acrylonitrile Butadiene Styrene (ABS), earth, glass, and seawater. The results of the study proved that the size of ABS and glass has a minute effect on the efficiency and resonant frequency of WPT systems using magnetic resonance coupling. However, with the increase in the size of earth obstacles, Cu obstacles, and seawater obstacles, there is a decrease in the efficiency of the WPT system, and the resonant frequency varies (Shi, Qi, and Ye, 2015).

Experiments conducted by Zhao, Wang, and Wang (2015) were based on using magnetic resonance coupling for WPT. The system included magnetically coupled resonator coils in a tightly coupled near-field arrangement. Coils with a diameter of 15 cm were used, producing 85 percent efficiency at a distance of 10 cm and producing 45 percent efficiency at a distance of 20 cm. The limitations, as stated by the researchers, were that series-resonant and shunt-resonant coupling models are not adaptable to real applications.

Khan, Jafar, Karimov, and Feroze (2016) proposed an optimised model of maximum wireless power transfer and an increase in the range between the transmitting and receiving coils. The researchers created the universal drive circuit, which was a slight improvement on the Colpitts oscillator and custom amplifier. The researchers stated that it was no longer required to generate a resonance frequency and then transfer it to the coil. This study was limited by a lack of resources.

A study on a series-parallel, mixed-resonance (SPMR) model of WPT through magnetic resonance coupling was analysed for greater power received and maximum efficiency. The performance of this circuit was simulated, and it was stated as having long-distance power transfer. This circuit

needs to be physically tested and compared against the results of the simulation (Wang, Chen, Hu, and Liu, 2016).

Shi, Qi, Qu, Ye, and Wang (2016) conducted research related to the effects of coil locations on WPT using magnetic resonance coupling. This research study consisted of four coil resonators, and the locations or distances between the coils were investigated. The researchers proved that the locations of the coils have an impact on the efficiency, resonant frequency, and bandwidth of the WPT system. The results of this research have provided guidelines for coil locations for WPT systems to produce high transfer efficiency or long transfer distance.

Wireless energy transfer (WET) by magnetic resonance coupling, consisting of two loads, was studied by Shi, Qi, Xu, and Ye (2016). It should be noted that WET and WPT are the same concept. This study focused on producing charges for two devices on demand. The researchers stated that this system is flexible with multiple loads; however, the maximum efficiency of the two loads is not the same, although the total efficiency of the WET system is the same. This study produced design guidelines for WET systems with multiple loads.

A new application of magnetic resonance coupling has been investigated in the medical field. Research conducted by Xia, Zhang, Lu, and Wu (2016) focused on a wireless capsule endoscope (WCE). According to the researchers, this system or capsule was used to capture images of the small intestine using a passive method. The WCE is swallowed by the patient, and a tiny camera within the WCE captures images that are wirelessly sent to external receivers by a transmission module. The 3D magnetic resonance coupling component can also charge the battery within the capsule wirelessly. The capsule behaves similarly to a micro-bot.

Research conducted by Abdou and El-Tager (2016) focused on an upgrade to the traditional WPT system using magnetic resonance coupling. This system includes a function generator, a Class B power amplifier, a transmitter helical coil, and a rectangular planar receiver. The experiment was carried out using two LEDs at a distance of 1.21 m, which is said to be the maximum distance covered thus far. Previous literature indicates experiments done at a distance of 40 cm. The limitation of this research, as stated by the researchers, was that the experiments were not conducted in an EMC laboratory.

The power security demands of WPT utilising magnetic resonance coupling are investigated by Zhu, Sun, Gao, Zhao, and Li (2017). This system was simulated and consisted of multiple transmitters, one receiver, and one unintended receiver. The results of the investigation proved that the proposed system does improve the power efficiency of the intended user, and the power security was well preserved; however, this system needs to be designed and compared to the results of the simulation.

Masaki, Gao, Deng, and Noge (2017) investigated an operator-based sliding mode control design for WPT using magnetic resonance coupling. Again, the focus was on high power efficiency in the WPT system, but using impedance matching control. The researchers' results indicate that the proposed method leads to an improvement in performance tracking and constant voltage control. The limitation is that results have been confirmed by simulations, and therefore, experiments should be conducted to verify the effectiveness of the proposed method.

Research conducted by Zhai, Yang, and Liu (2017) looked at the WPT systems' compliance with the variation of position and angle within the transmitting coil and the receiving coil. The results of the experiment proved that system transfer efficiency can be improved without changing the distance between the transmitting coil and the receiving coil by adjusting the frequency and the coupling coefficient concurrently.

WPT systems with magnetic resonance coupling to produce high high-precision stage were investigated by Yazaki, Nishimura, Ohnishi, Imura, and Fujimoto (2017). The experimental results proposed a novel moving coil wireless linear motor using resonant coupling. The researchers have stated that future work will be to use multiple coils in the transmission aspect of the WPT system.

A simulation study was conducted by Liu, Fan, Zuo, Zhang, Dong, and Liu (2017) regarding a series model of WPT using magnetic resonance coupling. This system comprised analysing the series-series (SS) type circuit by using circuit theory. The key factors affecting system transmission efficiency and output power were analysed. The researchers conducted the analysis using the simulation software MATLAB.

A new framework for analysing and optimising coupled resonator WPT systems is proposed by Thackston, Mei, and Irazoqui (2018). This framework is based on bandpass filter (BPF) models of

magnetic resonators. The results of the study provided insights into the relationships between resonator parameters, inter-resonator coupling, and the complete system.

Badowich and Markley (2018) investigated the idle state of the WPT system and the suppression of power losses in that idle state. The system consisted of a four-coil magnetic resonance coupling unit. The experiment produced the following result: a mismatch in input to the system to limit the idle power losses. The benefits of this research indicated an improvement in the long-term efficiency of the WPT system and a reduction in transmitter field emissions.

WPT is classified into two categories: near-field and far-field. Near-field WPT utilises two aligned coils and inductive coupling to transfer energy over very short distances, typically within tens of millimetres. Far-field WPT makes use of electromagnetic (EM) radiation to transmit energy over extended distances. The extended operating range of far-field WPT enhances its flexibility, making it particularly suitable for power multi-casting. This enables the transmitter and receiver to move freely, even in Non-Line-of-Sight (NLoS) environments (Huang, Zhou, Ning, and Gharavi, 2019).

2.1.1 Methods of Wireless Transmission of Electrical Power

Table 2.1 below summarises the methods of wireless transmission of electrical power (Singh, Hasarmani, and Holmukhe, 2012) (Zhang, Pang, Georgiadis, and Cecati, 2019) (Detka, and Górecki, 2022) (Wang, Sun, Guan, and Xu, 2023).

1: Table 2.1: Methods of Wireless Transmission of Electrical Power

Method	Description
Induction	The transfer of energy takes place due to electromagnetic coupling between the two coils.
Electromagnetic Transmission	Converts electricity into light, such as a laser beam, then fires this beam at a receiving target, such as a solar cell on a small aircraft. The power is beamed to a single target. Also referred to as power beaming.
Evanescent Wave Coupling	Wirelessly transfers power using non-radiative electromagnetic energy resonant tunnelling.

Electrodynamic Induction	Near-field wireless transmission of electrical energy between two magnetically coupled coils that are part of resonant circuits tuned to resonate at the same frequency.
Radio and Microwave	Power transmission via radio waves can be made more directional, allowing longer-distance power beaming, with shorter wavelengths of electromagnetic radiation, typically in the microwave range.
Electrostatic Induction	Method to create or generate static electricity in a material by bringing an electrically charged object near it.

2.1.2 Critical Synthesis of Research Based on WPT

The evolution of WPT technologies from theoretical foundations laid by Maxwell (1865) and practical demonstrations by pioneers like Hertz and Tesla, to modern commercial systems such as WiTricity (Kurs et al., 2007), demonstrates significant progress in the field. However, a closer examination of experimental findings reveals notable gaps in system efficiency, power range, coil optimisation, and circuit integration, areas this study aims to address.

Early large-scale attempts, including Tesla's 'Magnifying Transmitter' and the Wardencliff Tower, highlighted the potential for high-power, long-distance energy transfer but lacked practical viability due to infrastructural and financial constraints (Raman, 2012). Later demonstrations, such as NASA's 30 kW over 1 mile (1975) and Rockwell's microwave-powered rover (1991), proved long-range viability but at low efficiencies and with complex infrastructure needs, limiting commercial adoption.

The introduction of magnetic resonance coupling (MRC) by the MIT group in 2007 (Kurs et al., 2007) marked a breakthrough by achieving mid-range high-efficiency transmission (~60–90%) between resonant coils over air gaps of 10–20 cm. Despite these advances, subsequent studies continued to grapple with the classic trade-offs between power, efficiency, and distance:

- Wang et al. (2013) optimized for efficiency at the expense of power, while Tanikawa et al. (2013) increased capacity through a three-phase system but restricted its application to rotating equipment.

- Shin et al. (2014) achieved 80% efficiency at 100 kW within 26 cm, but the short air gap limited real-world scalability, especially for electric vehicle (EV) roadway applications.
- Conversely, Abdou and El-Tager (2016) extended the distance to 1.21 m, surpassing most prior works, but lacked controlled testing environments, compromising reproducibility.

Some studies attempted to expand versatility or accommodate multiple loads (e.g., Shi et al., 2016) but reported uneven load efficiency. Others, like Munir and Ranum (2015), explored mobile device charging with MRC but cited component inefficiencies and poor radiator performance, a challenge similarly observed in the current work and tackled through circuit tuning and antenna optimization.

The integration of RF energy harvesting has received less attention in mainstream WPT literature, typically being studied in isolation or simulated environments (Wang et al., 2016). Real-world integration with MRC systems remains largely unexplored, presenting a critical research gap that this study seeks to bridge. Moreover, few works investigate material effects or obstacle impact on WPT efficiency. Shi et al. (2015) showed significant degradation with conductive or absorptive materials like seawater or copper, while others ignored such real-world interferences entirely. Further limitations across reviewed studies include:

- Simulation-only validation (e.g., Liu et al., 2017; Masaki et al., 2017)
- Short-range effectiveness (<20 cm), even in high-efficiency designs (Zhao et al., 2015)
- Neglect of component availability and layout design constraints, a critical aspect that hindered practical implementation in several cases, including this study.

This research contributes by:

- Experimentally validating an MRC-based system capable of charging real mobile devices.
- Identifying and resolving antenna inefficiencies for improved RF energy harvesting
- Addressing component layout and assembly challenges is often under-reported
- Proposing future integration of solid copper coils to reduce voltage loss, thus improving transfer stability

In conclusion, while considerable progress has been made in developing WPT systems, most existing research either emphasizes simulation over hardware or prioritizes power or distance at the cost of efficiency and real-world applicability. By grounding its approach in practical

experimentation and integrating MRC with RF energy harvesting elements, the current work addresses these gaps and sets the stage for the next generation of efficient, scalable, and accessible wireless charging systems.

2.2 WIRELESS CHARGING TECHNOLOGY

Wireless charging technology allows power to be transferred wirelessly from a charger to a mobile device's load (Lu, Niyato, Wang, Kim, and Han, 2014).

WPT, also known as wireless energy transmission, is the process of transferring electrical energy from a power source to an electrical load, such as a power grid or a device, without the need for physical, man-made conductors. Wireless power is a comprehensive term containing several power transmission technologies that utilise time-varying electric, magnetic, or electromagnetic fields. In WPT, a transmitter without wires connected to a power source emits field energy across an expanse to one or more receivers, where it is transformed back into electrical current and subsequently used. Wireless transmission is significant for providing power to electrical devices in conditions where connecting wires is inopportune, hazardous, or impossible (Davis, 2014; Marks, 2014) (Van Mulders, Delabie, Lecluyse, Buyle, Callebaut, Van der Perre, De Strycker, 2022).

Wireless power techniques are divided into two categories: non-radioactive and radioactive. In non-radioactive techniques, power is generally transferred through magnetic fields via inductive coupling between wire coils. Applications of this technology include chargers for electric toothbrushes, RFID tags, smart cards, and implantable medical devices like artificial cardiac pacemakers, as well as inductive powering or charging for electric vehicles such as trains and buses. A key focus is on developing wireless systems to charge mobile and handheld devices, such as cell phones, digital music players, and portable computers, without the need to be connected to a wall outlet. Power can also be transferred through electric fields via capacitive coupling between metal electrodes. In radiative far-field techniques, also known as power beaming, energy is transmitted through beams of electromagnetic radiation, such as microwaves or laser beams. These techniques can transmit energy over longer distances, but they must be directed at the receiver. Potential applications for this type of charging include solar power satellites and wireless-powered drone aircraft (Davis, 2014).

A study by Sharma and Balaji (2014) highlights the challenge of storing and processing energy harvested from ambient sources for low-powered devices, such as sensors, which require advanced hardware and consequently face limitations in energy storage and processing capabilities.

2.2.1 Types of Wireless Charging

Smith (2019) has defined the following types of wireless charging methods (Table 2.2).

2: Table 2.2: Types of Wireless Charging

Type of Wireless Charging Technology	Battery Charging Size	Description	Applications
Radio charging	Small	Involves a transmitter to generate radio waves and a device receiver with the same frequency as the radio transmitter to charge the device battery.	Wireless keyboards, wireless mice, smartphones, medical devices, hearing aids, watches, and music players.
Inductive Charging	Medium	The device is connected to a wireless charging pad that is connected to a wall socket.	Smartphones, tablets, and MP3 players.
Resonance Charging	Large	Involves a copper coil, which is attached to the device that requires charging, with another copper coil attached to a power source.	Large computers, electric cars, vacuum cleaners, or robots.

Smith (2019) further explains the new and upcoming wireless charging technologies, outlined in Table 2.3.

3: Table 2.3: New Wireless Charging Technologies

Type of New Wireless Charging Technology	Description	Applications
Powermat	Charging areas are available on table-tops and counters in restaurants and coffee shops.	Smartphones
Nexus Wireless Charger	Attaches to a table, countertop, desk, or any other area for convenient access to battery charging. Created by Google.	Nexus devices
Samsung Wireless Charger	This leaves the micro-USB port open for other uses or for charging when a wireless charger is unavailable.	Smartphones
PowerSquare	Covers a large charging area. Eliminates the need to align your mobile device with a charging pad.	Multiple mobile devices
Intel Charging Bowl	Place mobile devices into the bowl for charging.	Smartphones and tablets
Dipole Coil Resonant System	Capable of charging up to forty smartphones simultaneously from as far as five metres away.	Smartphones, electrical appliances, and TV
uBeam	Uses ultrasound to charge devices over longer distances. Conversion of sound to electricity.	Mobile devices

2.2.2 Wireless Charging Standards

The primary wireless standard, Qi, was developed by the Wireless Power Consortium (WPC) for inductive charging over a distance range of up to 40 mm. The Qi wireless charging method has been adopted by numerous smartphone manufacturers, including Samsung, Apple, Sony, LG,

HTC, Huawei, Nokia (HMD), Motorola, and BlackBerry. Currently, Qi wireless charging is being incorporated into numerous electric vehicles. (Grabham and Langridge, 2019).

Another wireless charging standard, as described by Grabham and Langridge (2019), is Powermat, which is used by some retailers, including Starbucks, to allow customers to charge their phones. In 2018, Powermat developed a commercial wireless charging technology that became compatible with Qi. Qi features three distinct power specifications, starting with low power for charging mobile devices. The wattages for the devices have 5W as a minimum, while some handsets support 7.5 W, 10 W and even up to 15 W. The Qi method includes a medium power specification that delivers up to 120W for devices like monitors and laptops, as well as a high-power specification capable of delivering up to 1kW for powering appliances such as kitchen utensils (Grabham and Langridge, 2019).

2.2.3 Comparison of Wireless Power Transfer (WPT) Technologies

Wireless power transfer (WPT) technologies have evolved significantly from early experiments by pioneers such as Hertz and Tesla to modern applications like WiTricity. WPT methods generally fall into two broad categories:

- Near-field techniques, such as inductive and magnetic resonance coupling, are suitable for short- to mid-range transmission with high efficiency.
- Far-field techniques, such as microwave or laser-based power beaming, are used for long-range applications but often with lower efficiency and safety concerns.

Table 2.4 below provides a comparative overview of the major WPT technologies, based on operating principle, typical range, efficiency, and key applications. (Lu, Niyato, Wang, Kim, and Han (2014); Davis (2014); Sharma and Balaji (2014); Smith (2019); Grabham and Langridge (2019):

4: Table 2.4: Comparison of WPT Technologies

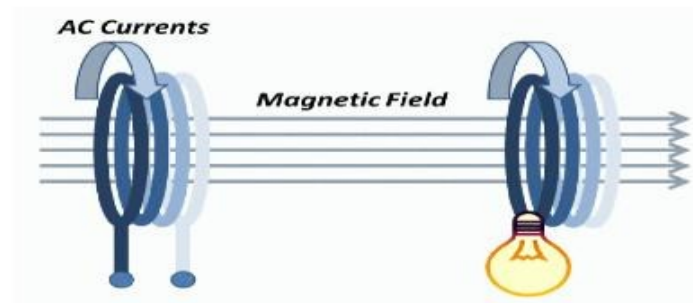
Technology	Principle	Range	Efficiency	Applications	Limitations
Inductive Coupling	Magnetic field coupling between coils	Very short (mm–cm)	High (80–95%)	Mobile phone chargers, electric toothbrushes	Requires precise alignment, close contact
Magnetic Resonance Coupling	Resonant energy exchange via magnetic fields	Short to mid-range (cm–m)	Moderate–High (60–85%)	EV charging, consumer electronics, implants	Sensitive to coil design & distance
Capacitive Coupling	Electric field between parallel plates	Very short	Low–Moderate	Lightweight sensors, wearable tech	Interference, low power handling
Microwave Transmission	Beamed radio/microwave waves	Long (m–km)	Moderate (30–60%)	Space solar power, drones, and remote sensors	Line-of-sight, safety issues
Laser Power Beaming	Directed light beam (e.g., laser diode)	Long (m–km)	High (in ideal cases)	Satellites, UAVs	Safety hazards, line-of-sight required
Evanescent Wave Coupling	Resonant tunneling of non-radiative EM waves	Mid-range	Moderate	Experimental setups	Still under research

Electrostatic Induction	Inducing charges via nearby fields	Very short	Low	Historical interest	Impractical for modern power needs
RF Energy Harvesting	Capturing ambient radio waves	Short to mid-range	Low	IoT devices, low-power sensors	Low power density, unpredictable sources

The choice of the WPT method depends heavily on the intended application. For instance, inductive coupling offers excellent efficiency for very short-range charging, whereas microwave or laser-based systems are suitable for long-range transmission but present safety and alignment challenges. This project focuses on RF energy harvesting combined with magnetic resonance coupling, aiming to offer a self-sustaining and flexible WPT solution. While this method is less efficient than short-range inductive systems, it benefits from wireless energy capture from ambient sources, mid-range operation, and no strict alignment requirements, making it ideal for low-power devices in remote or mobile settings.

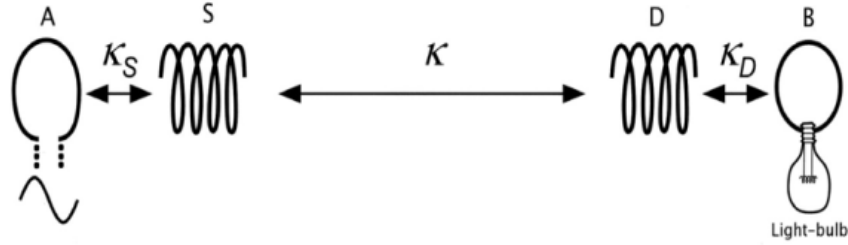
2.3 MAGNETIC RESONANCE COUPLING

Magnetic resonance coupling utilises evanescent-wave coupling, which transfers electrical energy between two resonant coils by generating oscillating magnetic fields. Magnetic coupling occurs when two objects transfer energy through their fluctuating or oscillating magnetic fields. Resonant coupling occurs when two objects have nearly identical natural frequencies, allowing efficient energy transfer (Figure 2.4).



4: Figure 2.4: Magnetic Resonance (Dansie, 2013)

Scientists at MIT have introduced WiTricity, a technology based on coupled magnetic resonance. This technology allows for the simultaneous charging of multiple devices and supports non-line-of-sight (NLoS) charging (Kurs et al., 2007).



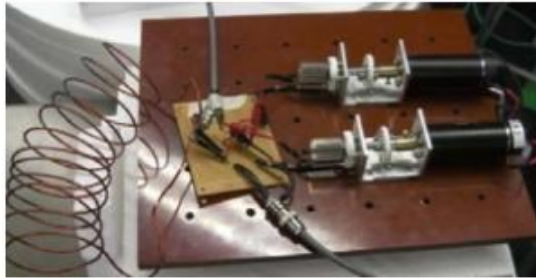
5: Figure 2.5: Two self-resonant coils (Kurs et al., 2007)

WiTricity power sources and capture devices function as magnetic resonators, facilitating efficient power transfer over long distances via the magnetic near-field. These innovative designs, combined with their electronic control systems, enable resourceful energy transfer over distances significantly greater than the size of the sources and devices themselves (Kurs et al., 2007). Resonant coupling (Figure 2.5) takes place when the natural frequencies of the source and receiver systems are nearly identical. WiTricity power sources and receiver systems are advanced magnetic resonators designed to efficiently transmit power over long distances using the magnetic near-field. According to Jawad, Nordin, Gharghan, Jawad, and Ismail (2017), the limitations of this charging technique include the need to satisfy the resonance condition, and if an error occurs, no power is transferred. Another limitation arises from the presence of strong ferromagnetic materials, which can reduce power transfer due to radiation losses.

Experiments conducted by Beh et al. (2010) have demonstrated the possibility of using impedance matching (IM) to achieve maximum power transmission. The simulations and trials (Figures 2.6 and 2.7) demonstrate that the IM circuits can adjust the frequency to 13.56 MHz for varying air gaps, enhancing power transfer efficiency. This study was limited to the charging of electric vehicles.

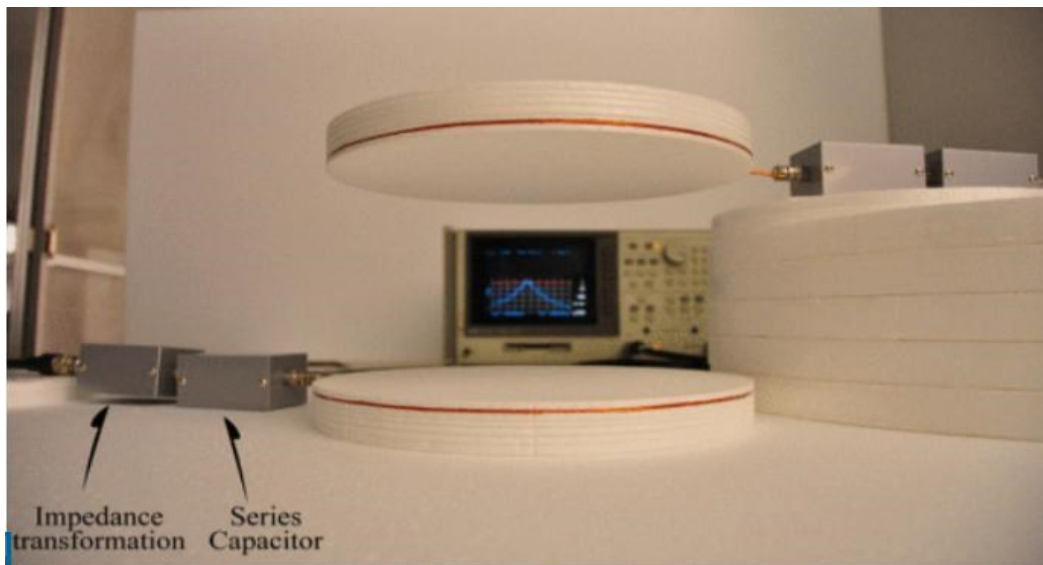


6: Figure 2.6: Transmitting antenna with tuning circuit and receiving antenna (Beh et al., 2010)



7: Figure 2.7: Air core coil and variable condensers (Beh, et al., 2010)

Imura and Hori (2011) assessed the relationship between the maximum efficiency air gap using equivalent circuits (Figure 2.8) and the Neumann formula. They also proposed equations defining the conditions necessary to achieve maximum efficiency for a given air gap. Their study included short-type helical antennas used for the electromagnetic field analysis.



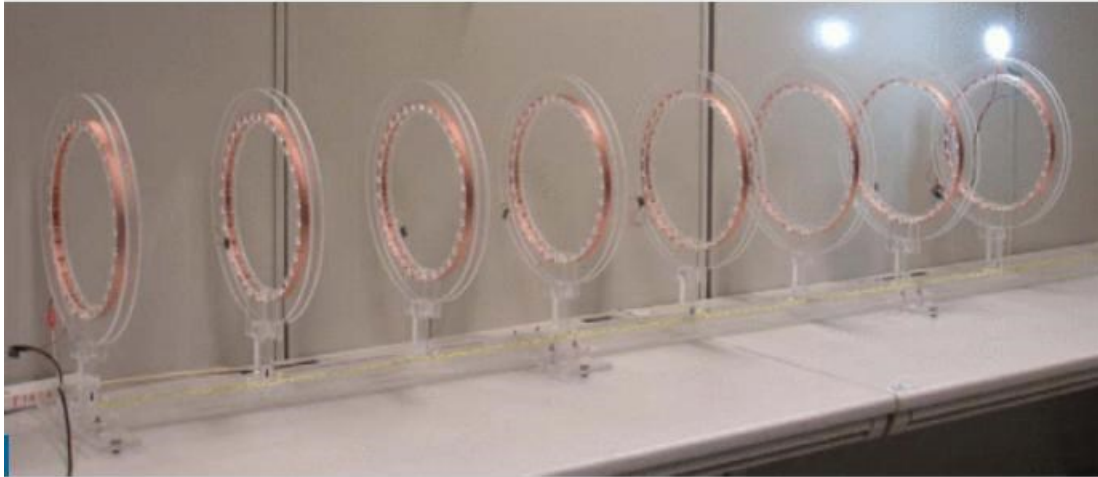
8: Figure 2.8: Short-type helical antennas (Imura and Hori, 2011)

Szondy (2012) describes a study by scientists at the NIMBUS lab, where they developed a quadrotor integrated with a system that utilises strongly coupled magnetic resonances (Figure 2.9) to wirelessly transmit power from its batteries to a receiving device without physical contact. This system presents a potential solution for supplying power to devices that cannot be easily accessed by conventional electrical sources. Research conducted by Jonah, Georgakopoulos, and Tentzeris (2012) analytically examined the optimal design of SCMR elements, and Helices were specifically analysed. The researchers derived equations to design SCMR systems.



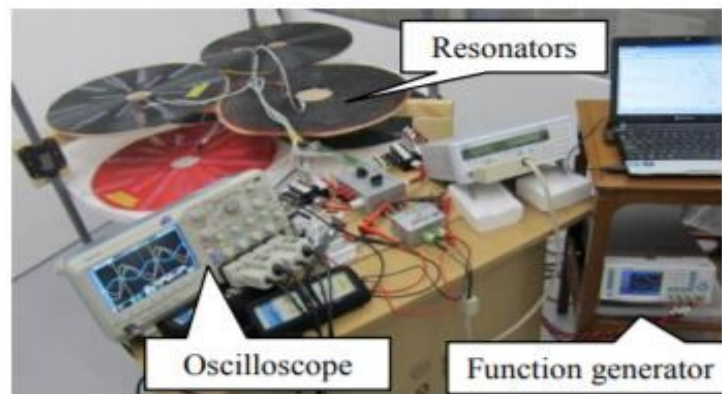
9: Figure 2.9: NIMBUS Lab's quadrotor uses strongly coupled magnetic resonance (Szondy, 2012)

Lee, Zhong, and Hui (2012) conducted experiments explaining a magnetically coupled circuit model used to examine the effects of magnetic coupling between nonadjacent resonators in wireless power transfer applications. The cross-coupling effects of the nonadjacent resonators caused a slight shift in the optimal frequencies of both equally spaced and optimally spaced resonator systems away from their resonance frequency. The researchers placed more relay resonators to increase the overall transmission distance. Figure 2.10 illustrates an 8-resonator system wirelessly transferring power to illuminate a 14W compact fluorescent lamp over a distance of 2.1 meters.



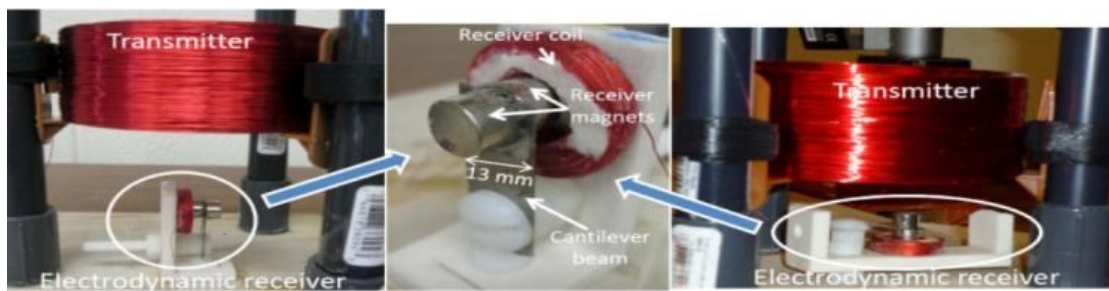
10: Figure 2.10: An 8-resonator system powering a fluorescent lamp (Lee et al., 2012)

According to Tanikawa et al. (2013), a three-phase WPT system has the following advantages compared to a single-phase WPT system: a simple circuit design (Figure 2.11) and limited power ripples. The experiments conducted prove that three-phase WPT is useful for rotating equipment. Experiments conducted by Ricketts, Chabalko, and Hillenius (2013) proved that WPT using strongly coupled magnetic resonance (SCMR) or traditional induction is the same and operates with the same efficiency, but differs in the implementation of the impedance match to the source/load coils (Figure 2.12).



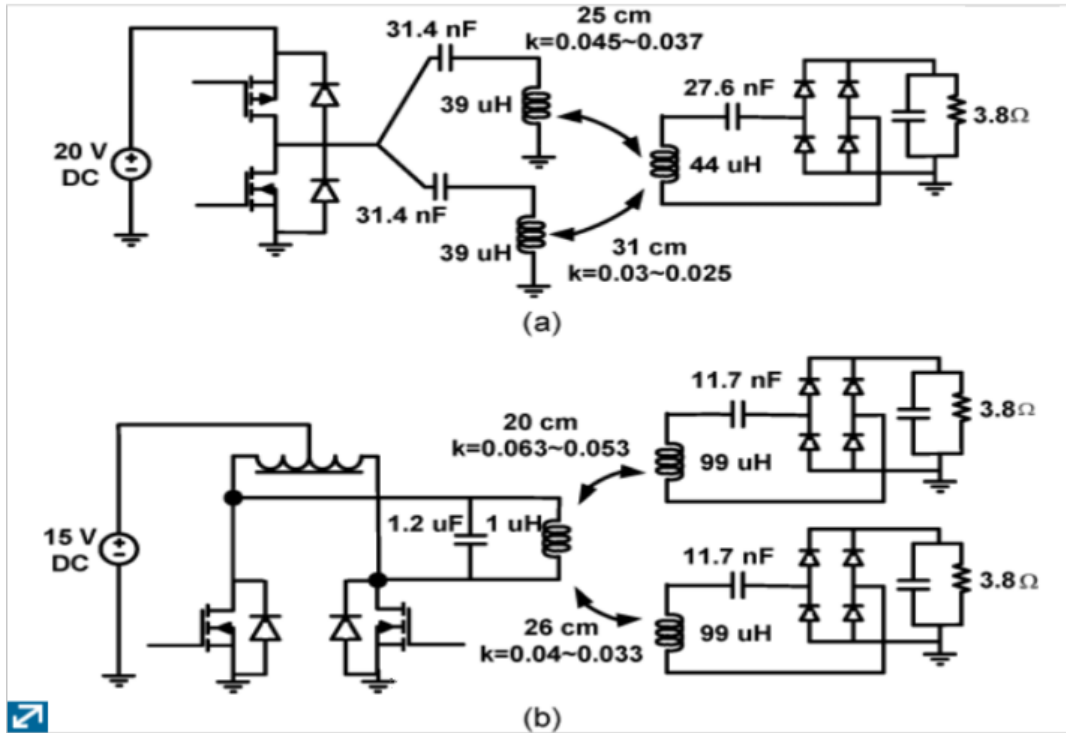
11: Figure 2.11: Three-phase WPT system (Tanikawa et al., 2013)

Challa, Mur-Miranda, and Arnold (2012) introduced a WPT system that utilises a magnetic field to drive the movement of a magnet on the receiver, rather than directly inducing voltage in a receiver coil. Two distinct receiver orientations, torque mode and force mode, were introduced, along with an analysis of their performance. In the prototype, the torque mode demonstrated three times the efficiency of the force mode (12% compared to 4.1%). However, the overall effectiveness of each mode depends on the receiver's dimensions. A multi-layer solenoid (Figure 2.14) acts as the transmitter, while an electrodynamic receiver operates as the electromechanical receiver. One drawback of this system is its lower efficiency compared to previously reported inductively coupled WPT systems.



14: Figure 2.14: A multi-layer solenoid (Challa et al., 2012)

Ahn and Hong (2013) investigated wireless power transfer systems (Figure 2.15) with multiple transmitters (TXs) or receivers (RXs). The researchers also claimed that the performance of multiple TXs or RXs, with the proposed modifications, surpasses that of a single TX and RX system. To increase simultaneous power transfer, the effective resonant frequency of the TXs should be matched to that of the RXs, which, under maximum efficiency conditions, is also equal to the driving frequency. The interactions between TXs or between RXs alter these effective resonant frequencies.



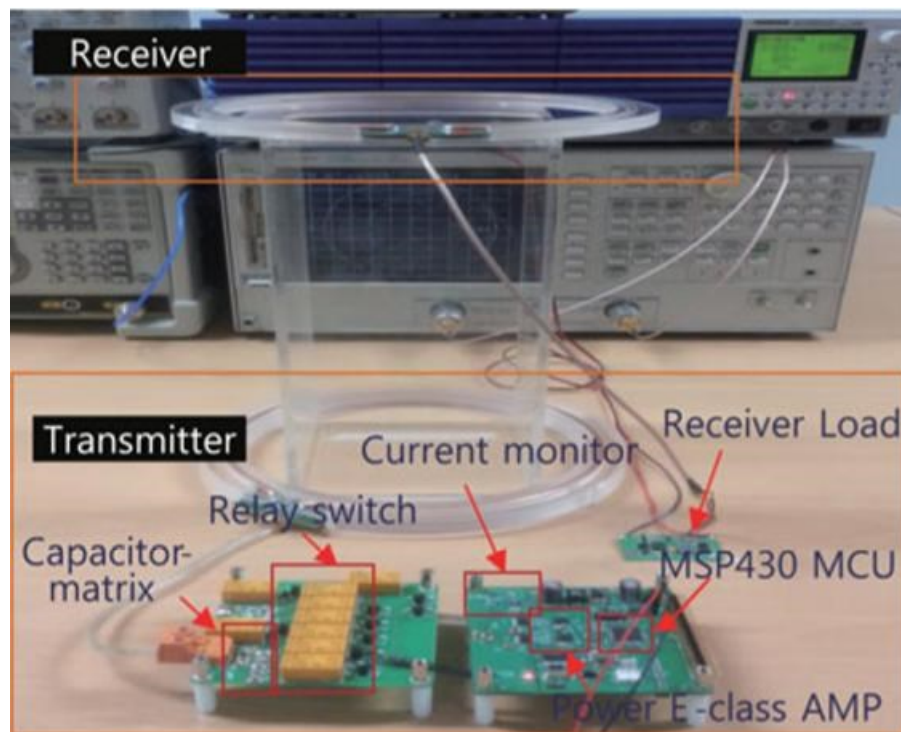
15: Figure 2.15: Wireless power systems. (a) With two TXs. (b) With two RXs. (Ahn and Hong, 2013)

Beh, Kato, Imura, Oh, and Hori (2013) developed an automated IM circuit to examine the effects of maintaining resonance in an MRC WPT system operating at a fixed frequency of 13.56 MHz. The IM system (Figure 2.16) employs a directional coupler to evaluate the refracted wave ratio at the transmitter's end and utilizes high-frequency relays to select matching parameters that reduce the refracted wave. Experimental results demonstrated that the proposed system enhanced efficiency and expanded the range of the WPT system. The experimental results have also shown that the efficiency increased to up to 85% within 0.5–1.5 s. The results have also verified the validity of the automation of the IM system.



16: Figure 2.16: IM circuit (Beh et al., 2013)

Lim, Tang, Lim, and Park (2014) introduced a self-regulating impedance-matching structure (Figure 2.17) utilising a capacitor matrix, which dynamically adjusts impedance values to sustain an optimal level of maximum power transfer. Impedance adaptation is achieved by adjusting the switch configuration of series or parallel capacitances, with the number of possible capacitance combinations growing rapidly as the number of capacitances in the matrix increases.



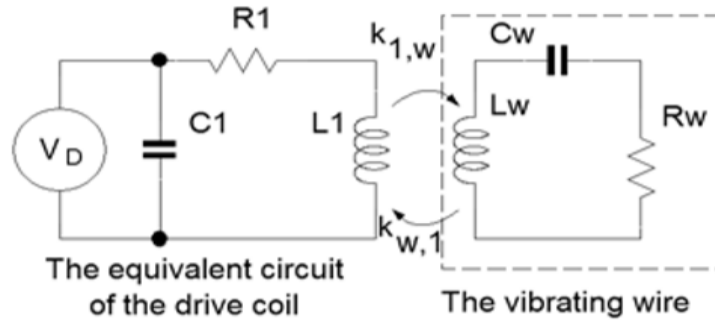
17: Figure 2.17: Impedance matching structure (Lim et al., 2014)

Huang, Li, Li, Yuan, and Cheng (2014) proposed a novel WPT system where the efficiency formulae of the system were derived and analysed using coupled model theory (CMT). Based on the experimental test outcomes, a procedure for enhancing efficiency was recommended by coordinating the load resistor and operating frequency. Evaluated against the standard WPT system, the recommended structure (Figure 2.18) and procedure achieve maximum efficiency. The researchers indicated that the recommended WPT system is well-suited for industrial applications due to its highly compact design and excellent transfer efficiency.



18: Figure 2.18: Proposed four-coil WPT system (Huang et al., 2014)

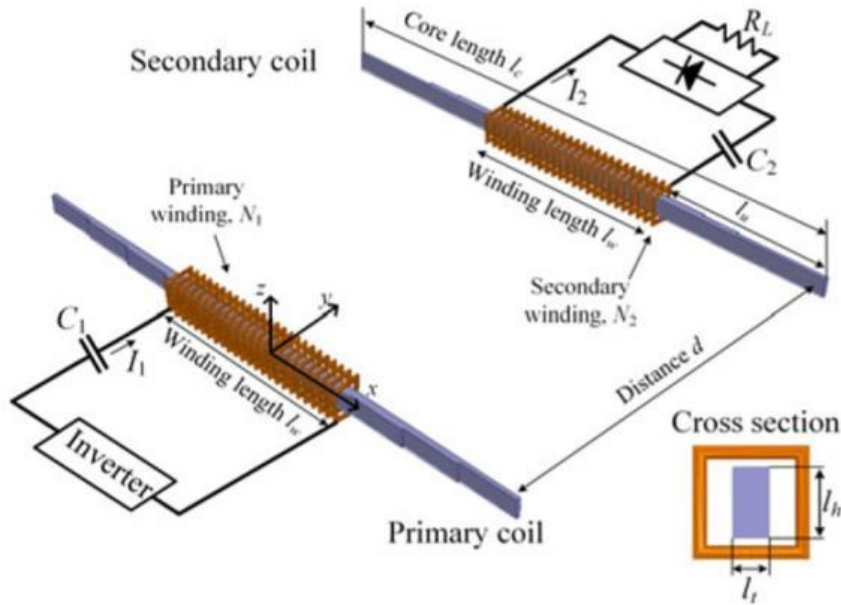
Pop, Pitica, and Bande (2015) analysed the vibrating nature of the receiving coil in the WPT system based on a theoretical and mathematical analysis. The WPT system consisted of two circuits magnetically coupled. The circuit (Figure 2.19) was examined in both operational regimes of the transducers: excitation and response, using time-domain analysis. During the excitation phase, the energy accumulated in the coil was transmitted to the wire through magnetic coupling. In the response phase, the wire oscillated freely at its resonant frequency. Using transient analysis, the relationship between the wire's mechanical movement and the mathematical representation of the current flowing through it was demonstrated. The results led to an analogy being created between the mechanical and the electrical parameters.



19: Figure 2.19: Vibrating Wire Transducer (Pop et al., 2015)

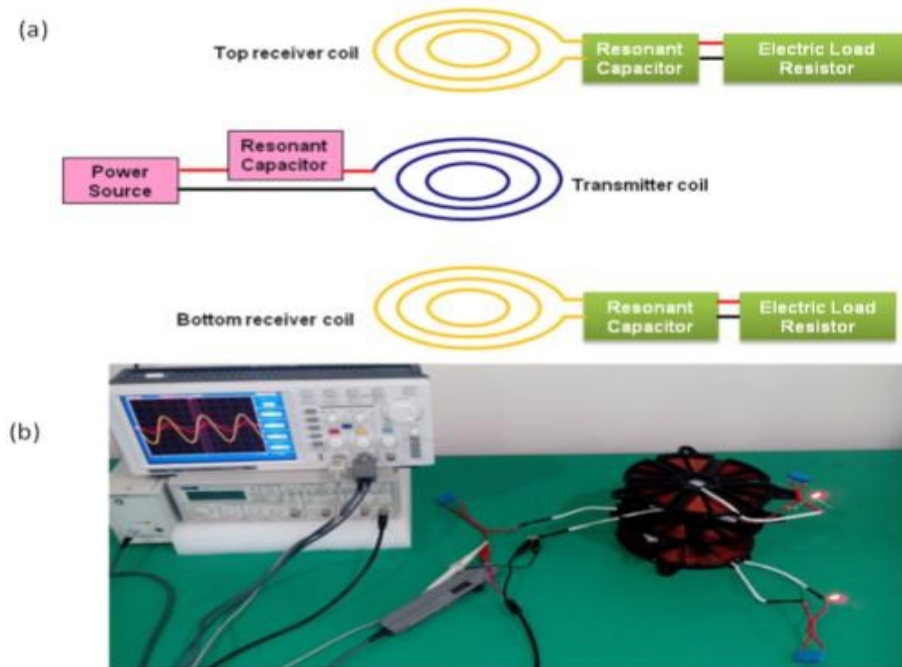
Park, Lee, Cho, and Rim (2015) demonstrated an induction power transfer system (IPTS) for a 5-m distance. The IPTS system (Figure 2.20) featured a dipole-structure coil with a ferrite core, rather than conventional loop-type coils, which were found to be more effective for extended power delivery. The results verified that the optimised stepped core experiences only 41% of the core loss compared to the unoptimised even core while still delivering 2.1 times more wireless power for the same core volume. According to the researchers, the proposed IPTS was still under

development at the time as a potential backup power source for essential sensors during severe accidents in a nuclear power plant.



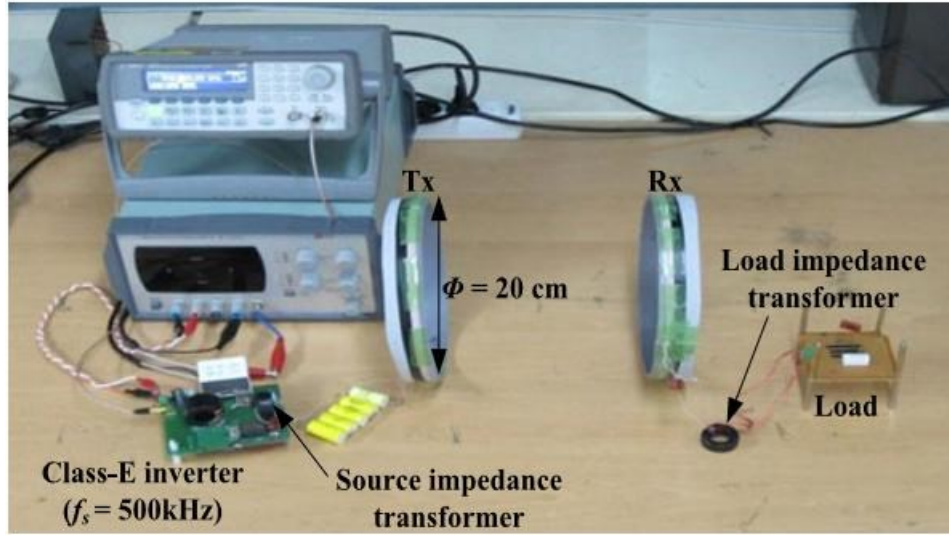
20: Figure 2.20: IPTS including primary and secondary coils (Park et al., 2015)

Kar, Nayak, Bhuyan, and Mishra (2015) recommended a bi-directional magnetic resonance-based WPT system (Figure 2.21) to demonstrate powering or charging electronic devices wirelessly. In Figure 2.21, (a) represents the block diagram of the bi-directional magnetic resonance WPT system, and (b) represents the prototype bi-directional magnetic resonance WPT system. Based on their observations, the received power reaches its peak at electromagnetic resonance, while the maximum power transfer efficiency is influenced by the operating frequency, the separation distance between the transmitter and receiver coils, and the electrical load connected to the receiving coils. According to the researchers, the bi-directional magnetic resonance coupling-based WPT procedure can concurrently transfer power to electrical appliances and charge portable electronic devices, such as cell phones, laptops, household electronics, micro-robots, actuators, motors, biomedical implantable electronics, wireless sensors, hearing aids, and solid-state devices.



21: Figure 2.21: Bi-directional WPT system (Kar et al., 2015)

Choi, Lee, Huh, and Rim (2015) examined a coupled magnetic resonance system (CMRS) incorporating two lumped impedance transformers (Figure 2.22). Two experimental kits, 1 W and 10 W, with theoretical load power and efficiency, validated the recommended CMRS. A low-quality factor of less than 100 was utilised to enable a 10 W power transfer with optimal performance of 80.2% over a distance of 13 cm. The recommended impedance transformer caused the CMRS to revert to a standard IPTS. The test findings demonstrated that the conventional CMRS, with its weak magnetic coupling, possesses an extremely high-quality factor for long-distance wireless power transmission.



22: Figure 2.22: Coupled magnetic resonance system (CMRS) (Choi et al., 2015)

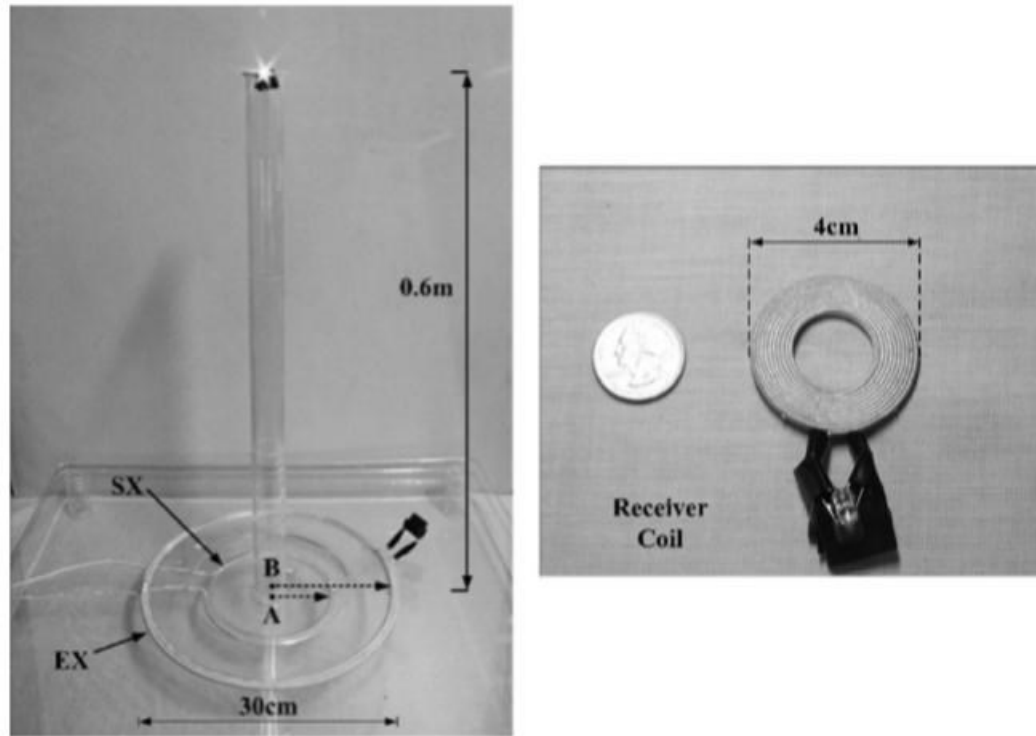
Choi, Thai, Lee, Kim, and Rim (2016) presented an IPTS designed for significantly loosely coupled dipole coils. The dipole-structure coil with a ferrite core was validated based on its magnetising inductance. Choi et al. (2016) performed a detailed analysis and recommended a design guideline (Figure 2.23) for the significantly loosely coupled case. This design enabled an energy transfer of 10.3 W over a distance of 7 m. The variation of the coupling factor concerning the secondary coil positions was measured over a range of 2–12 m. According to the researchers, the proposed IPTS was being developed as an emergency backup power unit at their facilities.



23: Figure 2.23: Primary and secondary coils (Choi et al., 2016)

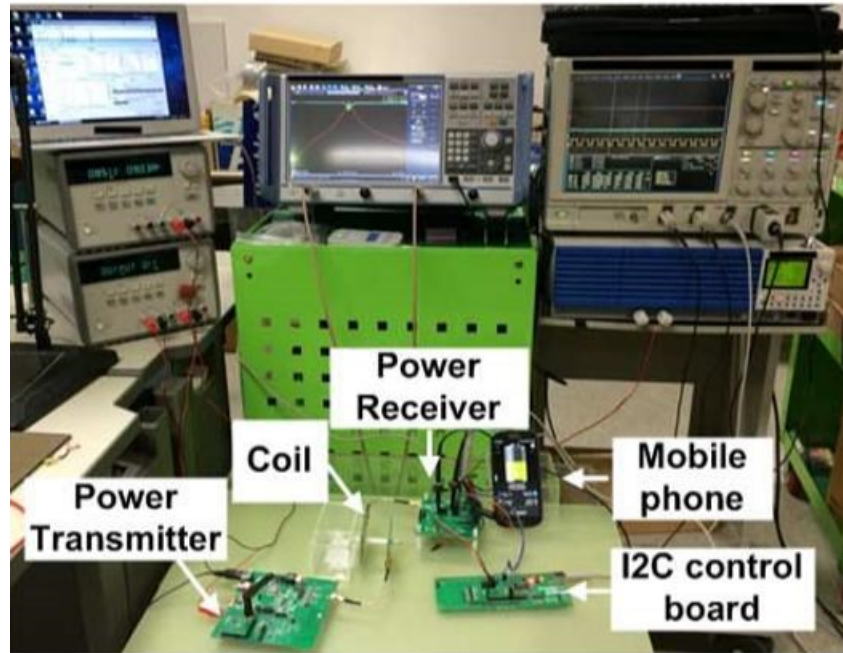
Mao, Zhang, Song, Wei, and Zhu (2016) assessed a WPT system operating with a low coupling coefficient. The test findings (Figure 2.24) led to the following conclusions: an energy

amplification ratio exists between the two inter-coupled coils, the inclusion of an enhancing coil (EX) improves system efficiency, and the use of an EX-structure alters the equivalent load on the power source.



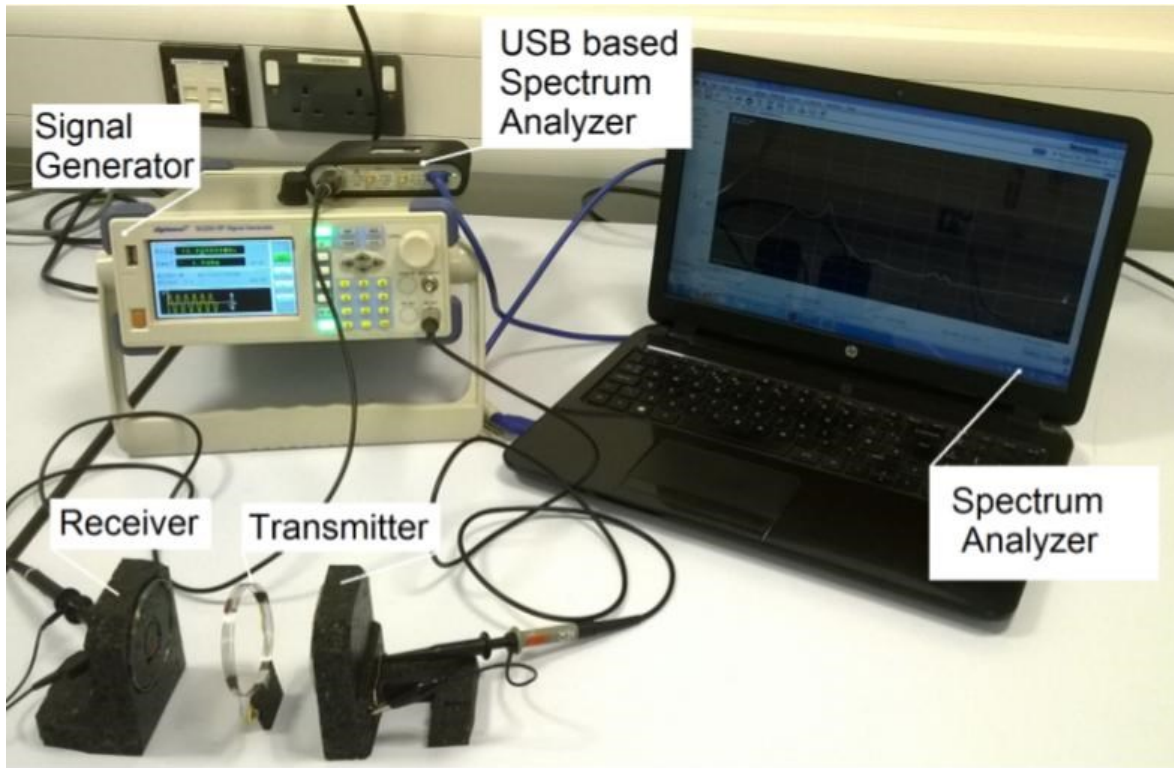
24: Figure 2.24: WPT system with receiver coil (Mao et al., 2016)

Moon, Hwang, Jo, Shin, and Kim (2016) introduced a resonant WPT system featuring a 5W fully integrated power receiver (Figure 2.25). The WPT system operated at a frequency of 6.78 MHz to comply with the A4WP standard. Optimised matching networks with shunt-series mixed-resonant structures were implemented in the primary and secondary coils to enhance system efficiency. In the WPT system, the power receiver provided energy to its internal circuit, as no other power source was available for the receiver. A power supply switching circuit (PSSC) was integrated into the WPT system to reduce power consumption in the receiver's power rail. Comprehensive system efficiency was determined by dividing the receiver's output DC power by the transmitter's input DC power.



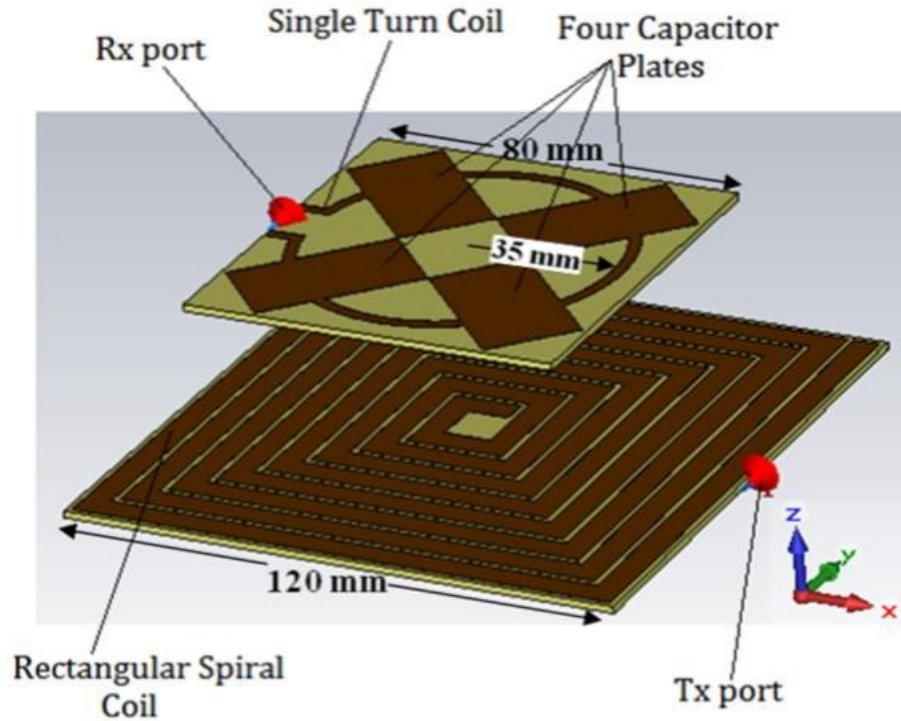
25: Figure 2.25: WPT system with PSSC (Moon et al., 2016)

Rozman, Fernando, Adebisi, Rabie, Kharel, Ikpehai, and Gacanin (2017) introduced a hybrid SCMR-CSCMR system. The recommended system (Figure 2.26) incorporated an adjustable SCMR concept on the transmitter side and a CSCMR model on the receiver end. As evidenced by the researchers, this also demonstrates that adaptively adjusting the distance between the source and transmitting (Tx) loops helps the circuit sustain maximum efficiency across the given transmission range, while the transmitting frequency remains constant. The validated results demonstrate that the recommended charger offers greater flexibility for charging devices within a 50 mm radius from the centre of the charging platform while maintaining a relatively high efficiency.



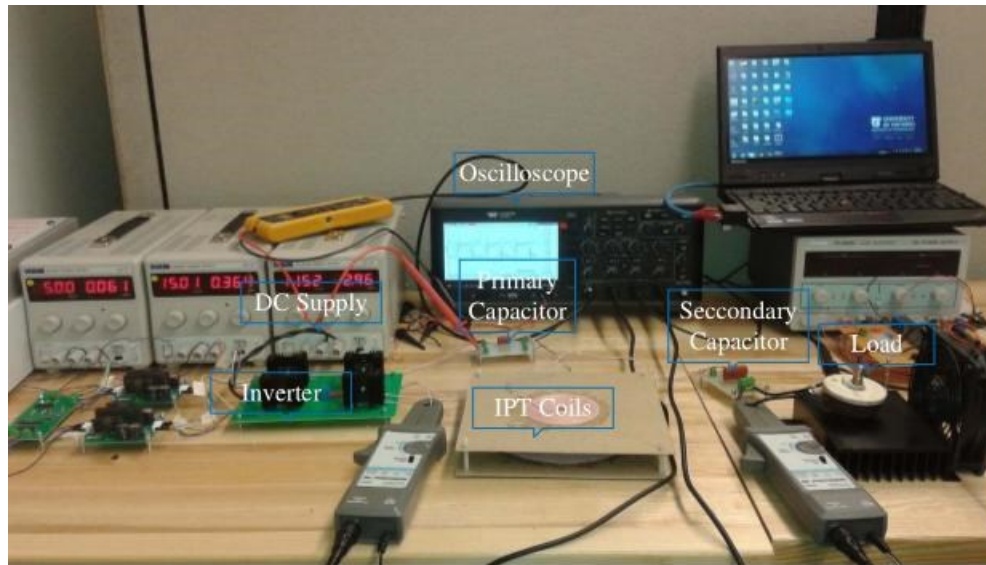
26: Figure 2.26: Combined CSMR-SCSMR system (Rozman et al., 2017)

Salleh, Seman, Zaidel, and Etang (2017) introduced the design of a pair of differently sized Witricity devices (Figure 2.27) incorporating a thin coil strip. The simulation and measurement results indicated that the device achieved coupling at a maximum air gap of 30 mm with an efficiency of 54.5%. Regarding the performance of the Witricity device under lateral and angular misalignment, a maximum lateral misalignment (LM) of 10 mm was achieved as the angular misalignment (AM) varied from 0° to 40° . The research findings suggest the potential for efficient wireless power transfer to devices with stricter receiver size constraints.



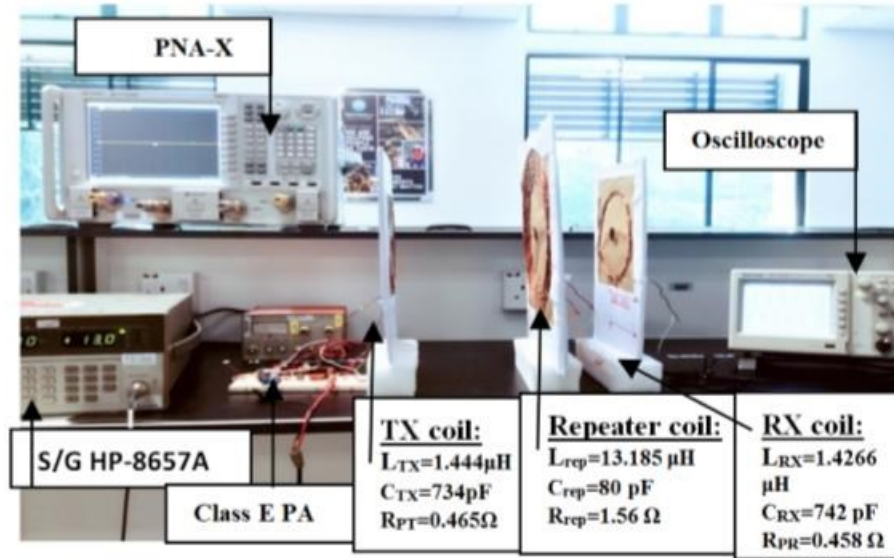
27: Figure 2.27: 3D view of the Witricity device (Salleh et al., 2017)

Aditya and Williamson (2017) conducted an evaluation and presented test findings on the power transfer ability and efficiency of a series-series (SS) resonant inductive link for current-sourced and voltage-sourced inputs (Figure 2.28). The results verified the following: ‘the maximum power transfer is influenced by the characteristics of the power supply. The experiments demonstrated that enhancing mutual coupling increases the output power for a current-sourced input. For a voltage-sourced input, an optimal coupling value exists at which maximum power transfer is achieved. It was also determined that a voltage-sourced SS resonant inductive link exhibits poor performance due to deviations from the ideal tuning condition and parameter misalignments. The combined performance of a current-sourced SS resonant inductive link remains consistent with theoretical values due to the regulated current flow in the primary winding. SS resonant inductive coupling is best suited to be designed and operated using a current-sourced input instead of a voltage-sourced input. As stated by the researchers, the findings on SS can inform the design of resonant circuits for emerging electric transportation inductive charging infrastructures.



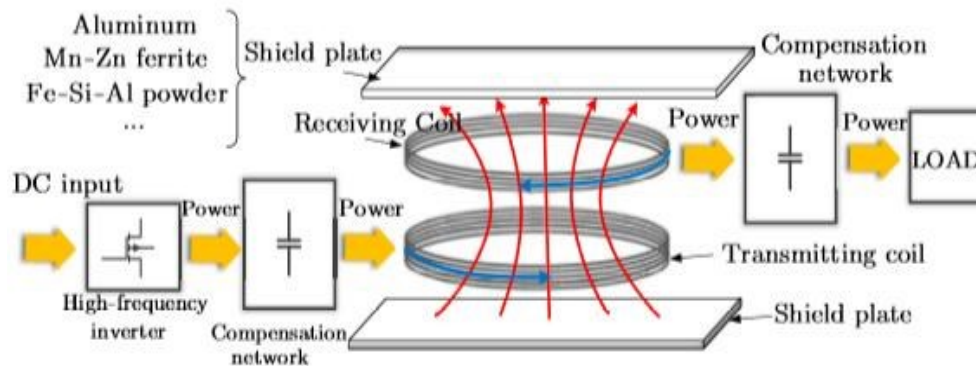
28: Figure 2.28: Series-series (SS) resonant inductive link (Aditya and Williamson, 2017)

A study by Anowar, Kumar, Ramiah, and Reza (2017) introduced a highly efficient resonant-based WPT system, incorporating a developed class-E power amplifier (PA) operation with a robust impedance matching technique (Figure 2.29). Loop-shaped TX and RX coils, along with a flat planar spiral magnetic repeater coil, were utilised to enhance the power transfer efficiency of the WPT system. The class-E PA design, integrated with the matching circuit, functions as the DC-AC inverter for the WPT system and achieves substantial improvement through the optimal tuning procedure. The aligned networks enabled the circuit to operate under suitable input and output impedance conditions. This exploration also suggested optimal tuning of repeater coil positions to maximize efficiency and output power. The optimal tuning led to an improvement of more than 3 dB in measured performance across various operating distances, with a consistent power transmission observed over a range of 5 to 25 cm for the application.



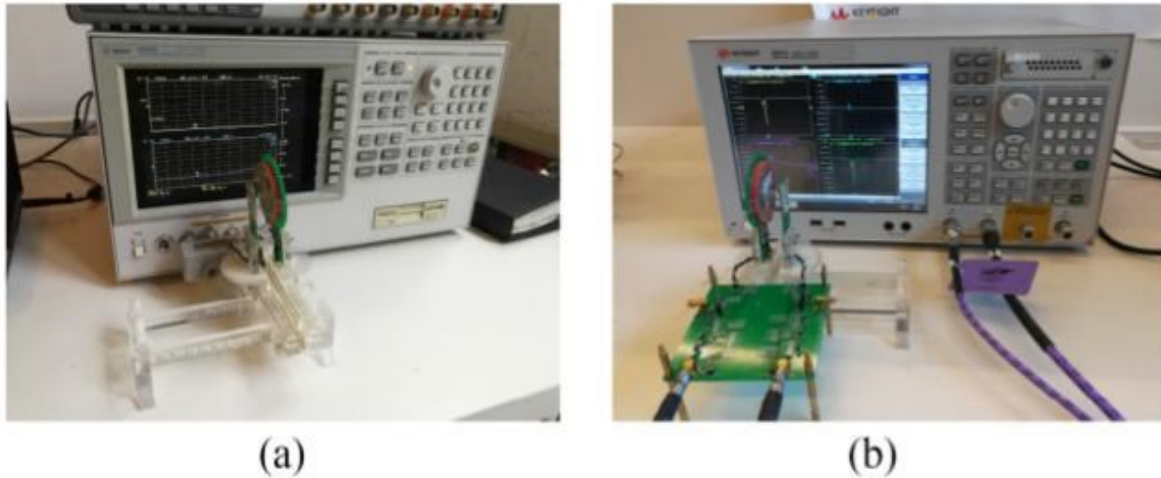
29: Figure 2.29: WPT system including transmitter, receiver, and repeater coil (Anowar et al., 2017)

Lu, Li, Chen, and Liu (2017) analysed the shielding effectiveness of various material shields for the magnetic-resonance wireless power transfer (MR-WPT) system using theoretical analysis and finite element simulation (Figure 2.30). At the common operating frequency range (10 kHz–10 MHz), high-conductivity materials exhibit maximum shielding effectiveness but weaken the coupling of transmission coils, whereas high-permeability materials enhance coupling but offer lower shielding effectiveness. Consequently, the double-layer shield scheme recommended by Lu et al. (2017) provides advantages in both shielding effectiveness and transmission efficiency for the MR-WPT system.



30: Figure 2.30: MR-WPT system with shield (Lu et al., 2017).

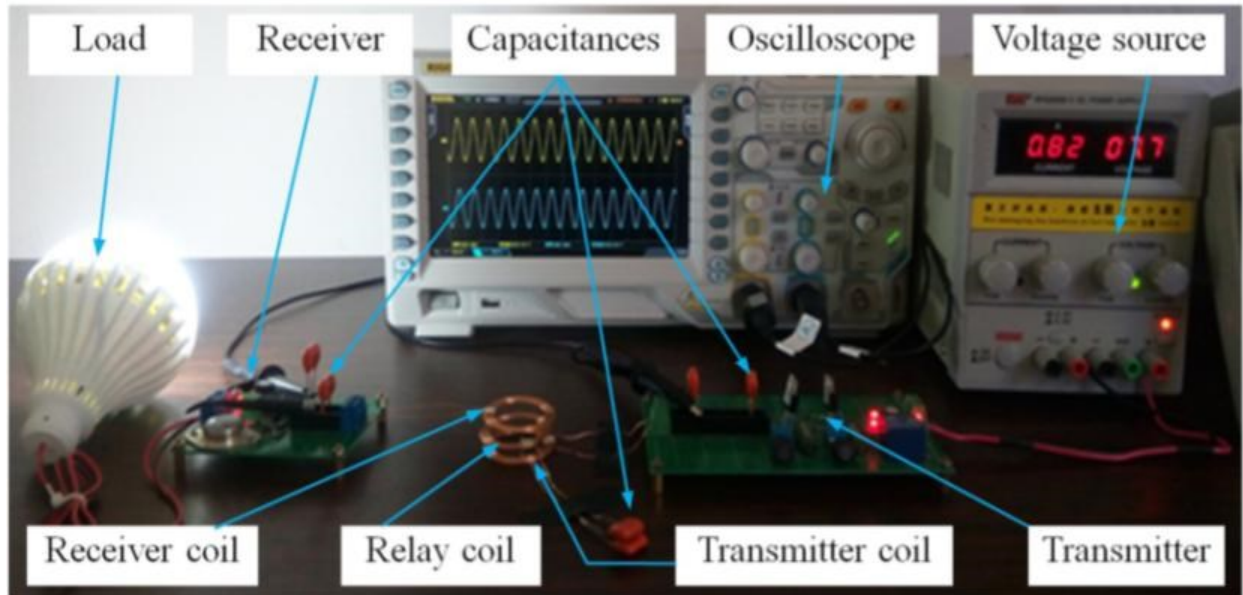
Miao, Liu, and Gong (2017) carried out research on an impedance-matching network designed to optimise an IWPT system (Figure 2.31). The aligning processes of an IWPT system matched by resonant capacitors (C-IWPT), an IWPT system matched by both resonant capacitors and impedance matching networks (IMN-C-IWPT), and an IWPT system matched solely by impedance matching networks (IMN-IWPT) are evaluated. To maximize efficiency, the IMN optimisation was analysed in three aspects: achieving maximum efficiency by ensuring the output power matches the load's required power level, minimising losses in the source and load circuits during IMN selection, and formulating the matching networks along with their parameters. Compared to the efficiency of the C-IWPT system, the recommended optimised system achieved a 1.73-fold increase in efficiency, while the optimised IMN-IWPT system demonstrated a 1.97 times higher efficiency than the IMN-IWPT system optimised using the traditional maximum power transfer method. All experimental and simulation findings demonstrated that the IMN-IWPT system, optimised using the recommended method, achieved high efficiency and extended operating time when powered by a battery.



31: Figure 2.31: (a) Inductance, series resistance and mutual inductance, (b) Efficiency and output power of the IWPT system (Miao et al., 2017)

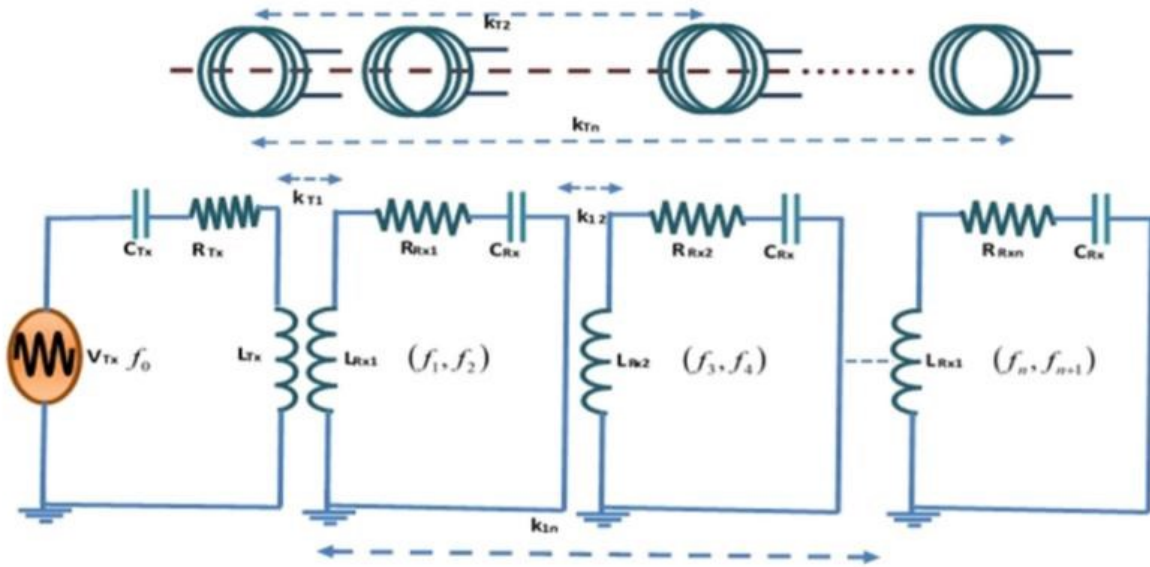
Liu, Tan, and Wen (2017) investigated the underlying principles of coupled magnetic resonance using self-organisation theory, which led to the development of criteria for a WPT system (Figure 2.32) based on self-organisation theory. The evaluation conducted led to the following conclusions: In an over-coupled region, it exhibits a hyperbolic trace-curve on the transmitting or

receiving side, respectively. Additionally, the vibration phenomenon of the receiver coil in a three-coil WPT system was predicted and explained using self-organization theory.



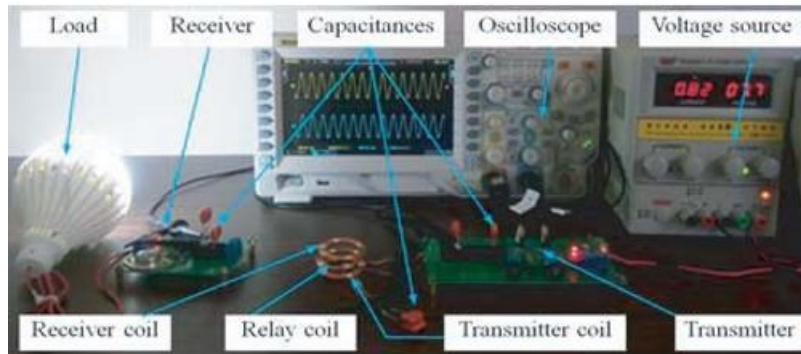
32: Figure 2.32: Three-coil WPT system (Liu et al., 2017)

Agbinya (2018) recommended and demonstrated a procedure for designing inductive filter banks through frequency splitting in inductive peer-to-peer systems (Figure 2.33). As stated by Agbinya (2018), split frequencies are created when critical coupling is achieved between pairs of inductive nodes. The test findings showed that by positioning the nodes relative to each other in a way that the coupling coefficient exceeds the value obtained at resonance, two frequency bands (lower and upper) are generated. The lower and upper bands from the split frequency response are utilised as the two bands of the filter bank. Simulations show that the centre frequencies are nearly the same, making it essential to separate these filters by deliberately introducing guard bands during the design process.



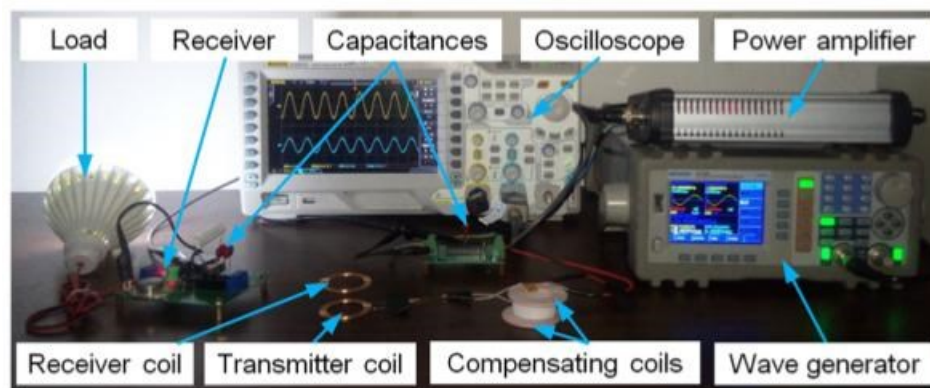
33: Figure 2.33: Multiple stages of inductive systems (Agbinya, 2018)

The research carried out by Liu and Tan (2018) presented the underlying principles of coupled magnetic resonances through the application of self-organization theory and energy entropy theory. The findings indicate that the WPT system (Figure 2.34) is part of a self-organizing system and examines the vibration of the relay coil. The output power surges from the receiver coil show periodic variation due to the periodic vibration of the relay coil. The energy transfer efficiency of the receiver coil shows periodic fluctuations. The energy transmission characteristics of the three-coil WPT system, especially the relay coil, could provide insights for achieving maximum output power and transmission efficiency across different operating conditions.



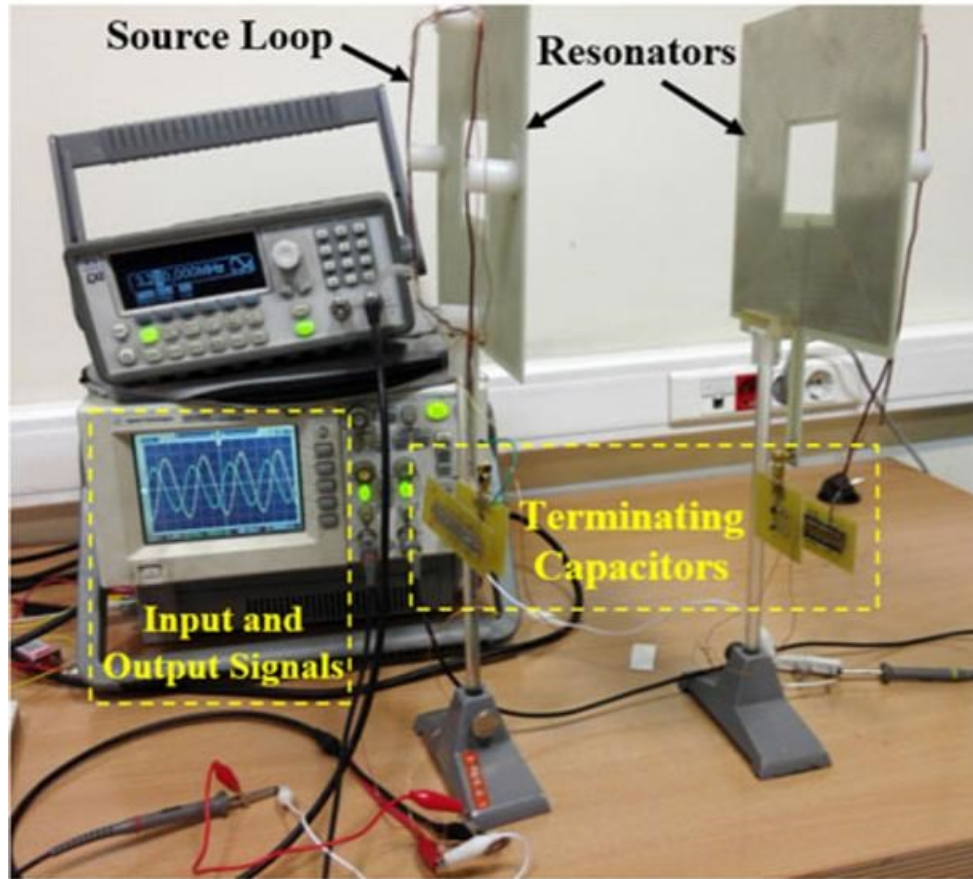
34: Figure 2.34: Three-coil system with relay coil vibration (Liu and Tan, 2018)

The study conducted by Liu, Tan, and Wen (2018) focused on impedance compensation in coupled magnetic resonance, utilizing circuit and entropy theory. The study also offered an evaluation of the impedance characteristics and power superposition in the WPT system. Liu et al. (2018) concluded from the study that the wireless power transfer system operates as a power superposition system. The corresponding power of the compensating loop was generated through a virtual three-coil WPT system (Figure 2.35) by introducing a pair of compensating coils into a two-coil resonator system. A two-coil resonator system attained power superposition, specifically dynamic impedance compensation for wireless power transfer. The comprehensive system reached maximum output power and transmission efficiency in a fixed-frequency mode.



35: Figure 2.35: Virtual three-coil experimental system (Lui et al., 2018)

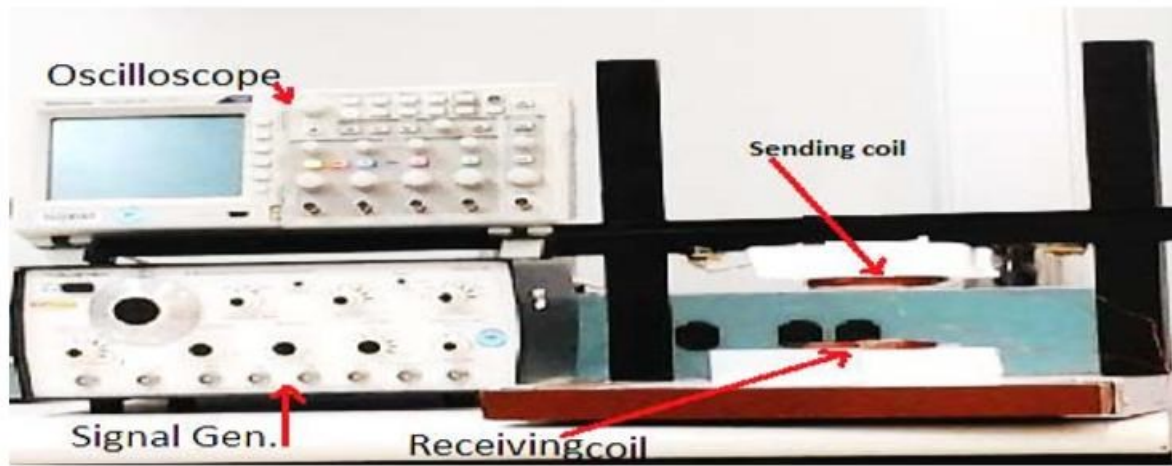
Najjarzadegan, Ghotbi, Ashtiani, Shoaie, and Shahabadi (2018) recommended an efficiency optimisation procedure applicable to any resonance-based WPT system (Figure 2.36), independent of the physical properties of the coils printed on a substrate. The findings of the research indicated that to enhance WPT efficiency and power transfer range, the resonators were terminated using a reactive termination. By adding an appropriate terminating capacitor, the efficiency for a spacing of 270 mm increased by up to 20%, compared to a 13% efficiency at the self-resonance frequency (SRF). The most efficient frequency lies between the self-resonance frequency (SRF) and the frequency at which the resonator behaves as a lumped inductor. The benefit of this procedure lies in the improvement of power transfer efficiency (PTE), regardless of whether the physically optimised resonators are used. Reactive termination has reduced the sensitivity of efficiency to nearby objects (Najjarzadegan et al., 2018).



36: Figure 2.36: WPT system with square spiral resonators (Najjarzadegan et al., 2018)

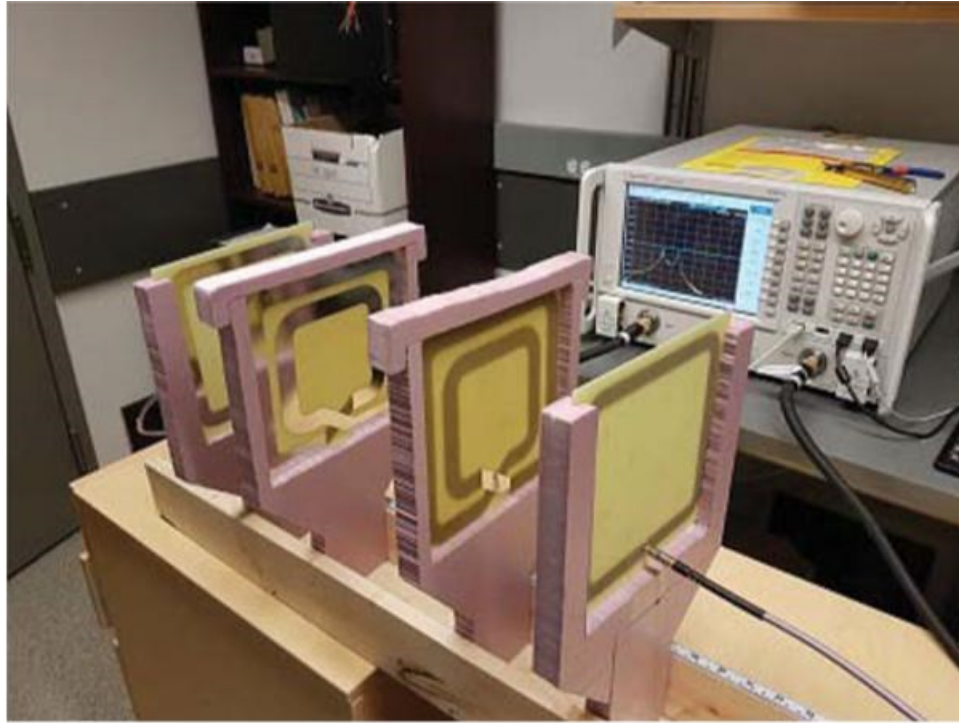
The magnetic flux density captured in the secondary coil for the WPT system was analysed by Talaat, Metwally, and Arafa (2018). The WPT system included an experimental model and three simulated models with varying coil geometries and coil arrangement positions (Figure 2.37). The study found that the magnetic flux density is precisely proportional to the increase in the number of turns of the coil, while it is inversely proportional to the coil height. The flux is accumulated inside the coil geometry with some distortion appearing in the receiving coil. Once the secondary coil is placed within the primary coil, the magnetic flux linked to the secondary coil increases by 1.22 times its original value, even though the ratio between the secondary coil's radius and the distance separating the two coils remains the same. When the secondary coil was slanted at an angle of 10° , the magnetic flux on the slanted side decreased to 22.2% of that on the aligned side. The experimental model was designed to demonstrate that, at each distance value, the voltage and maximum power received were dependent on the operating frequency. The experimental model

showed that the maximum distance between the two coils should be less than 1.2% of the coil radius for optimal frequency and maximum WPT.



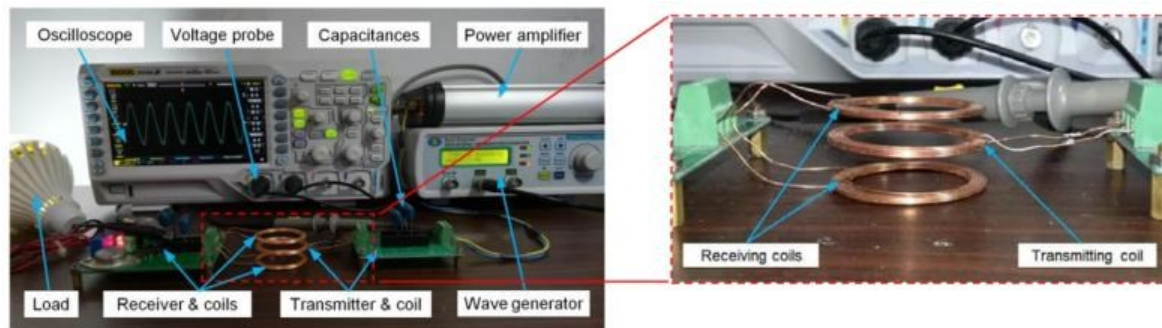
37: Figure 2.37: WPT system (Talaat et al., 2018)

Badowich and Markley (2018) carried out research on an MRC system (Figure 2.38) designed for efficient WPT, while minimising idle power losses through the re-optimisation of the source and load match. A misalignment was introduced as input to the system to reduce idle power losses, while the receiver was designed to compensate for this mismatch to maintain high transfer efficiency to the load. Equations were obtained for active transfer efficiency and idle power losses based on a four-coil equivalent circuit network, as well as to characterize idle power loss suppression and optimize the design. A 13.56 MHz MRC system was developed, and the efficiency and losses were measured to verify the findings. Idle power losses were reduced by 25 percent, while the active efficiency decreased by only 9 percent compared to the efficient system. Idle loss suppression provided the following benefits: enhanced long-term efficiency for a WPT system undergoing intermittent charging cycles and reduced transmitter field emissions, as most of the power was reflected to the source. Furthermore, carefully designed matching networks for MRC systems demonstrated promising results for enhanced power transfer bandwidth and broadband coupling of tightly coupled high-Q resonators.



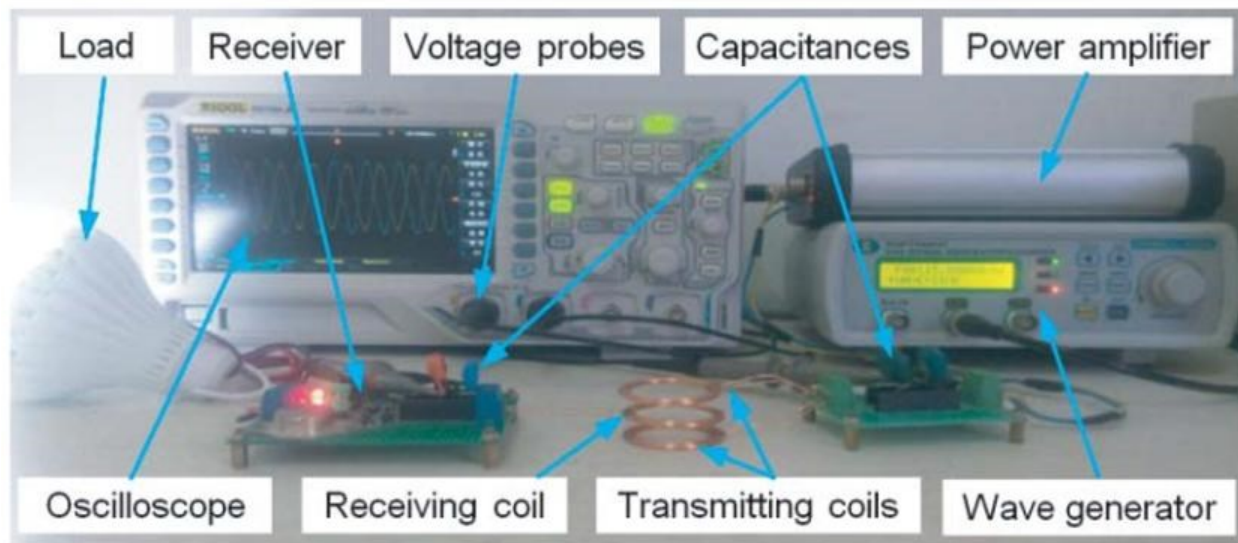
38: Figure 2.38: The 13.15 MHz four-coil wireless power transfer (Badowich and Markley, 2018)

Lui and Lui (2019) recommended a MCR-WPT system with two receiving coils (Figure 2.39). The transmission characteristics of the MCR-WPT system were examined using the Biot-Savart Law. The results of the research concluded that two receiving coils could be employed to generate a uniform magnetic field. In the higher frequency mode, when the distance between the two receiver coils was optimal, constant output power and high transfer efficiency were attained in the fixed-frequency mode. Overall, the findings of the research showed that the topology utilising two receiving coils led to optimal transmission performance.



39: Figure 2.39: WPT system using two receiving coils (Lui and Lui, 2019)

Liu, Tan, and Liu (2019) presented an evaluation and simulation of the transmission characteristics of an MCR-WPT system (Figure 2.40) by applying the magnetic field superposition principle. In the lower frequency mode (LFM), the MCR-WPT system with two transmitting coils achieved magnetic field superposition and maintained constant output power and transfer efficiency in fixed-frequency mode. If the distance between the two transmitting coils is optimal and the receiving coil moves between them, the fluctuation in output power and transfer efficiency of the MCR-WPT system remains under 5%. In the higher frequency mode (HFM), when the receiving coil moves a certain distance away from the midpoint, the phase between the main transmitting and receiving coils is inverted. This phase inversion results in a significant drop in performance. The researchers suggested that the results of this study could help other researchers identify an approach that ensures constant output power and transfer efficiency in open areas, such as charging pads. It is anticipated that this research will speed up the practical applications of wireless power transfer.



40: Figure 2.40: Two transmitting coils to achieve the magnetic field superposition (Lui et al., 2019)

Based on the reviewed literature on WPT for maximum power efficiency, various models, coil designs, and laws were examined and are referenced in the current research for model, circuit, and coil designs.

2.3.1 Magnetic Resonance Coupling to Wirelessly Charge Mobile Device Batteries

Currently, there is restricted research available on wireless power charging systems based on magnetic resonance coupling for mobile devices. Research carried out by Munir and Ranum (2015) illustrates a charging system that includes a transmitter circuit to generate the AC signal for transfer, transmitting and receiving radiators to wirelessly transfer the power of the AC signal, and a receiver circuit to convert the received AC signal into DC voltage for charging the mobile device. One area of the charging system that needs improvement is the transmission efficiency of the radiator. An additional study explores a method for a novel motor that uses magnetic resonance coupling (MRC) to enable the practical use of electric aircraft (Takishima and Sakai, 2022).

2.3.2 Other Applications of Magnetic Resonance Coupling

This section highlights research conducted in both the electric vehicle field and the medical field. Mathematical theories, frameworks, and models were reviewed to aid in the current research of magnetic resonance coupling for wireless charging of mobile device batteries.

Research based on magnetic resonance coupling for charging electric vehicles (EVs) started to become popular in 2005 and remains a popular area of research. Various research articles focused on stationary charging, charging an EV while being driven, or the design specifications of the current EV battery charger for improvement. Table 2.5 summarises the research related to the charging of electric vehicles:

5: Table 2.5: Magnetic Resonance Coupling for Electric Vehicles

Author	Title of Research	Description
Wang, Stielau, and Covic (2005)	Design considerations for a contactless electric vehicle battery charger	Based on an inductively coupled power transfer (ICPT) system is designed to deliver power from a stationary primary source to one or more movable secondary loads over relatively large air gaps via magnetic coupling.

Matsuda, Sakamoto, Shibuya, and Murata (2006)	A non-contact energy transferring system for an electric vehicle charging system based on recycled products	Presents a non-contact, automatic charging system for electric vehicle applications.
Imura and Hori (2011)	Maximizing Air Gap and Efficiency of Magnetic Resonant Coupling for Wireless Power Transfer Using Equivalent Circuit and Neumann Formula	Proposes the equations for the relationship between maximum efficiency and air gap length in magnetic resonant coupling, using the Neumann formula and the equivalent circuit method.
Wang, Zhang, and Liu (2013)	Analysis of the Efficiency of Magnetic Resonance Coupling Wireless Charging for Electric Vehicles	The system model consists of magnetic resonance coupling-based stationary vehicle charging.
Shin, Shin, Kim, Ahn, Lee, Jung, Jeon, and Cho (2014)	Design and Implementation of Shaped Magnetic-Resonance-Based Wireless Power Transfer System for Roadway-Powered Moving Electric Vehicles	Describes the design and implementation of a wireless power transfer system for moving electric vehicles, with examples involving the practical Online Electric Vehicle (OLEV) system
Chun, Park, Kim, Kim, Kim, Kim, Kim, Ahn. (2014)	Electromagnetic Compatibility of Resonance Coupling Wireless Power Transfer in an On-Line Electric Vehicle System	The concept of an online electric vehicle (OLEV) is presented with its wireless power transfer mechanism to analyse the electromagnetic compatibility characteristics.
Koh, Beh, Imura, and Hori (2014)	Impedance Matching and Power Division Using an	Proposes a new impedance matching and power division

	Impedance Inverter for Wireless Power Transfer via Magnetic Resonant Coupling	method using impedance inverters at only the receiver sides.
Jiwariyavej, Imura and Hori (2015)	Coupling Coefficients Estimation of Wireless Power Transfer System via Magnetic Resonance Coupling Using Information from Either Side of the System	Derivations of equations for estimating coupling coefficients in several configurations of a WPT system are presented, using information from only one side of the system, either the transmitting side or the receiving side.
Miller, Onar, and Chinthavali (2015)	Primary-Side Power Flow Control of Wireless Power Transfer for Electric Vehicle Charging	A new analytical concept for power flow in WPT, in which the primary coil provides frequency selection, and the tuned secondary coil is analysed as a transmission network.
Chung, Lee, Kang, and Park (2016)	Design Considerations of Superconducting Wireless Power Transfer for Electric Vehicles at Different Inserted Resonators	Uses superconducting wireless power transfer for electric vehicle (SUWPT4EV) system.
Gunji, Imura, and Fujimoto (2017)	Novel Transmitting Power Control Method without Signal Communication for Wireless Power Transfer via Magnetic Resonance Coupling	A novel feedback control method for the primary side based on conversion ratio estimation is presented.

Gao, Duan, Oliveira, Ginart, Farley, and Tse (2017)	3-D Coil Positioning Based on Magnetic Sensing for Wireless EV Charging	A magnetic positioning approach is proposed to solve the misalignment issue associated with wireless EV charging.
Talaat, Metwally, and Arafa (2018)	Experimental and Simulation Study of Wireless Power Transfer Using Resonators with Coupled Electric Fields	Presents a simulation model, with different geometries and system setups, and an experimental model; two identical coils shunted with two variable capacitors are used as sending and receiving coils.
Zheng, Song, Huang, Xu, and Gao (2019)	Simulation of the magnetic coupling phenomena in electric vehicle wireless charging	Addresses the inter-operation problem of the magnetic coupling mechanism in different technical routes.
Hutchinson, Waterson, Anvari, and Naberezhnykh (2019)	Potential of Wireless Power Transfer for Dynamic Charging of Electric Vehicles	Explains how to charge electric vehicles using Dynamic Wireless Power Transfer (DWPT), i.e., while the vehicle is being driven.
Ebot and Fujimoto (2020)	A Motor Design Based on Wireless Magnetic Resonance Coupling Technology	Delivers a novel motor design in which magnetic resonance coupling (MRC) is used for wireless resonant power transfer of energy from a stator multiphase coil to a rotor multiphase coil.

Akhil, Harisankar, Jishnu, Sreenand, Vijay, Asha, and Preetha (2021)	Coupled Wireless Charging System for Electric Vehicles	Examines the charging for electric vehicles using coupled wireless charging methods.
Shi, Tang, Wang, Li, Zhou, and Fei (2022)	A Magnetic Integrated Method Suppressing Power Fluctuation for EV Dynamic Wireless Charging System	The study focuses on a magnetic integrated method for the coupler of the electric vehicle dynamic wireless charging system on the road.
Hussain, Gharghan, Al-Nabe, and Mahmood (2023)	Design of inductive wireless power transfer for electric vehicles using magnetic resonance coupling	Examines the wireless charging of a car battery.
Liu, Zhang, Xu, Cheng, Huang, Ouyang, Qian, Zhang, and Che (2023)	Synergistic Dielectric–Magnetic Enhancement via Phase-Evolution Engineering and Dynamic Magnetic Resonance	A multi-domain coupling and long-range magnetic interaction theories are presented that offers a dynamic magnetic resonance mechanism for magnetic loss within a precarious grain size.

Wireless power transfer for sensor devices has been extensively researched in the medical field from the year 2006 to the present day. Below is a summary of only the research literature based on magnetic resonance coupling in the medical field (Table 2.6).

6: Table 2.6: Magnetic Resonance Coupling in the Medical Field

Author	Title of Research	Description
Tadic and Fallone (2010)	Design and Optimisation of a Novel Bored Bi-planar Permanent-Magnet Assembly for Hybrid Magnetic Resonance Imaging Systems	A novel design for a bi-planar permanent-magnet assembly for use in hybrid magnetic resonance imaging (MRI) systems is presented.

Blanquer, Guillaume, Letouzey, Lemaire, Franconi, Paniagua, Coudane and Garric (2012)	New magnetic-resonance-imaging-visible poly(epsilon-caprolactone)-based polyester for biomedical applications	Presents a new MRI-visible polymer for the MR visualisation of implantable medical devices and the post-operative management of patients.
Cabot, Lloyd, Christ, Kainz, Douglas, Stenzel, Wedan, and Kuster (2013)	Evaluation of the RF heating of a generic deep-brain stimulator exposed in 1.5 T magnetic resonance scanners	Evaluate the advantages and shortcomings of a four-tier approach designed to demonstrate the safety of implants during MR scans.
Wang, Hemour, and Wu (2014)	Coupled Resonance Energy Transfer Over Gigahertz Frequency Range Using Ceramic-Filled Cavity for Medical Implantable Sensors	Proposes a transmitter topology for inductive or magnetic resonance coupling transfer with minimized radiation.
Tang (2015)	A Low-Operating-Voltage Wireless Intermediate-Range Scheme for Energy and Signal Transmission by Magnetic Coupling for Implantable Devices	Demonstrates a low-operating-voltage wireless energy and signal transmission method to achieve these aims.
Na, Jang, Ma and Bien (2015)	Tracking Optimal Efficiency of Magnetic Resonance Wireless Power Transfer System for Biomedical Capsule Endoscopy	Presents a method to track the optimal efficiency of a magnetic resonance (MR)-wireless power transfer (WPT) system for biomedical capsule endoscopy.
Xu, Yang, Yang, Zhao and Li (2016)	Design of Magnetic Coupling Resonance Wireless Energy	Presents a wireless energy transmission system based on magnetic coupling resonance

	Transmission and Monitoring System for Implanted Devices	technology for implanted devices.
Seo, Khang, Chae, Yu, Lee, and Lee (2016)	Open-loop self-adaptive wireless power transfer system for medical implants	Proposes an open-loop self-adaptive wireless power transfer system using magnetic resonance coupling for implantable biosensors.
Xiao, Wei, Cheng, and Liu (2017)	Wireless Charging System Considering Eddy Current in Cardiac Pacemaker Shell: Theoretical Modelling, Experiments, and Safety Simulations	The precise implant position of receiving coils is theoretically and experimentally investigated.
Alzaidi, Yahya, Swee, and Idris (2017)	A wireless bipolar electrosurgical device using power energy transfer	This venture is intended for charging and controlling a rechargeable cordless remote used in an operating room.
Mao, Wang, Mao, and Sun (2018)	A double-helix and cross-patterned solenoid used as a wirelessly powered receiver for medical implants	A concentric double-helix (DH) coil with an air core is presented for use in implantable devices.
Zeng, Wang, Zheng, Kainz, and Chen (2018)	Evaluation of MRI RF electromagnetic field-induced heating near leads of cochlear implants	Evaluate the RF-EMF induced heating for the cochlear implant system in a 1.5 T MRI coil and highlight the factors that have significant effects on the heating.
Xiao, Cheng, and Wei (2018)	An LCC-C Compensated Wireless Charging System for Implantable Cardiac Pacemakers: Theory,	The prototype of the wireless charging system for implantable cardiac

	Experiment, and Safety Evaluation	pacemakers has been developed.
Tu, Chu, Spetzler, Hayes, Dong, Liang, Chen, He, Wei, Lisenkov, Lin, Lin, McCord, Faupel, Quandt, and Sun (2019)	Mechanical-resonance-enhanced thin-film Magnetoelectric Heterostructures for Magnetometers, Mechanical Antennas, Tuneable RF Inductors, and Filters	Reviews thin-film characterisation techniques for both piezoelectric and magnetostrictive thin films.
Gambal, Pannicke, Magdowski, Hensen, Wacker Vick (2021)	Design and Implementation of a Test Procedure for the Evaluation of Interference Coupling in Magnetic Resonance Imaging	The focus is on the reverberation chamber (RVC) to assess interferences in the magnetic resonance (MR) environment.
Alipour, Seifert, Delman, Robson, Shrivastava, Hof, Adriany, Zahi, Fayad, and Balchandani (2021)	Improvement of magnetic resonance imaging using a wireless radiofrequency resonator array	A passive inductively coupled radiofrequency resonator array design is presented that works in conjunction with conventional coils.
Islam, Gulati, Domic, Pal, Kant, and Kim (2022)	Performance Evaluation of Magnetic Resonance Coupling Method for Intra-Body Network (IBNet)	This study looks at MR coupling in biological tissue.
Anazodo, Ng, Ehiogu, Obungoloch, Fatade, Mutsaerts, Secca, Diop, Opadele, Alexander, Dada, Ogbole, Nunes, Figueiredo, Figini, Aribisala, Awojoyogbe, Aduluwa, Sprenger,	A framework for advancing sustainable magnetic resonance imaging access in Africa	The study presents a framework for advancing imaging needs in other low-resource settings.

Wagner, Olakunle, Romeo, Sun, Fezeu, Orunmuyi, Geethanath, Gulani, Nganga, Adeleke, Ntobeuko, Minja, Webb, Asllani, and Dako (2022)		
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2.3.3 Summary of Literature Findings for Magnetic Resonance Coupling

This section summarises the literature findings based on magnetic resonance coupling to maximum power efficiency over larger air gaps. The authors either focused on the different design considerations for the coil structure or the type of antenna to maximise power transfer.

Table 2.7 provides a summary of the reviewed literature in the field of ‘magnetic resonance coupling for maximum power efficiency.

7: Table 2.7: Related literature on MRC for Maximum Power Efficiency

Author	Title of Research	Model
Maxwell (1865)	VIII. A Dynamic Theory of the Electromagnetic Field	Theory of electromagnetism
Kurs, Karalis, Moffatt, Joannopoulos, Fisher, and Soljacic (2007)	Wireless Power Transfer via Strongly Coupled Magnetic Resonances	Two self-resonant coils
Beh et al. (2010)	Wireless Power Transfer System via Magnetic Resonant Coupling at Fixed Resonance Frequency- Power Transfer System Based on Impedance Matching	WPT system based on impedance matching (IM)
Imura and Hori (2011)	Maximizing Air Gap and Efficiency of Magnetic Resonant Coupling for Wireless Power	WPT system using Neumann formula

	Transfer Using Equivalent Circuit and Neumann Formula	
Jonah, Georgakopoulos, and Tentzeris (2012)	Optimal Design Parameters for Wireless Power Transfer by Resonant Magnetic	Strongly coupled magnetic resonance (SCMR) method
Lee, Zhong, and Hui (2012)	Effects of Magnetic Coupling of Nonadjacent Resonators on Wireless Power Domino-Resonator Systems	Straight domino-resonator systems
Challa, Mur-Miranda, and Arnold (2012)	Wireless power transmission to an electromechanical receiver using low-frequency magnetic fields	Integration of electromechanical energy conversion and mechanical resonance
Tanikawa, Kato, Imura, and Hori (2013)	Experiment of Magnetic Resonant Coupling Three-Phase Wireless Power Transfer	Three-phase WPT system for rotating equipment
Ricketts, Chabalko, and Hillenius (2013)	Experimental demonstration of the equivalence of inductive and strongly coupled magnetic resonance wireless power transfer.	Strongly coupled magnetic resonance (SCMR)
Ahn and Hong (2013)	Effect of Coupling Between Multiple Transmitters or Multiple Receivers on Wireless Power Transfer	Adjustment of the resonant and/or the driving frequencies
Beh, Kato, Imura, Oh, and Hori (2013)	Automated Impedance Matching System for Robust Wireless Power Transfer via Magnetic Resonance Coupling	Automated Impedance Matching (IM) system
Lim, Tang, Lim, and Park (2014)	An Adaptive Impedance-Matching Network Based on a	An automatic impedance matching system based on a

	Novel Capacitor Matrix for Wireless Power Transfer	serial/parallel capacitor matrix in the transmitter.
Yan, Li, Zhang and Yang (2014)	Influence factors analysis and improvement method on the efficiency of wireless power transfer via coupled magnetic resonance	Mutual inductance theoretical analysis
Huang, Li, Li, Yuan, and Cheng (2014)	A Comparative Study Between Novel and Conventional Four-Resonator Coil Structures in Wireless Power Transfer	A novel four-coil system
Pop, Pitica, and Bande (2015)	Analysing a Vibrating Wire Transducer using Coupled Resonator Circuits	Two-coil transducers based on a mathematical analysis
Park, Lee, Cho, and Rim (2015)	Innovative 5-m-Off-Distance Inductive Power Transfer Systems with Optimally Shaped Dipole Coils	Inductive power transfer system (IPTS) driven by an inverter of 20-kHz switching frequency
Kar, Nayak, Bhuyan, and Mishra (2015)	Bi-directional magnetic resonance-based wireless power transfer for electronic devices	Bi-directional WPT system
Choi, Lee, Huh, and Rim (2015)	Lumped Impedance Transformers for Compact and Robust Coupled Magnetic Resonance Systems	A coupled magnetic resonance system (CMRS) with two lumped impedance transformers
Choi, Thai, Lee, Kim, and Rim (2016)	Dipole-Coil-Based Wide-Range Inductive Power Transfer Systems for Wireless Sensors	Dipole-coil-based loosely coupled IPTS
Mao, Zhang, Song, Wei, and Zhu (2016)	Wireless power transfer using a field-enhancing coil and a small-	WPT system with a small receiver

	sized receiver with a low coupling coefficient	
Moon, Hwang, Jo, Shin, and Kim (2016)	Design of a 5-W Power Receiver for a 6.78 MHz Resonant Wireless Power Transfer System with Power Supply Switching Circuit	WPT system with PSSC
Rozman, Fernando, Adebisi, Rabie, Kharel, Ikpehai, and Gacanin (2017)	Combined Conformal Strongly Coupled Magnetic Resonance for Efficient Wireless Power Transfer	Hybrid circuit combining CSCMR and SCMR
Salleh, Seman, Zaidel, and Eteng (2017)	Investigation of Unequal Planar Wireless Electricity Device for Efficient Wireless Power Transfer	Unequally sized Witricity devices integrated with a thin coil strip
Aditya and Williamson (2017)	A Review of Optimal Conditions for Achieving Maximum Power Output and Maximum Efficiency for a Series–Series Resonant Inductive Link	Series–series (SS) resonant inductive link
Anowar, Kumar, Ramiah, and Reza (2017)	Efficiency Enhancement of Wireless Power Transfer with Optimum Coupling Mechanism for Mid-range Operation	WPT using three magnetically coupled coils
Lu, Li, Chen, and Liu (2017)	Numerical Analysis of Magnetic-Shielding Effectiveness for Magnetic Resonant Wireless Power Transfer System	Magnetic-resonance wireless power transfer (MRWPT) system
Miao, Liu, and Gong (2017)	Efficiency Enhancement for an Inductive Wireless Power Transfer System by Optimizing	Optimisation method of impedance matching networks (IMN)

	the Impedance Matching Networks	
Liu, Tan, and Wen (2017)	Modelling of the coupling mechanism of the wireless power transfer system and the vibration phenomenon of the receiver coil in the three-coil system	Three-coil WPT system
Agbinya (2018)	Recursive Frequency Allocation Scheme in Wireless Power Transfer and Magnetic Induction Communication Systems	Frequency splitting in the WPT system
Liu and Tan (2018)	Study on the Vibration Mechanism of the Relay Coil in a Three-Coil WPT System	WPT system as a part of a self-organizing system
Lui, Tan, and Wen (2018)	Dynamic impedance compensation for wireless power transfer using conjugate power	Three-coil WPT system
Najjarzadegan, Ghotbi, Ashtiani, Shoaee, and Shahabadi (2018)	Improved Wireless Power Transfer Efficiency Using Reactively Terminated Resonators	WPT system with two identical square spiral resonators
Talaat, Metwally, and Arafa (2018)	Experimental and Simulation Study of Wireless Power Transfer Using Resonators with Coupled Electric Fields	The WPT system focused on the magnetic flux.
Badowich and Markley (2018)	Idle Power Loss Suppression in Magnetic Resonance Coupling Wireless Power Transfer	A WPT system that suppresses power loss
Liu and Liu (2019)	Using Two Receiving Coils to Achieve Constant Output Power for Wireless Power Transfer	MCR-WPT SYSTEM

Liu, Tan, and Liu (2019)	Achieving the Constant Output Power and Transfer Efficiency of a Magnetic Coupling Resonance Wireless Power Transfer System Based on the Magnetic Field Superposition Principle	MCR-WPT system model with two transmitting coils
Sato, Tanaka, Tsuruda, and Nakamura (2020)	Basic Investigation on Wireless Power Transfer System via Magnetic Resonant Coupling with Magnetic Field Suppression at Any Point	Particle Swarm Optimization (PSO)
Rong, He, Liu, Wang, Liu, Lu, Zeng, and Liu (2021)	Omnidirectional Free-Degree Wireless Power Transfer System Based on Magnetic Dipole Coils for Multiple Receivers	Omnidirectional and multiple-pickup energy transfer.
Luo, Qiu, Gu, Zhang, Chen, and Xiao (2021)	Multiload Wireless Power Transfer System with Constant Output Power and Efficiency	Multiload WPT system
Dong, Li, Liu, Xu and Yang (2021)	A Novel All-Direction Anti-Misalignment Wireless Power Transfer System Designed by Truncated Region Eigenfunction Expansion Method	Wireless power transfer (WPT) system using antiparallel windings.
Xu and Zhong (2021)	Push–Pull Magnetic Field Excitation to Improve Efficiency of Wireless Power Transfer	WPT is based on a push–pull (PP) system.
Hou, Wang, Su, Liu and Deng (2022)	A Dual-Frequency Dual-Load Multi-relay Magnetic Coupling Wireless Power Transfer System Using Shared Power Channel	MC-WPT system.

Tian, Chau, Liu, Pang, and Lee (2022)	Maximum Power Tracking for Magnetic Field Editing-Based Omnidirectional Wireless Power Transfer	Omnidirectional WPT system.
Feng, Zuo, Sun, Dai, Wu, and Zhu (2022)	A Reticulated Planar Transmitter Using a Three-Dimensional Rotating Magnetic Field for Free-Positioning Omnidirectional Wireless Power Transfer	Free-positioning omnidirectional wireless power transfer (WPT) system.
Sun, Yang, Zhang, Cao, Tan and Pei (2022)	Modelling and optimization of pavement scale model for magnetically coupled resonant in wireless power transmission systems	The pavement scale model is based on MCR wireless power transmission.
Zhang, Dai, Li, Yan, Zhang, Mao, and Hu (2023)	Analysis of Power Transfer Characteristics of IPT System with Near-Field Magnetic Coupling	Near field magnetic coupling.
Tian, Liu, Song, Jin, Dong, and Zheng (2023)	Design and Optimization of Resonance-Based Wireless Power Transmission for Millimetre-Sized Planar Square Inductors Micro-Magnetic Stimulation	A wireless passive micro-magnetic stimulation.
Qing, Li, Wu, Liu, Zhao, and Su (2023)	A Hybrid Wireless Power Transfer System with Constant and Enhanced Current Output Against Load Variation and Coupling Misalignment	Hybrid wireless power transfer (HWPT) system.
Wen, Li, Zhang, Ye, Yan, Song, and Tong (2023)	Enhancing Power Transmission Stability of AUV's Wireless Power Transfer System with	A WPT system with a compact planar magnetic coupler.

	Compact Planar Magnetic Coupler	
Zhu, He, Yang, Luo, Yang, Gao, Mai and He (2023)	A Magnetic Field Concentration Enhanced I-Shaped Transmitter for DWPT System to Achieve Low Power Fluctuation	An optimized I-shaped structure.
Guo, Su, Yin, Lan and Li (2023)	Self-adaptive Resonance Technology for Wireless Power Transfer Systems to Eliminate Impedance Mismatches	A self-adaptive mistuning correction circuit.
Cai, Wang, Zhao, Luo, Yuan, Xue, Rao, Yang, Hong and Wang (2023)	Hybrid Interference Field Mitigation of Dual-Rectangular Transmitter Pad for Universal Wireless Charging Area Expansion	Hybrid interference field mitigation method.
Zhang, Lu, Zhao, Wu, Chen, and Xu (2023)	A Novel Asymmetric Magnetic Coupler Applied to Multiple-Receiver Wireless Charging System for Automated Guided Vehicles	Asymmetric flat cross-shaped solenoid magnetic coupler.
Li, Khaleghi, Hasanvand, Narayanan, and Balasingham (2024)	A New Design and Analysis for Metasurface-Based Near-field Magnetic Wireless Power Transfer for Deep Implants	Tunable metasurface (MTS)-based near-field magnetic wireless power transfer (WPT) system.

2.3.4 Critical Synthesis of Literature Findings on Magnetic Resonance Coupling (MRC)

The reviewed body of literature on Magnetic Resonance Coupling (MRC) reflects both the technological evolution and diversification of wireless power transfer (WPT) systems. While the foundational theoretical underpinnings by Maxwell (1865) laid the groundwork, modern advancements emphasise optimisation of power transfer efficiency, increased spatial freedom, and

robustness across varying environmental and load conditions. Key trends in MRC research include:

- Focus on coil design and impedance matching: Numerous studies (e.g., Beh et al., 2010; Lim et al., 2014; Miao et al., 2017) demonstrate that impedance matching remains central to achieving maximum power transfer efficiency. Adaptive and automated matching systems have become increasingly popular to accommodate dynamic load conditions and misalignments. Additionally, the shift from conventional circular or helical coils to complex geometries (e.g., dipole coils, four-resonator structures, I-shaped coils) marks a trend toward structural innovation aimed at enhancing field concentration and alignment tolerance (e.g., Park et al., 2015; Zhu et al., 2023).
- Air gap extension and omnidirectional transfer: A core limitation in early MRC systems was the efficiency drop across larger air gaps. Recent works (e.g., Rozman et al., 2017; Tian et al., 2022; Feng et al., 2022) address this by employing multi-relay configurations, rotating magnetic fields, and optimised couplers, enabling free-positioning and omnidirectional power delivery. These systems target applications such as autonomous vehicles, implantable medical devices, and smart infrastructure.
- Multi-receiver and multi-load adaptation: Several researchers (e.g., Rong et al., 2021; Luo et al., 2021) investigate the performance of systems with multiple receivers or simultaneous charging of diverse devices. These studies highlight the challenge of maintaining constant output power and efficiency across heterogeneous loads, a problem partially mitigated using feedback loops and hybrid configurations.
- Interference management and misalignment compensation: Interference fields and physical misalignments remain critical issues in practical deployments. Studies such as those by Cai et al. (2023) and Guo et al. (2023) introduce interference field mitigation and self-adaptive resonance correction, respectively. This indicates a growing concern with electromagnetic compatibility and real-world system robustness.
- Specialised applications and emerging use cases: Recent literature (Li et al., 2024; Tian et al., 2023) explores niche applications such as wireless charging for deep-body implants and microscale magnetic stimulation. These works point to the miniaturisation and medical relevance of MRC, with a focus on safety, precision, and bio-compatibility.

2.3.5 Research Gaps and Unresolved Challenges

- Limited experimental validation: Despite broad theoretical and simulated validation, relatively few studies (e.g., Tanikawa et al., 2013; Moon et al., 2016) include full-scale physical prototypes, especially for multi-receiver or omnidirectional systems.
- Trade-off between efficiency and spatial freedom: Systems optimised for wide-angle or omnidirectional transmission often suffer efficiency losses. Only a few (e.g., Feng et al., 2022) manage to balance both, indicating a need for improved optimisation algorithms or field-concentration techniques.
- Material and environmental effects: Very few studies examine how coil material properties or surrounding media (e.g., moisture, obstacles) affect magnetic resonance coupling. This introduces uncertainty when deploying WPT in real-world, variable environments.
- Circuit integration with other energy systems: Most MRC literature treats RF harvesting, capacitive coupling, or photovoltaic systems as separate tracks. There remains a significant gap in research on hybrid system integration, such as combining RF energy harvesting with MRC-based circuits, a direction this current work addresses directly.
- Positioning of the current study: This study contributes by experimentally validating an MRC-based WPT system and exploring the integration with RF energy harvesting, bridging a critical gap in practical hybrid systems. It also addresses the challenges of coil material selection, antenna optimisation, and circuit assembly, all areas underrepresented in existing literature. Furthermore, by emphasising real-world feasibility over simulation, it adds much-needed empirical insight into component performance, system layout, and device compatibility.

2.4 ENERGY HARVESTING

Energy harvesting refers to the process of capturing ambient energy from sources such as motion, heat, light, and electromagnetic radiation, providing an attractive, eco-friendly alternative for powering mobile devices (Rincon-Mora, 2011; Ramsaroop and Olugbara, 2017). Related studies on energy harvesting include powering wireless sensor networks (WSN) and the Internet of Things (IoT), and research in this area is still ongoing.

WSN is defined as a network of sensor nodes responsible for detecting physical events and transmitting their data to a sink node for further processing. Energy conservation is one of the primary concerns in the operations and applications of WSNs. Integrating harvesting units with sensor nodes offers an effective solution to the challenges of charging battery-powered sensors.

For harvesting sensors (Akbari, 2014), there are numerous readily accessible sources to be harvested, such as sunlight, wind, and RF signals. A study by Ulukus, Yener, Erkip, Simeone, Zorzi, Grover, and Huang (2015) summarises the findings on energy harvesting for wireless communications and wireless energy transfer, analysing them through the perspectives of communication theory, signal processing, information theory, and wireless networking. Energy harvesting presents new barriers for wireless communication, such as the unpredictability and variability of available energy, along with the possibility of sharing energy between nodes in a network via wireless energy transfer. This necessitates a reassessment of wireless communication protocols at the physical, medium access, and networking layers, along with a reconsideration of the core performance limits, such as channel capacity.

Ulukus et al. (2015) provided a summary of the advancements in research from an information-theoretic viewpoint on energy harvesting and the related challenges in wireless systems and wireless sensor networks (WSNs). The article further clarified that the key difference between wireless sensor networks and wireless systems is that the devices in WSNs are specifically designed to fulfill the requirements of data transmission and source acquisition. In particular, individual sensors track source acquisition by combining sensing, sampling, and compression. These processes typically demand an energy rate similar to that of radio transmission. As a result, it is crucial to allocate the limited energy resources effectively between source acquisition and transmission.

Energy harvesting offers an eco-friendly and sustainable solution to this challenge. It involves capturing ambient energy and converting it into electricity to recharge the battery/sensors. Numerous sources of ambient energy include solar energy, wind energy, tidal energy, electromagnetic energy, thermal energy, mechanical energy, and more (Divakaran, Krishna, and Nasimuddin, 2018).

Unlike thermal or kinetic energy, electromagnetic energy is not constrained by space or time. RF waves are accessible both indoors and outdoors, in both rural and urban areas, at all times of the

day. Although its power density in the environment is low, an intentional source can be introduced for more efficient power transmission, and a boosting circuit can be designed to meet the specific requirements of the load application. Table 2.8 presents an outline of the current sources of energy available for power harvesting (Tran, Cha, and Park, 2017).

8: Table 2.8: Alternative Sources of Energy to Replace Batteries (Tran et al., 2019)

Source	Harvesting Technology	Advantages	Disadvantages
Solar	Photovoltaic	High power density Mature	Not always available Requires exposure to light (not implantable) Expensive
Vibration	Piezoelectric Electrostatic Electromagnetic	Implantable High efficiency	Not always available Material physical limitation
Thermal	Thermoelectric Pyroelectric	High power density Implantable	Not always available Excess heat
RF	Antenna	Always available Implantable	Low density Efficiency is inversely proportional to distance

2.4.1 Critical Synthesis and Alignment to the Current Research

Energy harvesting (EH) represents a pivotal innovation in sustainable power generation, capturing ambient energy from sources like motion, heat, light, and particularly electromagnetic radiation, a central focus in this research. Rincon-Mora (2011) and Ramsaroop and Olugbara (2017) emphasise the eco-friendly appeal of EH as an alternative for powering mobile devices, offering a foundation

for this study's dual strategy of integrating magnetic resonance coupling and RF energy harvesting in a WPT system.

- Energy harvesting in WSN and IoT contexts: Much of the existing literature emphasises the relevance of EH within wireless sensor networks (WSNs) and the Internet of Things (IoT). These systems demand ultra-low power and long-term operation, typically hindered by battery limitations. Integrating energy harvesters, particularly from RF sources, addresses this constraint by enabling autonomous, self-powered nodes. Akbari (2014) outlines commonly harvested sources like solar, wind, and RF signals. This aligns with the experimental aspect of this research, which explores ambient RF signal collection using antennas and RF-to-DC conversion to charge small electronics.
- Information-theoretic insights into EH systems: Ulukus et al. (2015) explore the integration of EH with wireless communication systems from an information-theoretic and protocol-level perspective, identifying challenges such as energy variability and resource allocation for source acquisition versus data transmission. This perspective resonates with findings in the current study, where the RF energy harvesting circuit suffered from inconsistent energy capture due to the fluctuating nature of ambient RF availability. The variability highlighted in theory was practically experienced during circuit testing and antenna experimentation, especially with regard to achieving sufficient DC output for battery charging.

Further, Ulukus et al.'s distinction between wireless communication systems and WSNs, with WSNs demanding dual energy allocation for sensing and transmission, reinforces this study's emphasis on circuit efficiency and power allocation. In the RF harvesting circuit, output power was significantly limited by antenna selection and conversion losses, confirming the need for optimised power budgeting in EH circuits.

- RF as a viable ambient energy source: RF energy holds specific advantages in EH applications; it is omnipresent, accessible both indoors and outdoors, and available 24/7, unlike solar or thermal energy, which depend on environmental conditions (Divakaran et al., 2018). This makes RF a compelling option for continuous charging of low-power devices. However, its primary drawback, low power density, was directly observed in this study's RF harvesting circuit, where even after simulation-based design, real-world performance was constrained by low voltage output and distance from the RF source. Tran, Cha, and Park (2017) also note that

efficiency is inversely proportional to distance, a fact echoed in this research where antenna distance and orientation significantly impacted energy transfer.

- Comparison of EH Technologies: Tran et al. (2019) compare various EH technologies, with RF harvesting marked as ‘always available’ and ‘implantable’, a distinct advantage. However, its low energy density and distance sensitivity render it less efficient than alternatives like solar or vibration. In this study, RF harvesting was tested alongside magnetic resonance coupling, which demonstrated more stable voltage delivery over short distances but still suffered losses due to coil material and alignment. This practical comparison aligns with the theoretical strengths and limitations outlined in Tran’s table and validates the combined approach used in this research.

Building on this synthesis, several future research directions emerge:

- Improved antenna designs: Investigate printed or satellite-based antennas to maximise voltage output from RF harvesting.
- Material testing: Replace copper wire coils with solid copper to stabilise magnetic resonance output.
- Distance optimisation: Systematically test WPT performance over various distances and coil orientations.
- Hybrid EH systems: Explore integrated EH systems combining multiple ambient sources for improved reliability in mobile charging applications.
- Smart circuit design: Implement adaptive power management ICs that optimise RF energy conversion based on environmental input and load demand.

2.5 MODELS OF ENERGY HARVESTING

This section examines energy harvesting for network architectures, node distributions, and accurate channel/inference models. A Mobile Ad Hoc Network (MANET) is a flexible wireless network in which mobile nodes operate independently or on an ad hoc basis, without relying on a fixed infrastructure. MANETs are self-organising and self-healing, allowing peer-to-peer communication between mobile nodes without depending on centralised resources or secure infrastructure (Ulukus et al., 2015). Nodes in a MANET are usually compact devices, such as sensors and wearable computing devices. Due to their positioning environment, the energy influx

processes at various transmitters are anticipated to exhibit random patterns, known as the energy arrival state. It is inferred that the batteries of energy harvesters have an unlimited capacity.

The issues connected with the MANET model include high node density and power levels, which may cause considerable interference and potentially breach the outage constraint. (Huang, 2013).

Hung (2013) examines the impact of spatial variations in renewable energy sources, such as solar or wind power, on the coverage of cellular networks. Huang et al. (2013) introduced a passive energy field model, where the energy at a specific location is determined by the spatial aggregation of Poisson-distributed energy midpoints, with fixed peak concentrations depicted as Boolean random functions. Consequently, harvesters are not able to transmit high-voltage power. Energy transmission losses may become substantial as the number of harvesters used for energy accumulation grows.

The cognitive radio network model, explored by Lee, Zhang, and Huang (2013), enables dormant secondary nodes to efficiently access the spectrum of primary nodes and harvest energy from radiation whenever feasible. Concurrent networks are modelled as superimposed spatial point processes. The transmission capacity of the secondary network, based on an effective energy harvesting strategy, is evaluated and optimised in terms of node density and transmission power.

Huang and Lau (2014) presented a model of cellular networks where mobile devices are wirelessly recharged through dedicated power stations using microwave power transfer (MPT). This model utilised a stochastic geometric method for network modelling and examination. The provision of resources in the MPT network architecture was examined for different MPT strategies.

Dhillon, Li, Nugehalli, Pi, and Andrews (2014) introduced a heterogeneous cellular network model incorporating energy harvesting, where multi-tier renewable-powered base stations (BSs) are modelled as independent Poisson point processes (PPPs). Small base stations, deployed in urban areas, assume independent energy influx processes for BSs, enabling the on/off states of BSs to be represented as independent Bernoulli random variables. Their effect on network coverage performance can be analytically assessed using stochastic geometry.

Energy harvesting systems generally operate over short distances, where the energy consumed by the transmitter/receiver circuitry may be equivalent to or even surpass the energy used for transmissions. The difficulty in creating a comprehensive model for total energy minimisation lies

in developing circuitry energy consumption models that are both analytically manageable and accurate enough to offer meaningful estimates of overall energy usage. Youssef-Massaad et al. (2008) and Cui et al. (2005) examined models in which transmitters and receivers operate as black boxes, consuming a constant amount of energy per unit time while powered on. Although the studies vary considerably, they produce similar results. Systems in the powered-on state consume circuit energy; therefore, both the receiver and transmitter must remain powered off for a certain period to minimise circuit energy consumption.

2.5.1 Critical Synthesis of Energy Harvesting in Wireless Network Architectures

The integration of energy harvesting (EH) into wireless networks has been extensively studied in the context of dynamic and heterogeneous architectures such as Mobile Ad Hoc Networks (MANETs) and cellular networks. These studies collectively contribute to the understanding of how EH mechanisms can sustain wireless communication, yet they also highlight important limitations and trade-offs that need to be addressed.

- Flexibility and decentralisation in MANETs: Ulukus et al. (2015) emphasise the self-organising nature of MANETs, which allows for decentralised communication without reliance on fixed infrastructure. This flexibility makes them suitable for EH implementation, especially in environments lacking stable power sources. However, this same flexibility introduces high levels of spatial and temporal unpredictability in energy availability. The assumption of unlimited battery capacity in such models is a clear oversimplification, as real-world EH devices often face stringent storage and capacity constraints. Furthermore, as Huang (2013) notes, high node density and power levels in such networks can result in substantial interference, potentially violating outage constraints and degrading overall network performance.
- Spatial modelling and renewable energy variability: Huang et al. (2013) advance the field by modelling energy availability as a passive energy field derived from Poisson-distributed midpoints and Boolean random functions. This spatial stochastic approach acknowledges the variability of renewable energy sources (e.g., solar, wind), but introduces a critical challenge: as the number of harvesters increases, so do energy transmission losses, diminishing the efficiency of large-scale EH deployment. These insights highlight the inefficiencies associated

with energy aggregation and suggest that more sophisticated routing and energy-sharing mechanisms may be needed in dense environments.

- Cognitive radio and opportunistic EH: The work of Lee, Zhang, and Huang (2013) on cognitive radio networks introduces the concept of spectrum sharing and opportunistic energy harvesting. Secondary nodes in such systems dynamically exploit both spectral gaps and radiative energy from primary users. Their modelling of concurrent networks as superimposed spatial point processes reveals the importance of node density and transmission power in optimizing EH performance. However, this model assumes a level of predictability and responsiveness in spectrum access that may not be feasible in congested or heavily regulated frequency environments.
- Dedicated microwave power transfer (MPT) in cellular networks: Huang and Lau (2014) shift the focus to structured cellular environments, where mobile devices are recharged using dedicated MPT stations. Their use of stochastic geometry to evaluate different power transfer strategies provides a valuable analytical framework. Yet, while promising in theory, the real-world implementation of such MPT systems raises questions of cost, safety, beamforming precision, and regulatory compliance, particularly in urban and residential areas.
- Heterogeneous cellular networks and tiered energy sources: Dhillon et al. (2014) introduce a multi-tier cellular architecture powered by renewable energy sources. By modelling base stations (BSs) as independent Poisson Point Processes (PPPs) with on/off states represented as Bernoulli random variables, they offer an elegant method for analysing energy-aware network performance. However, the assumption of independence in BS energy influx processes may fail in scenarios where environmental conditions (e.g., sunlight, wind) are spatially correlated. This could result in synchronous power deficits, affecting large portions of the network simultaneously.
- Circuit energy consumption and transmission efficiency: Youssef-Massaad et al. (2008) and Cui et al. (2005) take a more granular approach by examining circuit-level energy consumption. Their models treat transmitters and receivers as black boxes consuming constant power when active. They argue convincingly that total energy minimisation requires duty-cycling, i.e., strategically powering down nodes to save circuit energy. While useful, these models often assume uniform hardware characteristics, neglecting the diversity in power profiles across different wireless devices and EH modules.

2.5.2 Overall Implications

The critical synthesis of these models and findings reveals a central tension in the design of EH-enabled wireless networks: the trade-off between theoretical scalability and real-world viability. Stochastic geometric models provide powerful tools for abstraction and performance evaluation, but they often rely on assumptions (e.g., unlimited storage, independent energy arrivals, ideal antenna performance) that may not hold in practice. Future research must strive to bridge this gap by:

- Integrating empirical data from field deployments into existing models.
- Exploring adaptive EH strategies that respond to environmental and network state in real-time.
- Developing energy-aware routing protocols that account for both harvested energy and circuit energy consumption.
- Testing multi-source EH systems (e.g., combining solar, RF, and kinetic sources) to reduce dependency on any single energy modality.

By aligning analytical modelling with the constraints of real-world hardware and environmental variability, researchers can move closer to deploying robust, self-sustaining wireless networks supported by energy harvesting. The reviewed studies offer conceptual and analytical insights that complement the practical findings of this research in the following ways:

- Random energy arrival in MANETs: Inconsistent voltage from RF sources.
- Energy aggregation leads to losses: Antenna type impacts voltage harvesting.
- Opportunistic spectrum access for EH: Ambient RF energy is insufficient without an optimal antenna.
- Dedicated MPT requires optimal placement: Coil distance and layout affect power transfer efficiency.
- Circuit energy outweighs transmission energy: Layout inefficiencies limited soldering and reduced voltage.
- Tiered network energy influx: Modular hybrid WPT system mimics this multi-source design.

These alignments validate the need for a more integrative and context-aware design of WPT systems. Future work should draw directly from stochastic and circuit models while addressing real-world limitations such as:

- Component accessibility.
- Antenna performance in diverse environments.
- Energy storage and circuit design constraints.
- Hybrid system stability under changing environmental conditions.

By doing so, theoretical models can be grounded in experimental realities, enhancing the viability of WPT systems for practical applications such as mobile device charging.

2.6 RF ENERGY HARVESTING

Radiofrequency (RF) energy refers to radio waves, a form of electromagnetic energy consisting of waves of electric and magnetic energy traveling together (radiating) through space. The region where these waves exist is known as an electromagnetic field.

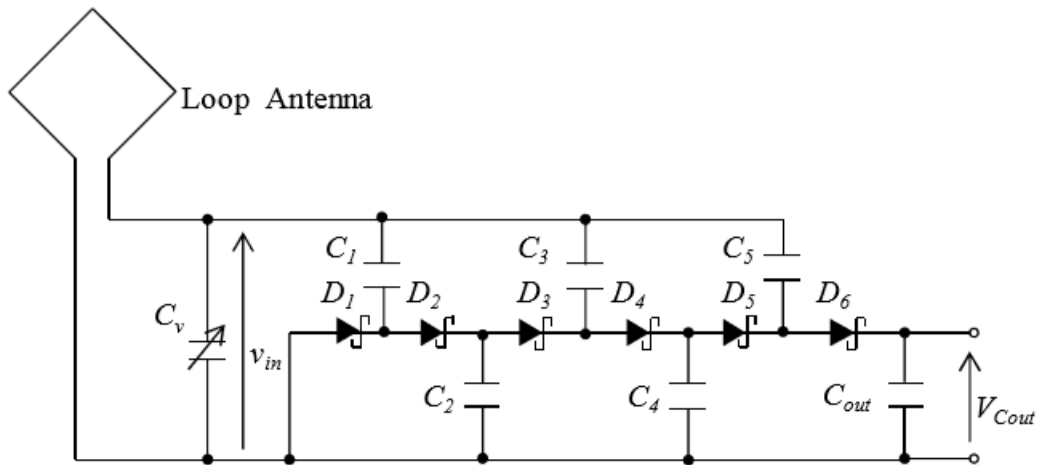
The development of RF power scavenging in free space began in the late 1950s with a microwave-powered helicopter system (Brown, 1969). The discovery of electromagnetic radiation traces back to Heinrich Hertz's experiments from 1886 to 1888, in which he demonstrated the existence of electromagnetic waves and radio waves. His experiments exhibited the propagation of electromagnetic waves in open space using parabolic reflectors at both ends of the setup, which facilitated the transmission and reception of radio waves. These experiments have a range of similarities with recent studies on RF energy harvesting. The original concept of wireless power transmission, grounded in the prediction and detection of radio waves, emerged in the late 19th century (Escala, 2010; Carlson, 2013).

In the late 19th century, Nikola Tesla outlined the idea of transmitting electrical energy between two points without a physical connection to a power source as being of all-surpassing importance to man (Tesla, 1904). Tesla built upon Heinrich Hertz's experiments by inventing the Tesla coil in 1891. This device included an air gap between the primary and secondary coils, along with a movable iron core that could be positioned differently inside or outside the coil (Cooper, 2015). The coil was connected to a 200-foot-high pole with a 3-foot-diameter sphere at its peak. The Tesla coil operated with approximately 300 kW of power. It oscillated at 150 kHz, with the RF potential

at the upper terminal reaching 100 MV. The experiment was not successful because the transmitted power was spread in all directions at 150 kHz, corresponding to a wavelength of 21 km (Brown, 1984).

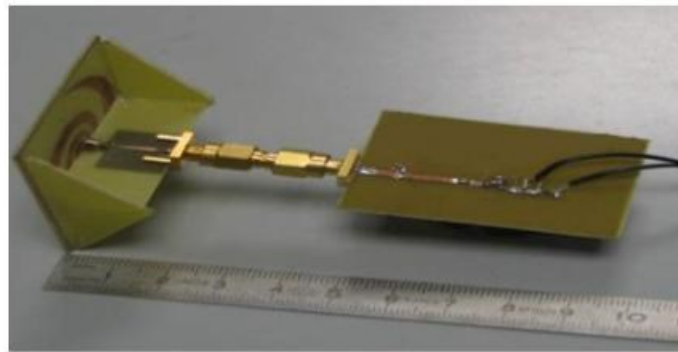
For mobile and compact electronic devices, a potential solution involves capturing and storing energy from external ambient sources, a technology referred to as energy harvesting. This technology is also referred to as power harvesting, energy scavenging, or free energy, as it harnesses energy from renewable sources (Sivaramakrishnan and Jegadishkumar, 2011). Energy harvesters collect fuel from ambient sources, making them cost-free for the user. Varieties of ambient sources considered and utilised for energy harvesting include wind, solar, vibration, electromagnetic, temperature gradient, thermoelectric, heel strike, push buttons, Radio Frequency (RF), acoustic, and more (Jabbar, Seong, and Jeong, 2010).

Muramatsu and Koizumi (2010) developed an RF energy harvesting circuit that combined a 6-stage Dickson charge pump with a loop antenna (Figure 2.41). The circuit harvested 60.2 μJ in thirty minutes from 954 kHz RF during the field experiment. The attained energy was insufficient to power a sensor node. When the energy storage element was switched to a larger capacitor and charged for a longer period, the harvested energy allowed the nodes to function for several hours or even days.



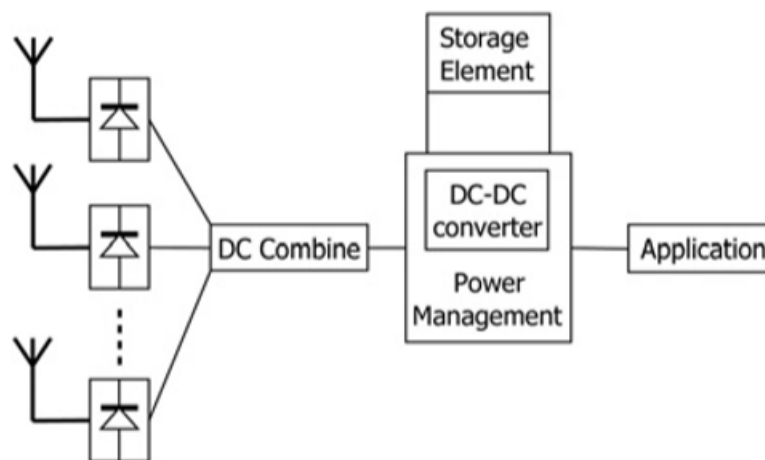
41: Figure 2.41: RF Energy harvesting circuit with 6-stage Dickson charge pump and loop antenna (Muramatsu and Koizumi, 2010)

Bouchouicha, Latrach, Dupont, and Ventura (2010) presented a study of energy harvesting (Figure 2.42) feasibility in an urban area. Despite the optimisation of rectennas mentioned in this research study, the measurements made in urban RF power density conditions produced very low DC energy, even on a wide frequency band. The energy harvested was too low to supply an electronic application. However, this energy could be stored for later use. To increase the DC power scavenged, the RF input power must be increased by using antenna arrays and/or a specific emitting source to charge the micro batteries for wireless sensors.



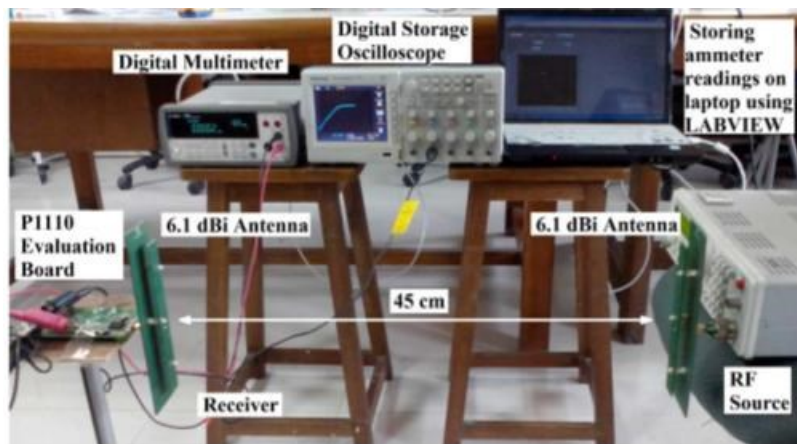
42: Figure 2.42: RF energy harvesting circuit with a rectenna (Bouchouicha et al., 2010)

Olgun, Chen, and Volakis (2012) demonstrated an efficient rectenna system that generated battery-like voltage to run low-powered consumer electronics. The design (Figure 2.43) generated a DC voltage with received power being as low as -40dBm, thus resulting in the system operating with small amounts of available RF energy. The experiments demonstrated the powering of a temperature and humidity meter with positive results.



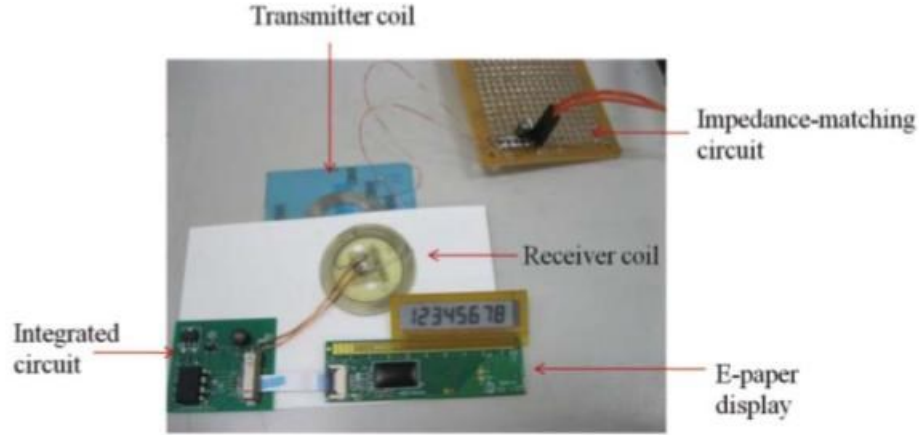
43: Figure 2.43: Rectenna system (Olgun et al., 2012)

Research conducted by Mishra, De, and Chowdhury (2015) focused on the charging behaviour of the RF energy transfer (RFET) system (Figure 2.44). The research study resulted in the development of analytical expressions for capacitor voltage, charging time in constant power charging, and charging time distribution as a function of the residual voltage. The experimental results for constant power charging included the charging of a supercapacitor via a dedicated RFET. The outcome of this research resulted in the development of the RF charging equation and charging time distribution as a function of residual voltage distribution. Nodal charging time distribution was derived for uniform and truncated normally distributed residual voltages, demonstrating that the charging time distribution does not necessarily follow the underlying residual voltage distribution.



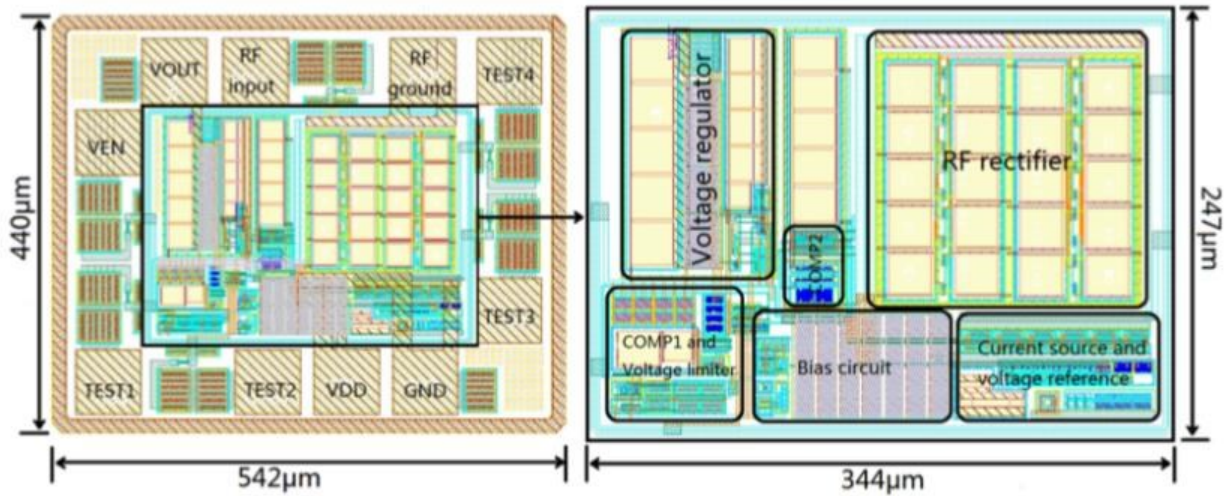
44: Figure 2.44: RFET charging system (Mishra et al., 2015)

Chang, Yen, Huang, and Chen (2015) developed an RF harvesting system based on an E-paper display incorporated in a smart card to improve the efficiency of power transmission (Figure 2.45). This system fulfilled the power demands for gap distances up to 4.3mm. The complete harvesting system included a small-radius coil of 13 turns of wire, namely the transmitter. The receiver coil comprised 10 turns. The transmitter coil was considerably larger than the receiver coil. For an increase in magnetic flux density and to improve transmission efficiency, an iron core was inserted above the coils to pull the magnetic field lines through the centre of the coils. The overall experimental results revealed that transmission efficiency has to be larger than 5.1 dB to ensure sufficient power is available to drive the circuitry on the smart card. The smart card received 220mW of RF power, with a loss of 30.0mW during the transmission process and a transmission efficiency of 88.0%.



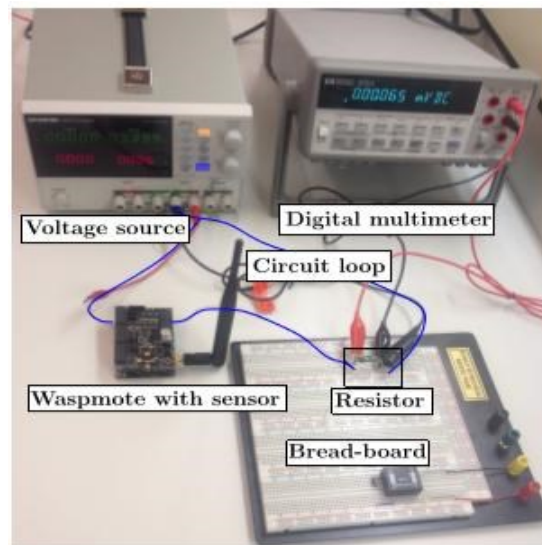
45: Figure 2.45: RF Energy Harvesting for E-paper Display (Chang et al., 2015)

Liu, Mu, Ma, Tu, Zhu, and Yang (2016) proposed a 915-MHz RF energy harvester system based on an SMIC 65-nm standard CMOS process (Figure 2.46). The RF energy harvesting circuit consisted of a multistage self-compensated rectifier and an ultra-low-power management unit (PMU). The RF energy harvester exploited the threshold voltage compensation and low charge-mode current consumption techniques that reduced the input sensitivity as low as 21.4dBm. The low-power voltage regulator with DFC compensation within the proposed harvester outputs 1V DC voltage and 10mA current for other portable or battery-less devices. According to the researchers, this design can be considered for the design of future RF-powered wireless sensor networks.



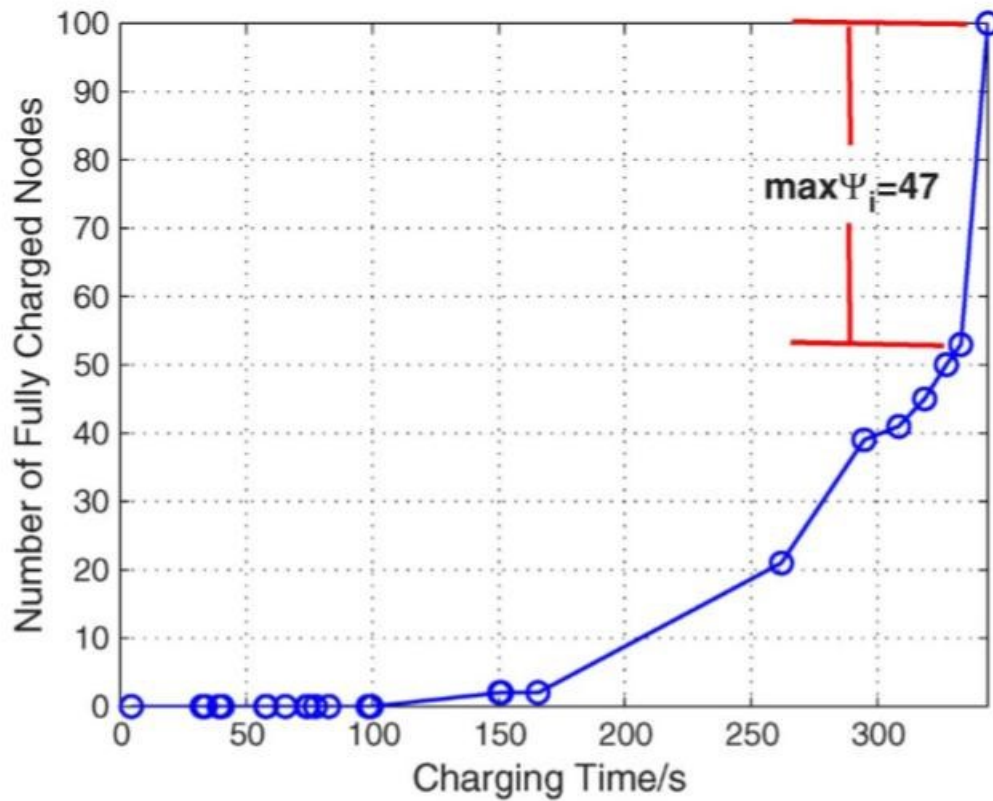
46: Figure 2.46: Proposed RF Energy Harvester on SMIC 65-nm CMOS process (Lui et al., 2016)

Mishra and De (2016) proposed a renewable energy cycle (REC) circuit (Figure 2.47) whereby the RF charging period and node lifespan terms for the supercapacitor structure were derived. Theoretically, due to a duality principle, constant-power loading time was derived from the RF charging time characteristics of the supercapacitors. A sustainable green sensor network based on a pollution-monitoring network was utilised in the experimental setup. Numerical results revealed a reduction of 28.80%. The developed models and observations presented by Mishra and De (2016) were noted to be beneficial in accurately planning and estimating the performance of green energy harvesting sensor networks.



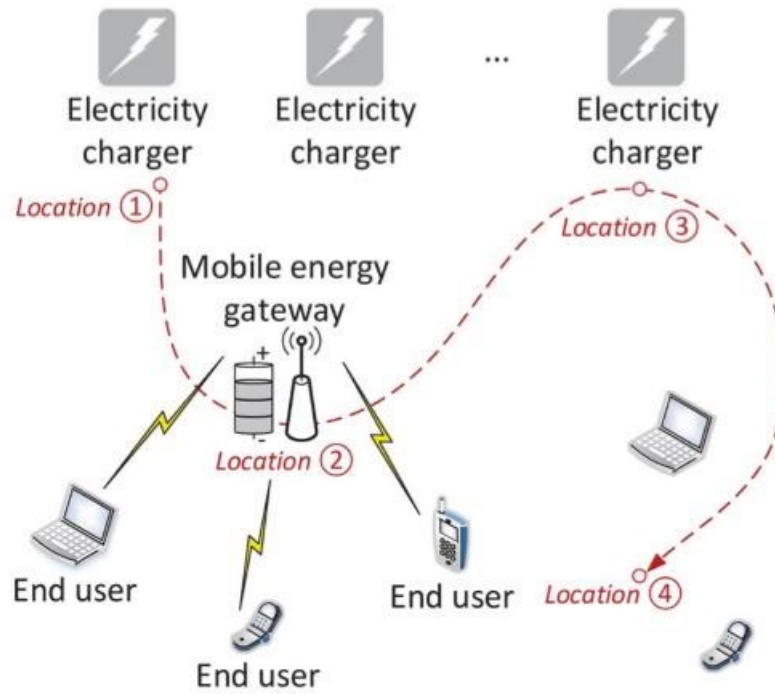
47: Figure 2.47: REC for Sustainable Sensor Network (Mishra and De, 2016)

Fu, Cheng, Gu, Chen, and He (2016) researched distributing energy between sensor nodes in a network. A theoretical and computational analysis was carried out using the linear programming (LP) method. The simulated experiments included randomly deployed sensor nodes, where a reader moved as a point way in the network and stayed for some duration at each location (Figure 2.48), respectively, to charge the nodes. The results of the simulation would be beneficial in a sensor node environment for charging each node in the network, thus keeping it operable.



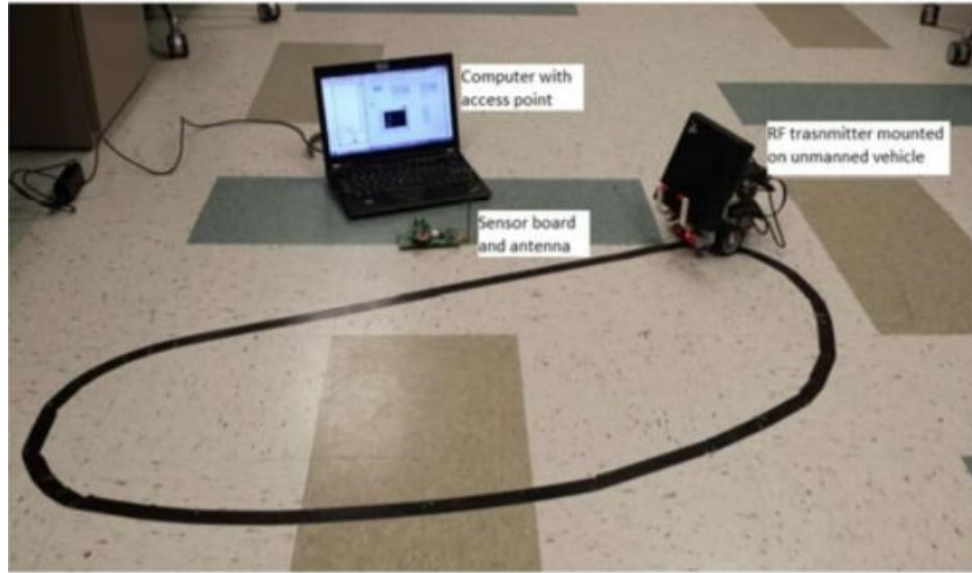
48: Figure 2.48: Charging Performance of the Reader (Fu et al., 2016)

Zhang, Niyato, Wang, and Kim (2015) proposed a mobile charging gateway system whereby users could request RF energy to charge their mobile devices for a fee. The mobile network consisted of fixed wireless chargers, namely the energy suppliers, an energy gateway, i.e., an energy messenger, and users or the energy consumers (Figure 2.49). Fixed time slots for charging were provided by the energy gateway. Signals were sent to the end users via the energy gateway to commence and terminate the energy transfer, resulting in identical durations for all the end users receiving energy. The Markov decision process (MDP) model was used to obtain the energy management policy (to charge or transfer) of the energy gateway.



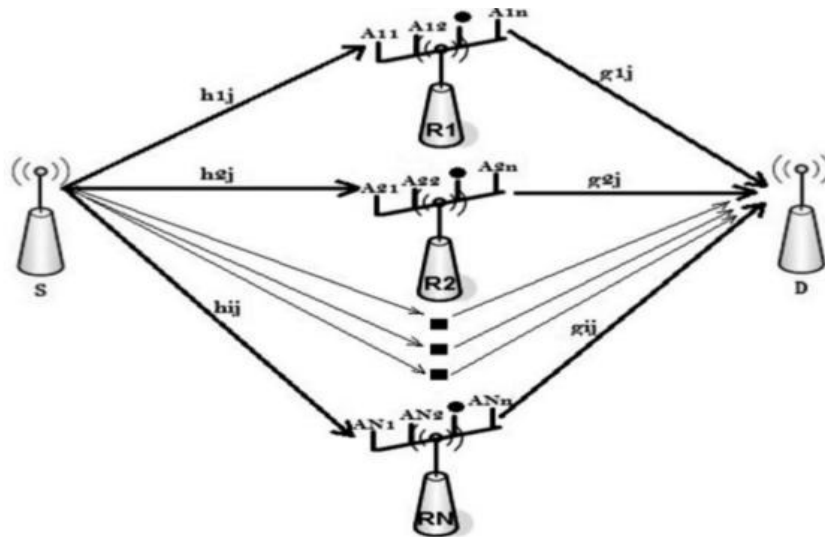
49: Figure 2.49: Mobile Charging Gateway System (Zhang et al., 2016)

Research conducted by Sangare, Xiao, Niyato, and Han (2017) considered the RF energy transfer-based wireless sensor networks in which each sensor was installed with an antenna or antenna array that can convert RF signals into electrical energy. A corresponding prototype was created to establish the path planning and mobile charge scheduling (Figure 2.50). The study was similar to research conducted by Zhang et al. (2015), where a mobile charging gateway was created based on the Markov decision process (MDP) model. Research conducted by Sangare et al. (2017), however, focuses on a wireless-powered sensor network consisting of a set of sensors powered by the energy transferred from a Mobile Energy Station (MES) without any payment or transaction.



50: Figure 2.50: Mobile Energy Station (Sangare et al., 2017)

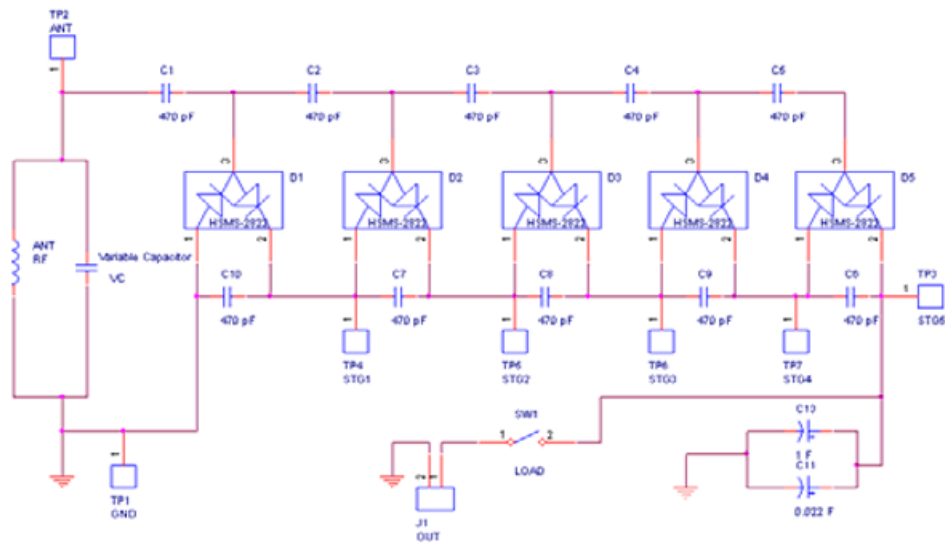
A multi-relay and multi-antenna scheme (Figure 2.51) was proposed by Albaaj, Makki, Alabkhat, and Zahedi (2017) for improving energy harvesting and the throughput of the communication system in delay-tolerant and delay-limited system conditions. The results of the simulated model revealed an effect on communication system performance, and the time and power needed for energy harvesting decreased. The results further displayed that improvement in the performance of the system is linearly proportional to the number of relays and the number of antennas.



51: Figure 2.51: Design of the multi-antenna system (Albaaj et al., 2017)

A study by Zeng, Wang, Zheng, Kainz, and Chen (2017) examined antenna design for RF energy harvesting. A compact fractal loop rectenna for RF energy harvesting was introduced for operation in the GSM1800 bands. The rectenna design featured a fractal loop with a novel in-loop ground plane (ILGP) for impedance matching. The design incorporated a high-efficiency rectifier based on the full-wave Greinacher circuit. The results demonstrated that the rectenna could transfer charge to an LCD watch without a battery at a distance of 10 meters from a cell tower. This rectenna is considered advantageous for various energy harvesting applications.

Aminov and Agrawal (2014) demonstrated an RF energy harvesting system. The system (Figure 2.52) consists of an antenna, a matching circuit, five stages of voltage doubling, and a storage capacitor. Based on supporting studies and analysis, it has been established that far-field RF energy harvesting is feasible when the circuit's centre frequency is focused on the medium wave frequency band, operating between 531 and 1,611 kHz. Limitations on the amount of energy harvested in an RF energy harvesting system are determined by the strength of the RF field, the performance of the antenna, and the efficiency of the multiplier circuit. The system can harvest RF energy from a local AM radio station by orienting the loop antenna toward the station's location. The system successfully harvested enough energy to charge a supercapacitor to 2.8 V and maintain the voltage when no load was connected to the circuit. This charge is sufficient to power a 1 k Ω load for approximately one hour.



52: Figure 2.52: Five-stage voltage doubler circuit (Aminov and Agrawal, 2014)

Xu, Yang, Yang, Zhao, and Li (2017) explored the design of real-time wireless information and power transfer (SWIPT) systems. Wireless power transfer using RF signals was introduced as an alternative method for charging wireless sensor networks. RF signals are currently used for wireless information transfer, enabling the transmission of data without physical connections. The combination of wireless power transfer and wireless information transfer leads to simultaneous wireless information and power transfer (SWIPT) (Varshney, 2008; Grover and Sahai, 2010; Zhang and Ho, 2013). SWIPT systems utilise RF signals to simultaneously transmit information to information receivers and deliver power to energy receivers. SWIPT system architectures have been studied in various scenarios. Zhang and Ho (2013) investigated broadcast channels, while Nasir, Zhou, Durrani, and Kennedy (2013) examined relay channels. Park and Clerckx (2014) and Ozelikkale and Duman (2015) proposed interference channels, whereas Huang and Larsson (2013) studied orthogonal frequency division multiple access (OFDMA) systems. According to Xu, Ozelikkale, McKelvey, and Viberg (2017), the challenge with a non-linear energy harvesting model is that measurement data are typically available only for a limited range of input power values.

Sangare and Han (2017) described the fifth generation (5G) of mobile technology as expected to enable a fully mobile and connected society, addressing the growing demands for higher frequency and mobility diversity, improved throughput, lower latency, and significantly enhanced connectivity density compared to 4G. The article further elaborated on the growing prevalence of smart services in urban areas, including metering, city and building light management, environmental monitoring, and traffic control. The integration of these services into high-density devices with diverse characteristics is expected to be unified within a shared communication and internet framework. This ultimately necessitates the development of ultra-low-cost devices with extended battery life. In WSNs, a key challenge is replacing batteries in sensors distributed over large areas. Xiao, Wang, Niyato, Kim, and Han (2015) proposed wireless energy harvesting as an alternative to batteries, utilising methods such as capacitive coupling, inductive coupling, magnetic coupling, or RF energy.

The radio signal sources used to power WSNs can be either dedicated, where energy is supplied through a specific bandwidth for operating designated sensors (Sangare, Arab, Pan, Qian, Khator, and Han, 2015), or ambient, where energy is freely harvested from atmospheric sources not

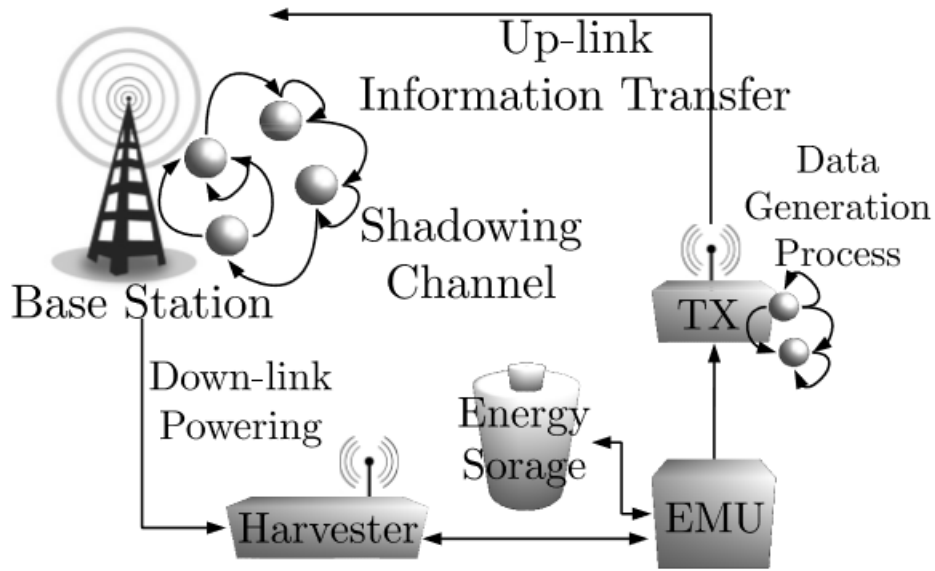
originally intended for energy transfer. Sangare and Han (2017) categorize these energy sources into two types: static RF sources and dynamic RF sources. Static RF sources include transmitters that emit relatively stable power over a specific period, such as TV and radio towers. The challenges associated with static RF sources include both long- and short-term instabilities caused by service schedules and signal attenuation. Dynamic RF sources include transmitters that operate intermittently or with varying transmission power over time, such as Wi-Fi access points and licensed users in a cognitive radio environment. The challenge with dynamic RF sources lies in their unpredictability, making them difficult to measure and integrate effectively. Consequently, the harvester must be adaptive and intelligent to efficiently seek out energy harvesting opportunities within a specified frequency range (Sangare and Han, 2017).

A research study conducted by Corte, Merenda, Bellizzi, Isernia, and Carotenuto (2018) was based on the effects of temperature on the conversion efficiency of Dickson charge pumps (Figure 2.53) used in energy harvesting rectennas. The results of the experimental study revealed that temperature has a significant influence on the circuit efficiency, with the temperature ranging from 25 °C to 85 °C. Further, the results revealed that when a Schottky diode was included with the 2-stage Dickson charge pump circuit, the efficiency increased.



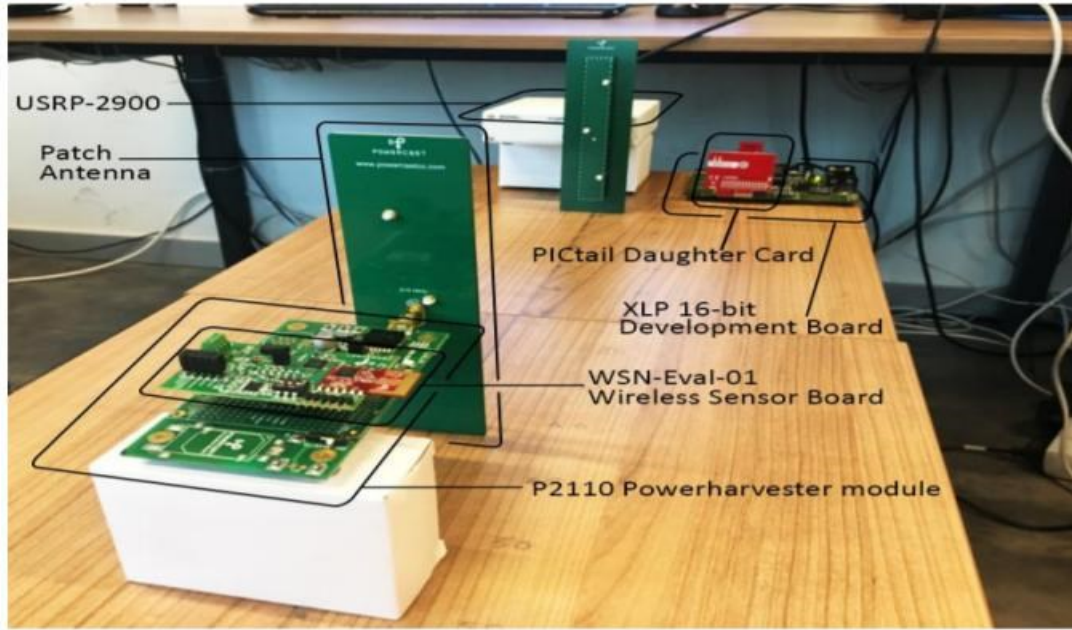
53: Figure 2.53: Simulation setup of the Dickson charge pump circuit (Corte et al., 2018)

Valentini, Levorato, and Santucci (2018) presented an optimisation framework for battery-equipped wireless sensors powered by RF energy harvesting (Figure 2.54). The optimisation issue aims to control the interchange between average throughput and battery degradation. The non-linear behaviour of the harvesting circuitry was considered in the system model. Markov Decision Process (MDP) theory was included in the RF energy harvesting model, where the resulting policy-controlled data transmission and battery connection to the energy harvester. Numerical results revealed the relationships between the statistical characterisation of key constraints.



54: Figure 2.54: Optimisation Framework for the RF Energy Harvester (Valentini et al., 2018)

To measure the charging times of the RF energy harvesting with Frequency Shift Keying (FSK) modulated signal, Cansiz (2019) established an advanced measurement system (Figure 2.55). The advanced measurement system consisted of an NI USRP-2900, P2110 Powerharvester module, WSN-Eval-01 Wireless Sensor Board, an XLP 16-bit Development Board, a PICtail Daughter Card, and Patch Antennas. According to the measurement results, the shortest charging time was measured as 1.00 s at a distance of 20 cm, and the longest charging time was measured as 7.00 s at a distance of 60 cm. It was determined that as the distance decreased, the charging time of RF energy harvesting reduced.



55: Figure 2.55: FSK Measurement System (Cansiz, 2019)

2.6.1 Critical Synthesis of RF Energy Harvesting

RF energy harvesting has evolved from theoretical foundations laid by pioneers like Hertz and Tesla into a viable subfield within wireless power transmission (WPT). While the early experiments, such as Tesla's high-frequency wireless power attempts, lacked directionality and efficiency, contemporary systems leverage advances in rectenna design, charge-pump circuits, and low-power electronics to scavenge RF energy from ambient or dedicated sources.

Numerous studies reviewed in this section highlight the technological progress and limitations of RF energy harvesting. Experiments like those of Muramatsu and Koizumi (2010) and Bouchouicha et al. (2010) confirm the feasibility of harvesting energy from ambient RF sources but underscore a common limitation: low energy yield, especially in urban environments with weak signal strengths. Similarly, Olgun et al. (2012) and Chang et al. (2015) achieved higher efficiency by using focused rectenna systems and specific antenna configurations, indicating the necessity for design-specific tuning and optimization.

Efforts such as the Mishra and De (2015, 2016) studies extended this work into modelling and energy storage, highlighting how RF energy can support intermittent operation of sensor nodes via supercapacitor charging. This makes RF harvesting more suitable for low-power, duty-cycled applications like IoT and wireless sensor networks (WSNs), rather than high-demand loads.

Advanced studies like those by Zhang et al. (2016) and Sangare et al. (2017) introduced economic and mobility models into RF harvesting systems, such as mobile gateways and energy scheduling, reflecting a shift toward integrated WPT ecosystems. The adoption of Markov Decision Process (MDP) modelling shows how resource allocation and energy efficiency are now central research concerns. Meanwhile, Aminov and Agrawal (2014), Zeng et al. (2017), and Cansiz (2019) addressed improvements in rectifier circuits, antenna designs, and measurement precision, offering incremental but vital enhancements to practical RF harvesting applications.

Despite these developments, practical challenges persist, particularly regarding low energy conversion efficiency, distance sensitivity, and environmental dependency. Solutions such as antenna arrays, multi-relay systems (Albaaj et al., 2017), and printed or fractal antennas (Zeng et al., 2017) offer improvements, but often at the cost of complexity and scalability.

2.6.2 Alignment to this Research Study

This review directly supports the research study's focus on hybrid WPT systems by validating RF energy harvesting as a viable complementary method to magnetic resonance coupling. It justifies the proposed integration of RF energy harvesting circuits with magnetic-based WPT systems, especially for extending charging capabilities in scenarios where inductive coupling is not feasible (e.g., for low-power remote sensors or intermittent devices).

Furthermore, the documented issues with antenna selection, low output voltages, and charging time variability reinforce the experimental challenges encountered during this study, specifically, the difficulty in choosing efficient antennas and achieving sufficient energy capture to power real-world loads. These correlations validate the research design and highlight clear pathways for future development, such as investigating printed antennas or adaptive RF harvesting circuits.

In summary, Section 2.6 establishes a strong foundation for the study's proposed future work: developing a hybrid WPT system that leverages both magnetic resonance and RF energy harvesting to broaden application potential, particularly in off-grid and sensor-based networks.

2.7 RESEARCH RELATED TO RECTENNAS

The bandwidth of an antenna is the range of frequencies at which the antenna can operate efficiently. A wide bandwidth antenna can collect signals from a wider range of frequencies than

a narrow bandwidth antenna. Hence, a wide bandwidth antenna is advantageous in retrieving incident energy but presents a high risk of interference by noise through unwanted frequencies (Tran, Cha, and Park, 2017).

The term ‘rectenna,’ coined by Brown (1984), is derived from combining the words ‘rectifying circuit’ and ‘antenna.’ A rectenna is a passive component connected to a diode that can receive and convert microwave power into DC, allowing it to operate without an external power source. There is a vast body of literature exploring the rectenna concept.

According to related research, different types of antennas can be used in a rectenna circuit. A dipole antenna, consisting of a straight electrical conductor measuring half a wavelength in length and connected at the centre to a radio frequency source (Brown, 1984; Degenford, Sirkis, and Steier, 1964), can function within a rectenna. A Yagi-Uda antenna, a directional antenna commonly used in communications at frequencies above 10 MHz (Gutmann and Gworek, 1979; Shinohara, Kunimi, Miura, and Matsumoto, 1998), can also function within a rectenna circuit.

A microstrip antenna, also known as a printed antenna, is fabricated using microstrip techniques on a printed circuit board (PCB) (Ito, Fujino, and Fujita, 1993; Fujita, Kaya, Kunimi, Ishii, Ogihata, Kusaka, Fujino, and Ida, 1996). A monopole antenna consists of a straight, rod-shaped conductor, typically mounted vertically above a conductive surface known as a ground plane (Shibata, Aoki, Otsuka, Idogaki, and Hattori, 1997). A loop antenna is a radio antenna composed of a loop or spiral of wire, tubing, or another electrical conductor, with its ends connected to a stable transmission line. Small loop antennas have low radiation resistance, leading to poor efficiency, and are primarily used as receiving antennas at low frequencies (Gutmann and Gworek, 1979; Strassner and Chang, 2002).

A coplanar patch consists of a patch surrounded by a closely spaced ground conductor and a coplanar waveguide (CPW) feed line, which has a geometric structure similar to a loop slot antenna (Chin, Xue, and Chan, 2005). The spiral antenna (Hagerty, Lopez, Popovic, and Popovic, 2000) and the parabolic antenna utilize a parabolic reflector, a curved surface with a cross-sectional shape of a parabola, to focus and direct radio waves. The final structure takes the form of a dish and is commonly known as a dish antenna or parabolic dish (Fujino and Ogimura, 2004).

Vullers, Schaijk, Doms, I., Van Hoof, and Mertens (2009) proposed a device for RF energy harvesting. The device consisted of an array of rectennas, i.e., rectifying antennas connected to a rectifying circuit for charging a battery. The RF-harvesting battery charger includes an array of optically transparent folded-dipole antenna elements realised on foil. This enables sticking the large area RF collector to a window without compromising the window function. The results of the study showed the feasibility of the components within the RF charger with an array of microstrip rectenna elements of 1.6 mm thick FR4, operating at 2.45 GHz.

Malisuwan, Tiamnara, and Suriyakrai (2017) proposed a microstrip antenna design of rectenna for a WPT system for LTE/WLAN with a resonant frequency of 1.88 GHz (TDD-LTE band number 35) and another rectenna with a resonant frequency of 2.45 GHz (ISM band). The proposed antenna with the resonant frequency of 1.88 GHz had a -24 dB return loss, and the antenna that resonates at 2.45 GHz had a -25 dB return loss. The conversion efficiency of the fabricated antennas was measured as 38% and 35%. In this research, the rectifying circuit was used to improve the RF-DC conversion efficiency.

Awais, Jin, Chattha, Jamil, Qiang, and Khawaja (2018) presented an innovative coplanar waveguide-fed rectenna with high efficiency for 2.45-GHz Bluetooth or wireless local area network applications. A compact rectenna circuit containing an efficient antenna with a peak gain of 5.6 dB and Schottky diode HSMS-2850-based rectifying circuitry was designed and tested at the 2.45 GHz frequency band. The proposed antenna has a wide measured bandwidth from 0.9 GHz to more than 9 GHz. The proposed rectifier achieved 75.5% simulated and 68% measured conversion efficiencies, respectively, at the WLAN 2.45 GHz band. According to the researchers, embedding the developed rectenna circuit in electronic gadgets reduces the charging requirement for the next-generation IoT devices and is also able to provide battery-less operation for devices with power requirements of 150 mW or less.

Kumar and Sathya (2019) presented an ultra-wideband rectenna for RF energy harvesting in ambient energy. The rectenna consists of a rectangular patch along with a rectifier circuit at the bottom of the same plane. The rectenna gives a -10 dB wide impedance characteristic of 1200 MHz (12 GHz-2.4 GHz) in the L band with a peak gain of 5 dB in the operating band. At 81% in the operating band, it is more suitable for energy harvesting applications.

Table 2.9 (Tran et al., 2017) summarises related literature regarding power-harvesting antennas. The power conversion efficiency (PCE) is the ratio between the amount of power applied to the load and that retrieved by the antenna.

9: Table 2.9: Summary of related literature on Power Harvesting Antennas

Author(s)	Type	Gain (dBm)	Frequency (GHz)	RF-DC PCE
Momenroodaki et al. (2016)	Air-substrate patch	7	2.45	30% @ 1 $\mu\text{W}/\text{cm}^2$
Lu et al. (2016)	Polarisation patch	-	5.1 – 5.8	23.8% - 31.9%
		-	5.8 – 6.1	22.7% - 24.5%
Sun (2016)	Patch	-	2.45	73.9% @ 207 $\mu\text{W}/\text{cm}^2$
Sun and Geyi (2016)	Dual-linearly polarised patch	7.45 – 7.63	2.45	78% @ 295.3 $\mu\text{W}/\text{cm}^2$
Zhu et al. (2015)	Microstrip	5.3	160	8.5% @ -2.46 dBm
Zhang et al. (2015)	Patch	-	1.9 – 3.2	70% @ 50 $\mu\text{W}/\text{cm}^2$
Hosain et al. (2015)	Patch	-20.20	0.915	~ 60%
Lu et al. (2015)	Patch, metal strip	4.33	4.9	65.2%
		6.64	5.9	64.8%
Matsunaga et al. (2015)	Stack differential	-	5.8	44.1% @ 0.041 W/m^2
Song et al. (2015)	Cross dipole	-	1.8 – 2.5	55% @ -10 dBm
Chou et al. (2014)	Dual-polarised patch	-	2.45	82.3% @ 22 dBm
Sun et al. (2013)	1 x 4 quasi-Yagi	10.9	1.8	40% @ 455 $\mu\text{W}/\text{cm}^2$
		13.3	2.2	
Niotaki et al. (2013)	Dipole	-	0.915	48% @ 0 dBm
		-	2.45	39% @ 0 dBm

Hucheng et al. (2012)	Microstrip	8.6	2.45	83%
Olgun et al. (2010)	Patch	4	2.45	70%
Ren et al. (2007)	Patch	2.19	2.45	65% @ 10 mW/cm ²
		3.6	5.8	46% @ 10 mW/cm ²

These prior studies on the aforementioned antennas were carried out from the 20th century into the 21st century. Currently, advancements in antenna design have progressed significantly, driven by the development of new components and devices. This research has used the Yagi-Uda antenna since it was easily available and convenient to use in the experimental circuit.

2.7.1 Critical Synthesis on Research Related to Rectennas

Research on rectennas, antennas integrated with rectifying circuits for RF-to-DC conversion, demonstrates extensive exploration of various antenna types and configurations. Studies show that while wideband antennas enhance energy collection across broader frequencies, they also introduce challenges related to signal interference and noise, necessitating trade-offs between bandwidth and selectivity.

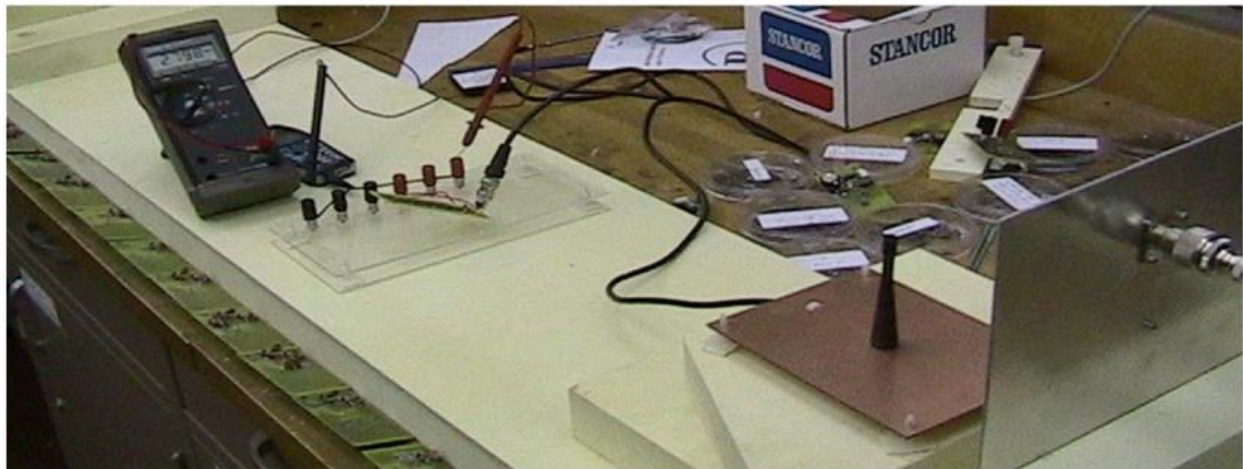
The literature reveals a focus on optimising power conversion efficiency (PCE) through antenna structure, diode selection, and frequency targeting. Microstrip and coplanar-fed designs have shown high efficiency (up to 83%), especially at the 2.45 GHz ISM band, commonly used for Wi-Fi and Bluetooth. However, efficiency often drops at lower power densities, which is critical in realistic ambient RF environments. The experimental emphasis on high-power lab conditions sometimes limits generalizability.

Notably, while many designs are theoretically and experimentally robust, few studies address practical deployment issues, such as device size, integration in IoT systems, or transparent/low-profile configurations for urban use. Vullers et al.'s (2009) transparent antenna-on-foil design and Awais et al.'s (2018) miniaturised solution mark exceptions aiming toward real-world applicability.

This research contributes to the field by choosing the Yagi-Uda antenna, a classic, directional, and accessible structure, highlighting a balance between experimental feasibility and performance, but also underscoring the need for further innovation in compact, efficient, and deployable rectenna systems for scalable wireless power transfer.

2.8 RF ENERGY HARVESTING TO CHARGE MOBILE DEVICE BATTERIES

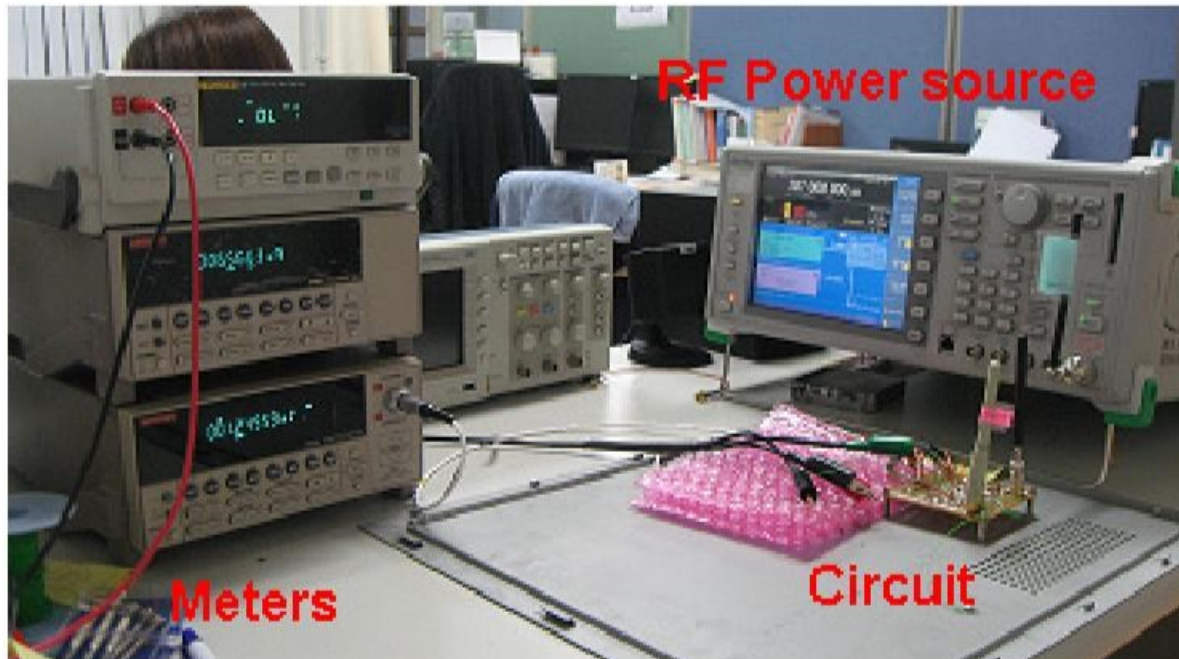
Harrist (2004) presented a system (Figure 2.56) using existing antenna and charge pump technology to charge a cellular phone battery without wires. Experimental results revealed that the charging circuit in a stand was able to charge the battery of a cellular phone while it was within the phone using a wireless RF source. This was not a completely wireless system since the charging stand was still connected via wires to the RF charging system.



56: Figure 2.56: Wireless phone charging stand (Harrist, 2004)

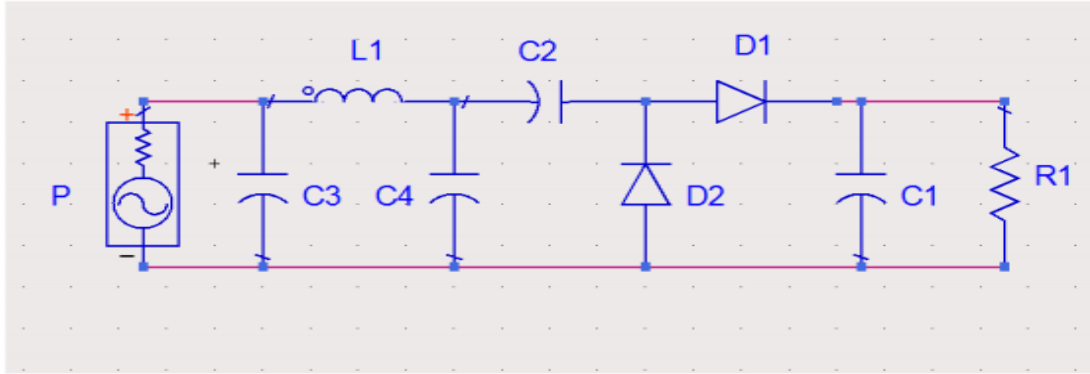
Jabbar, Song, and Jeong (2010) presented the CMOS-based Villard voltage multiplier circuit compatible with CMOS processes. The circuit (Figure 2.57) was used in RF energy harvesting and RF power transmission systems. The circuit parameters were set according to a design, and the input power ranged from -10 dBm to 5 dBm. The experiments revealed low series resistance Schottky diodes to be suitable for implementing the RF energy harvesting circuit due to their high forward bias current for a given voltage. The implemented circuit in low sub-micron manufacturing processes achieved higher performance. The circuit captured the RF energy from RF sources when placed adjacent to the RF source (wireless routers, mobile handsets, etc.).

According to the results of the experiments, the circuit could be implemented in mobile handsets, wireless sensor nodes, etc.



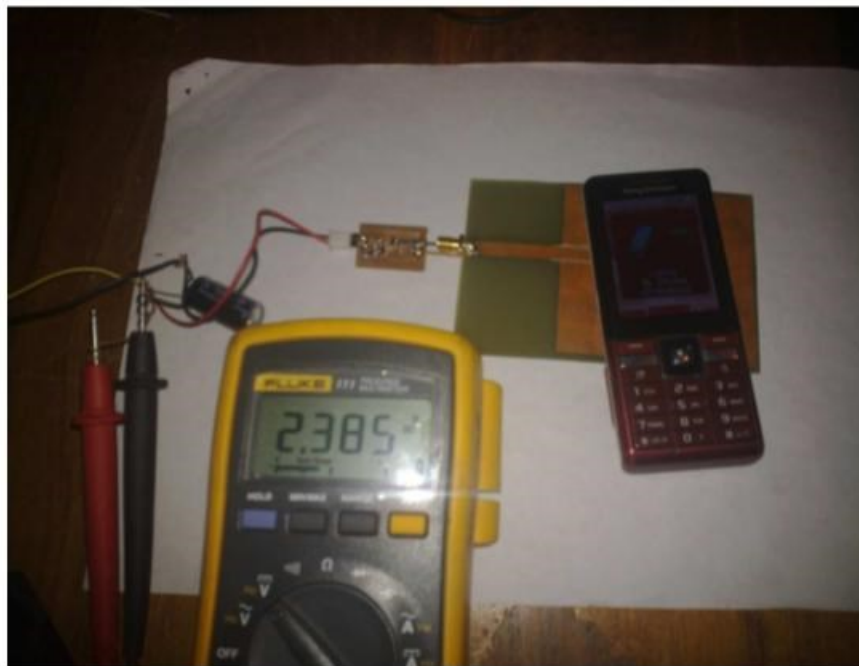
57: Figure 2.57: Schottky diode-based voltage doubler circuit (Jabbar et al., 2010)

A study by Sivaramakrishnan and Jegadishkumar (2011) proposed a circuit for harvesting energy from the received RF signal (Figure 2.58) that generated a minimum rectified output voltage and current. The proposed circuit conveniently captures the RF energy from transmitting mobile phone towers or even the Bluetooth device of some paired portable device and converts it into a useful power source that can be used to run mobile phones or to charge the drained batteries of mobile phones. According to the researchers, due to the miniature size of the circuit, it can be easily implemented inside mobile phones without any space constraints.



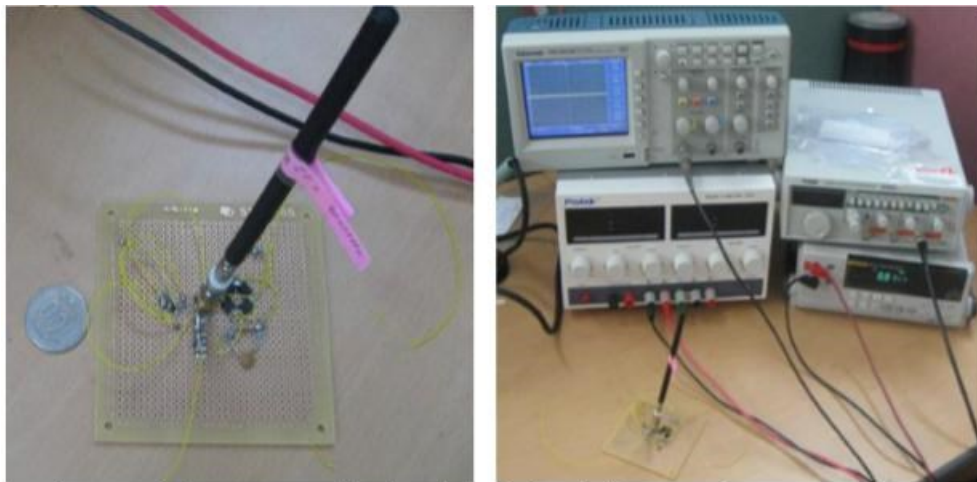
58: Figure 2.58: Voltage doubler circuit (Sivaramakrishnan and Jegadishkumar, 2011)

Gunathilaka, Dinesh, Gunasekara, Narampanawe, and Wijayakulasooriya (2012) demonstrated the charging of a mobile phone using an RF energy harvesting system (Figure 2.59). When the mobile phone is near the patch antenna (within about 10 cm), the harvester could harvest RF energy from it, usually near a mobile phone, giving more than 2V (typically 2V ~ 3V.), which is more than enough to drive an LED and a calculator. The major advantage of the patch antenna is that it is not very directional. The antenna can harvest energy within its usual range of harvest without concern for the direction or the position of the energy source.



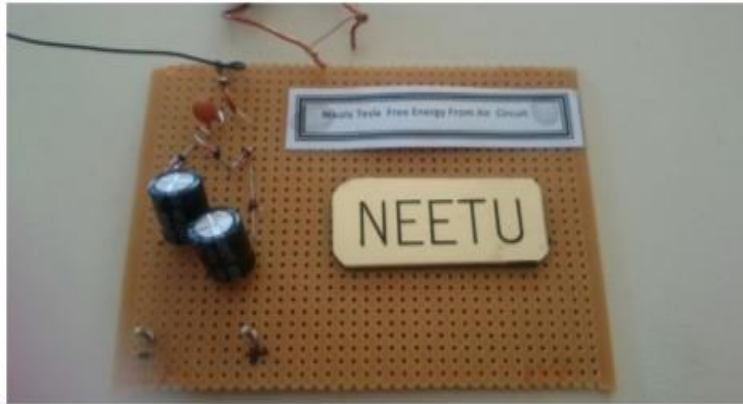
59: Figure 2.59: RF energy harvesting circuit to charge mobile phone (Gunathilaka et al., 2012)

Jabbar, Song, and Jeong (2010) designed an RF circuit that was able to charge mobile handsets, resulting in continuous charging of the devices in metro areas where the density of RF sources is high. The design consisted of a diode and a capacitor as the main components in the prototype of a wireless charging circuit. Due to the circuit being small, it can be fitted or integrated into cellular or mobile devices. Figure 2.60 shows the antenna with the developed circuit and waveform generation with the antenna and matching circuit. The experiments conducted led to another way to charge the battery from the proposed circuit, which is to place the circuit near another cellular phone, where the present device containing the circuit will act as a parasite, draining the other mobile device's battery.



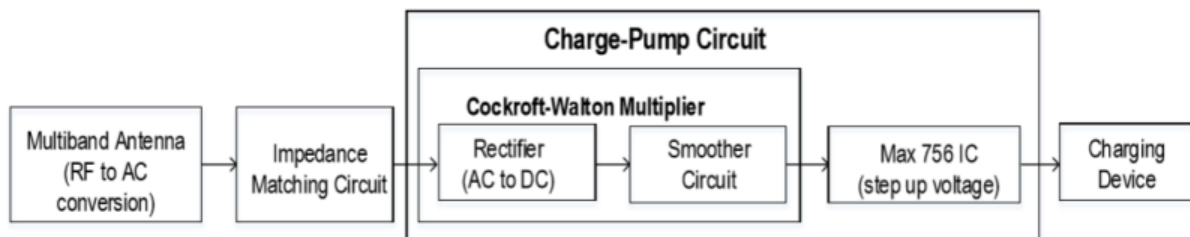
60: Figure 2.60: Proposed RF Energy Harvesting Circuit (Jabbar et al., 2010)

Ramsaroop, Olugbara, and Joubert (2017) proposed an RF energy harvesting system designed to charge mobile device batteries (Figure 2.61). The results of the prototype model demonstrated the feasibility of capturing RF signals and quantified the amount of energy harvested from them. Limited power was harvested from the prototype circuit, and it was not enough to charge the mobile device battery. The research further proved that using a capacitor to store the harvested energy would be useful for charging the mobile device battery.



61: Figure 2.61: RF Energy Harvesting Prototype (Ramsaroop et al., 2017)

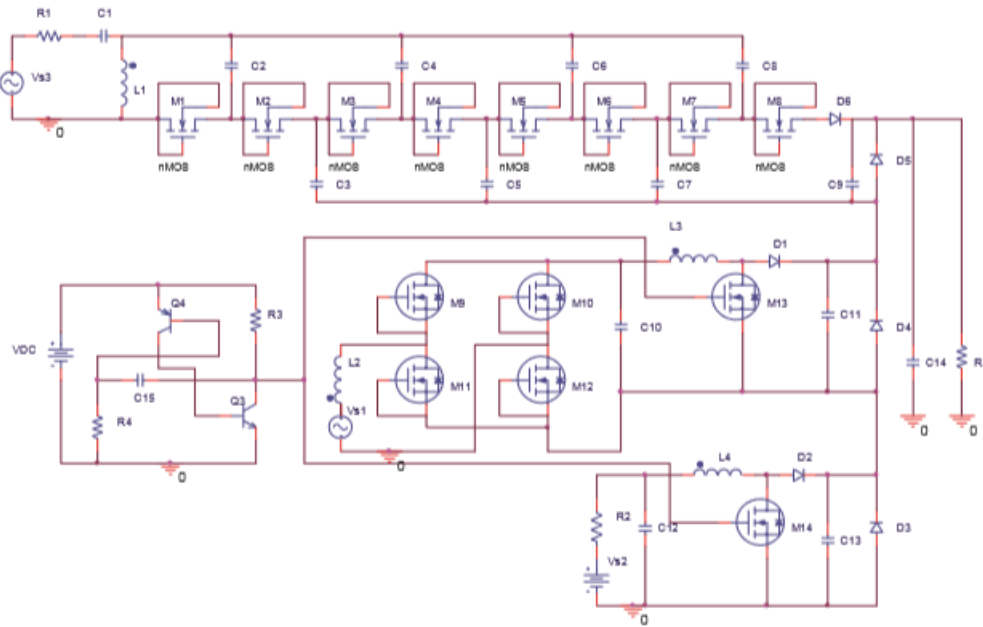
A research study by Nataraj, Careem, Lakshmanan, Selvaperumal, and Abdulla (2019) revealed an RF energy harvesting system (Figure 2.62), which enabled wireless charging in any location at any time without restriction. The developed system included an optimal omnidirectional antenna and a matching and charge pump circuit for effective signal harvesting. The results displayed the following: the amount of power more than -30 dB can be captured relatively easily irrespective of place and time; the system is supported of generating a voltage of more than 0.6 Vs conveniently and; the use of arrays of patch antennas in conjunction with optimisation exhibits much better return loss and gain metrics. The Cockroft-Walton charge pump was capable of boosting the voltage supplied by the antenna to the required usage levels.



62: Figure 2.62: Block diagram of the Charge pump circuit (Nataraj et al., 2019)

Sampe, Albrni, and Ali (2019) presented the architecture of a Low Power Hybrid Energy Harvester (LP HEH) based on thermal energy, vibration energy, and RF for mobile phones (Figure 2.63). Thermal circuit input was represented by 0.02 V DC, vibration circuit input was represented by 0.5 VAC, and RF circuit input was represented by as low as -17 dBm. The proposed energy harvester circuitry achieved an output of 4.2 V for charging mobile phones. The simulation

revealed that the target output of 4.2 V was achieved with the combination of these three input sources.



63: Figure 2.63: Hybrid Harvester Circuit (Sampe et al., 2019)

The reviewed literature indicates that limited research has been conducted on utilising RF energy harvesting to charge mobile device batteries. The models and theories explained in this section have been taken into consideration for the development of the WPT charging circuit with RF energy harvesting and magnetic resonance coupling. Currently, there are no research or related articles on RF energy harvesting combined with magnetic resonance coupling to charge mobile device batteries.

2.8.1 Critical Synthesis on RF Energy Harvesting to Charge Mobile Device Batteries

The reviewed studies present a growing body of work demonstrating the feasibility of RF energy harvesting for mobile device charging, although with varying degrees of success and practical applicability. Early contributions, such as Harrist (2004), laid the groundwork for wireless charging concepts, but the reliance on wired stands limited their classification as fully wireless systems.

Subsequent works by Jabbar et al. (2010) and Sivaramakrishnan and Jegadishkumar (2011) advanced the field through the development of CMOS-compatible and miniaturised rectifier circuits, proving that low-power RF sources (e.g., from routers and mobile handsets) could be captured and converted efficiently using Schottky diodes and voltage multipliers. These designs emphasised circuit integration potential within mobile devices and sensor networks.

More practical implementations, like those by Gunathilaka et al. (2012) and Ramsaroop et al. (2017), demonstrated real-world applications using patch antennas or custom-built prototypes, though challenges remained around low harvested power and inconsistent energy output. Innovations such as omnidirectional antennas and Cockcroft-Walton charge pumps (Nataraj et al., 2019) showed promise in enhancing power capture and boosting output voltage, especially in dense urban environments with RF signals.

A notable shift is seen in Sampe et al. (2019) with their hybrid harvester that combines RF, thermal, and vibrational sources, highlighting the limitations of relying solely on RF and suggesting a multimodal approach for reliable energy supply.

Despite these advancements, the literature reveals a significant research gap in combining RF energy harvesting with magnetic resonance coupling to create a hybrid system capable of reliably charging mobile device batteries. This research seeks to address that gap, building on past work while integrating complementary wireless power transfer techniques to enhance overall system efficiency and feasibility.

2.9 SUMMARY OF LITERATURE FINDINGS FOR RF ENERGY HARVESTING

The behaviour of electromagnetic waves varies according to the distance, frequency, and conducting environment. Depending on the requirements of the application, the designer needs to select suitable parameters for electromagnetic waves to obtain the best results. This section provides a summary (Table 2.10) of reviewed literature related to RF energy harvesting, based on distance, frequency, conducting environment, and feasible components for the RF energy harvesting circuit.

10: Table 2.10: Reviewed Literature on RF Energy Harvesting

Author	Title of Research	Model
Brown (1969)	Experiments involving a microwave beam to power and position a helicopter	Microwave beams
Harrist (2001)	Wireless Battery Charging System using Radio Frequency Energy Harvesting	RF energy harvesting system to charge a mobile device battery
Jabbar, Song, and Jeong (2010)	RF Energy Harvesting System and Circuits for Charging of Mobile Devices	CMOS-based voltage doubler circuit
Muramatsu and Koizumi (2010)	An Experimental Result Using an RF Energy Harvesting Circuit with a Dickson Charge Pump	RF energy harvesting circuit with Dickson charge pump
Jabbar, Song, and Jeong (2010)	Wirelessly Charging Mobile Devices from Ambient RF Sources	RF energy harvesting circuit
Bouchouicha, Latrach, Dupont, and Ventura (2010)	An Experimental Evaluation of Surrounding RF Energy Harvesting Devices	Energy harvesting system with a rectenna
Sivaramakrishnan and Jegadishkumar (2011)	A Highly Efficient Power Management System for Charging Mobile Phones using RF Energy Harvesting	RF energy harvester using a simple voltage doubler.
Olgun, Chen and Volakis (2012)	Design of an Efficient Ambient WiFi Energy Harvesting System	WiFi energy harvesting circuit
Gunathilaka, Dinesh, Gunasekara,	Ambient Radio Frequency Energy Harvesting	RF energy harvesting using a microstrip antenna

Narampanawe and Wijayakulasooriya (2012)		
Aminov and Agrawal (2014)	RF Energy Harvesting	RF energy harvesting with a five-stage doubling circuit
Mishra, De, and Chowdhury (2015)	Charging Time Characterization for Wireless RF Energy Transfer	Radio Frequency Energy Transfer (RFET) with a supercapacitor
Chang, Yen, Huang, Chen, and Hsu (2015)	A Smart-Card E-paper Display System Based on RF Power Harvesting	Smart card display with power harvesting
Liu, Mu, Ma, Tu, Zhu and Yang (2016)	An Ultra-Low-Power Integrated RF Energy Harvesting System in 65-nm CMOS Process	CMOS RF energy harvester with 10-stage rectifier
Mishra and De (2016)	Effects of Practical Re-chargeability Constraints on Perpetual RF Harvesting Sensor Network Operation	Renewable energy cycle (REC) via RF energy transfer based on sensor networks.
Fu, Cheng, Gu, Chen, and He (2016)	Optimal Charging in Wireless Rechargeable Sensor Networks	Based on the sensor network
Zhang, Niyato, Wang, and Kim (2016)	Optimal Energy Management Policy of Mobile Energy Gateway	Markov decision process (MDP) model
Sangare, Xiao, Niyato and Han (2017)	Mobile Charging in Wireless-Powered Sensor Networks: Optimal Scheduling and Experimental Implementation	Wireless-powered sensor network consisting of a mobile energy station
Albaaj, Makki, Alabkhat, and Zahedi (2017)	Simultaneous energy harvesting and information processing in wireless multiple relays with multiple antennas	A multi-relay and multi-antenna scheme

Ramsaroop, Olugbara, and Joubert (2017)	Exploring energy harvesting technology for wireless charging of mobile device batteries	RF energy harvesting circuit based on the full-wave rectifier
Corte, Merenda, Bellizzi, Isernia and Carotenuto (2018)	Temperature Effects on the Efficiency of Dickson Charge Pumps for Radio Frequency Energy Harvesting	Ultrahigh-frequency energy harvesters based on diode-capacitor Dickson charge pumps
Valentini, Levorato, and Santucci (2018)	Optimal Aging-Aware Channel Access and Power Allocation for Battery-Powered Devices with Radio Frequency Energy Harvesting	RF energy harvesting based on MDP
Nataraj, Careem, Lakshmanan, Selvaperumal, and Abdulla (2019)	Wireless charging system using spectral energy harvesting technique	Energy harvester circuit with a charge pump circuit
Sampe, Albrni and Ali (2019)	Design of a Low Power Hybrid Energy Harvester System Using Radio Frequency, Thermal, and Vibration Inputs for Mobile Phone	Low Power Hybrid Energy Harvester (LP HEH) system
Cansiz (2019)	Radio Frequency Energy Harvesting with Frequency Shift Keying Modulation Technique	Frequency shift keying modulation technique

2.10 CONCLUSION

All the research articles reviewed investigated the concept of WPT via magnetic resonance coupling (MRC) regarding different aspects, for example, either the function of the WPT system

with MRC in a medical field, with different obstacles, or the idle state resulting in power loss. These studies focused mostly on maximum power efficiency and maximum transfer efficiency. None of these articles has combined harvested radio frequency energy with the WPT system via MRC. The load source to the WPT system and to create the magnetic field was done using a generator or a battery.

The reviewed literature on RF energy harvesting primarily focused on wireless sensor networks due to the limited energy accumulated by the harvesting circuits.

This PhD research addresses this aspect and attempts to prove that harvested radio frequency energy can be combined with the WPT system via MRC to charge the battery of mobile devices. The focus will also be on increasing the accumulated power from the RF energy harvesting devices.

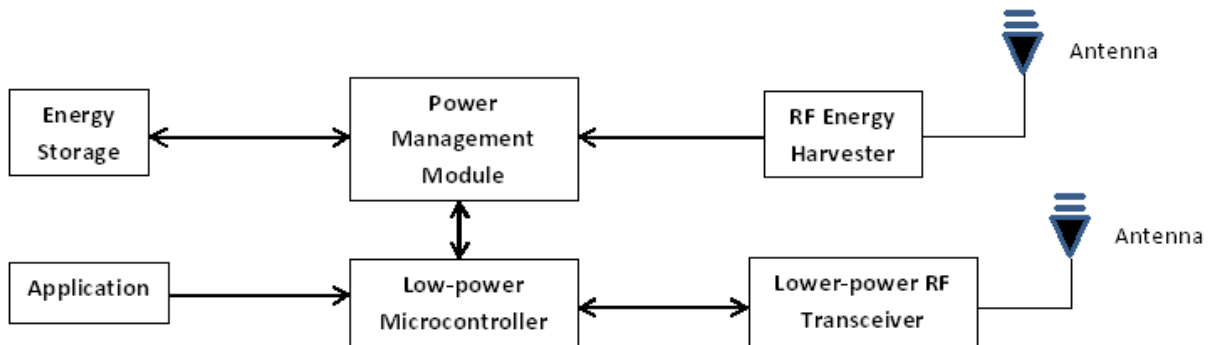
CHAPTER 3

THEORETICAL FOUNDATION

This chapter presents the theoretical foundation that forms the basis for this research. The block diagram and model for the WPT circuit, components, formulas, coupling, and RF energy harvesting WPT circuit are explained. The components of the initial WPT charging model are further explained. Magnetic coupling resonant wireless power transmission is grounded on the concept of near-field coupling. The elementary principle is that two objects with similar resonant frequencies can attain effective energy transfer, while the energy transfer between non-resonant objects is very weak.

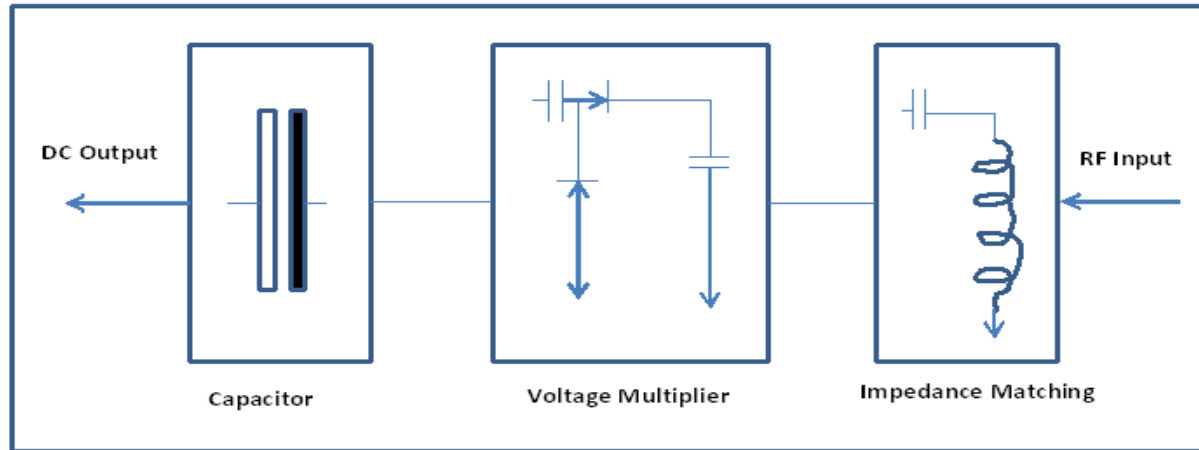
3.1 CIRCUIT MODEL

The circuit model consists of the RF harvesting circuit. This represents the input to the WPT system using magnetic resonance coupling. Figure 3.1 represents one part of the research method adopted for this study, constructed on the block diagram for the energy harvesting system. The received RF signals are transformed into electrical power via the RF energy harvester circuit. The power management module directs this transformed electrical power, which is used as the input source, to the transmitting coil in the WPT system. The receiving coil will transmit the electrical power wirelessly via magnetic resonance coupling to the load or mobile device battery for charging.



64: Figure 3.1: Block diagram of the Energy Harvester (Sivaramakrishnan and Jegadishkumar, 2011)

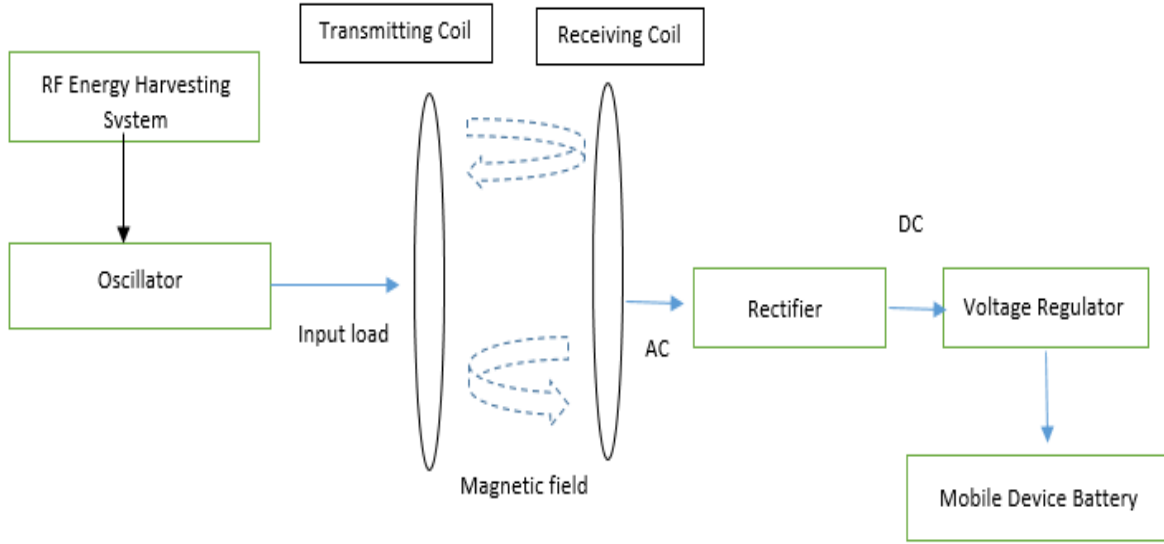
Figure 3.2 shows the authentic RF energy harvesting circuit based on a research study conducted by Ramsaroop et al. (2017), within the harvesting system as depicted in Figure 3.1.



65: Figure 3.2: Block diagram of the energy harvester (Sivaramakrishnan and Jegadishkumar, 2011)

Figure 3.2 illustrates the block diagram of the authentic energy harvesting circuit within the harvesting system. The RF power received by the antenna passes through the rectifier circuit and then through a power converter circuit, which boosts the rectified voltage. Finally, the converted DC output power serves as the input source for the transmitting receiver in the WPT system. The impedance matching (IM) circuit is designed to align the impedance of the antenna with that of the rectifier circuit, ensuring maximum power transfer. This enhances efficiency in maximizing the output power. According to the study by Sivaramakrishnan and Jegadishkumar (2011), the use of an impedance transformation circuit confines the circuit's operation to a specific frequency range of 0.9 GHz – 1.8 GHz, which corresponds to the operating band for mobile communication.

The WPT charging system for this PhD research is centred on the block diagram in Figure 3.3.



66: Figure 3.3: The proposed WPT system

Optimal efficiency of the WPT charging circuit is important for the circuit to be practically worthwhile, and maximum energy can be transmitted to the load (mobile device battery) with minimal loss in power. The efficiency of the wireless power transfer can be measured using equation 3.1:

$$E = \frac{DcPo}{DcPi} \times 100\% \quad (3.1)$$

Where E represents the efficiency, $DcPo$ is the direct current power output, and $DcPi$ is the direct current power input.

1: Equation 3.1: The efficiency of the wireless power transfer

3.2 COMPONENTS FOR THE MODEL

3.2.1 Antenna Design

An antenna is essentially a conductor positioned in space. When the conductor's dimensions correspond to a specific ratio or multiple of the signal's wavelength, it functions as an antenna. The state known as resonance occurs when the electrical energy supplied to the antenna is efficiently radiated into free space (Ramsaroop et al., 2017).

The performance of an antenna depends on its surroundings. Whether placed on a countertop, mounted on a developer's board, or exposed in a device, each scenario leads to different

operational characteristics. Unlike most components in a design structure that function with predictable outcomes in a circuit, an antenna's performance is influenced by its surrounding environment. The electromagnetic fields emitted by an antenna interact with nearby materials, potentially shifting its operational frequency. The antenna must be placed in its final environment and impedance-matched to ensure optimal performance within the designated frequency band. A poorly matched antenna can cause a signal loss of 10-30 dB, significantly reducing the range. All antennas, whether purchased or developed in a lab, will likely require matching (Ramsaroop et al., 2017).

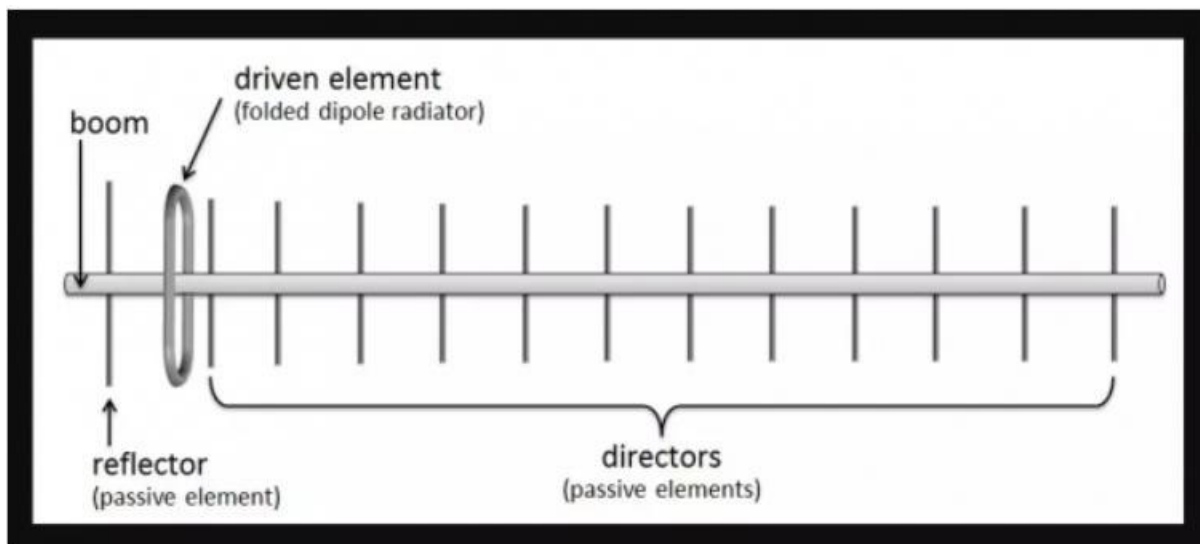
The WPT circuit used the Yagi-Uda antenna. A Yagi antenna, or Yagi-Uda antenna (Figure 3.4), is named after its inventors, Shintaro Uda and Hidetsugu Yagi of Japan, and is a directional type of antenna with a single dipole, a reflector, and multiple elements. Yagi antennas can be used for point-to-point or point-to-multi-point WiFi applications.



67: *Figure 3.4: Photograph of the Yagi-Uda (roof-top) Antenna*

The Yagi-Uda antenna is a prevalent and easy-to-use type of antenna with improved performance and is well-known for its increased gain and directivity. The frequency range in which the Yagi-Uda antennas activate is around 30 MHz to 3 GHz, which fits in the VHF and UHF bands (tutorialspoint, 2019).

The structure of the Yagi-Uda antenna includes the boom, reflectors, driven elements, and directors (Figure 3.5). The feeder is the folded dipole. The reflector is the extended element, which is at the end of the assembly. The centre rod-like edifice on which the elements are attached is called a Boom. According to Vishnu (2018), the element to which a thick black head is connected is the driven element to which the transmission line is connected internally, through that black stud. The single element existing at the back of the driven element is the reflector, which reflects all the energy towards the track of the radiation pattern. The additional elements, before the driven element, are the directors, which direct the beam towards the desired angle (Kibona and Sam, 2014).



68: Figure 3.5: Design of a Yagi-Uda Antenna (tutorialspoint.com, 2019)

The RF antenna structure concept was first outlined in a paper presented by Yagi in 1928 (Yagi, 1928). Since then, it has become widely used to the stage where, currently, a television antenna is an RF antenna consisting of a central boom with lots of elements attached.

The table below (Table 3.1) summarises the advantages and disadvantages of the Yagi-Uda antenna.

11: Table 3.1: Advantages and Disadvantages of the Yagi-Uda Antenna (engineering-notes.com, 2019)

Advantages	Disadvantages
It is directional, permitting interference levels to be minimised for receiving and transmitting.	Gain is restricted to around 20 dB or so for a single antenna, as else it becomes too great and the beam width contracts.
Has gained the ability to permit inferior strength signals to be received.	For increased gain levels, the antenna becomes very lengthy.
Encompasses a conventional forward construction.	
The design allows the antenna to be attached effortlessly to vertical and other poles with average mechanical fixings.	

The benefits of the antenna overshadow the drawbacks, resulting in the Yagi-Uda antenna being an applied method of RF antenna design appropriate for applications where gain and directivity are required.

The Friis Transmission Equation (Equation 3.2) estimates the expected power output of an antenna with gain G_r when transmitted from another antenna with gain G_t , separated by a distance r , and operating at the frequency corresponding to the wavelength λ , given by Equation 3.2:

$$\frac{P_r}{P_t} = G_r G_t \left(\frac{\lambda}{4\pi r} \right)^2 \quad (3.2)$$

2: Equation 3.2: The Friis Transmission Equation

Where G_t and G_r are the antenna gains referenced to an isotropic radiator for both the transmitting and receiving antennas, respectively. λ is the wavelength of the antenna, and r is the distance between the antennas. P_t is the transferred power, and P_r is the received power of the antennas. The difference in the third factor results in a loss of signal strength within the line of sight (LoS) between the antennas (Ismail, 2008).

The behaviour of electromagnetic waves governs the distance from the transmitting antenna. These individualities are classified into two sections: far-field and near-field (Yaghjian, 1986). While the electromagnetic wave pattern at the far-field is moderately unchanging, in the near-field, the electrical and magnetic components are very sturdy and self-governing such that one component can dictate the other.

Near-field or the Fresnel area is described as that region of the field of an antenna between the reactive near-field region and the far-field region wherein radiation fields predominate and wherein the angular field distribution is dependent upon the distance from the antenna. If the antenna has a maximum dimension that is not large compared to the wavelength, this region may not exist. For an antenna focused at infinity, the radiating near-field region is referred to as the Fresnel region based on analogy to optical terminology. If the antenna has a concentrated overall dimension that is very minor compared to the wavelength, this field region may not exist. (Balanis, 2005)

The internal border is taken to be the distance (Equation 3.3):

$$Rd = \frac{2D^2}{\lambda} \quad (3.3)$$

where Rd is the radial distance and D is the overall dimension.

3: Equation 3.3: Radial Distance

Far-field or the Fraunhofer area is detailed as that region of the field of an antenna where the angular field distribution is principally liberated of the distance from the antenna. If the antenna has a supreme overall dimension D , the far-field region is frequently taken to occur at distances superior to $2D^2/\lambda$ from the antenna, λ being the wavelength. The far-field patterns of certain antennas, such as multi-beam reflector antennas, are delicate to disparities in phase over their apertures. The dispersion of the near and far field areas is calculated using Fraunhofer's distance equation and is defined in Equation 3.4 (Balanis, 2005):

$$d_F = \frac{2D^2}{\lambda} \quad (3.4)$$

4: Equation 3.4: Fraunhofer's distance

where d_F He Fraunhofer's distance, D , is the maximum dimension of the radiator (or diameter of the antenna), and λ is the wavelength of the electromagnetic wave. Although Fraunhofer produces a boundary region, the authentic change between regions is not diverse (Tran et al., 2017).

For a transmitter-receiver antenna in the far-field unrestricted space, the power propagation at the receiver antenna is articulated as Equation 3.5:

$$P_{Rx} = \frac{P_{Tx} G_{Tx} G_{Rx} \lambda^2}{(4\pi R)^2} \quad (3.5)$$

5: Equation 3.5: Power at the receiver antenna

where P_{Rx} is the power at the receiver antenna. P_{Tx} refers to the power at the transmitting antenna; G_{Rx} is receiver antenna gain relative to the isotropic source (dBi); G_{Tx} is the transmitting antenna gain and λ is the wavelength of the electromagnetic signal equal to the speed of light in vacuum divided by the signal frequency, $\lambda = cf$ and $k = 2\pi/\lambda$ is the wave number.

Free-space path loss (FSPL) is the loss in signal strength of an electromagnetic wave that would occur via a line-of-sight path through unrestricted space, generally air, minus close-by hindrances that cause reflection or diffraction. It does not comprise factors such as the gain of the antennas utilised at the transmitter and receiver, nor any loss related to hardware inadequacies. Balanis (2005) notes that free-space path loss is relative to the square of the distance between the transmitter and receiver, and also relative to the square of the frequency of the radio signal. Referring to Equation 3.5, the FSPL, path loss (P_{loss}) for far-field is calculated by Equation 3.6 or Equation 3.7 (Balanis, 2005):

$$P_{Loss} = \frac{P_{TX}}{P_{RX}} = \frac{(4\pi R)^2}{G_{TX} G_{RX} \lambda^2} = \frac{(4\pi f R)^2}{G_{TX} G_{RX} c^2} = \frac{4}{G_{TX} G_{RX}} (kR)^2 \quad (3.6)$$

6: Equation 3.6: Path Loss for Far-Field

Or

$$P_{Loss} (dB) = 20 \log_{10} (f) + 20 \log_{10} (R) + 20 \log_{10} \left(\frac{4\pi}{c} \right) - G_{TX} - G_{RX} \quad (3.7)$$

7: Equation 3.7: Path Loss for Far-Field

Balanis (2005) comments that in the event f is measured in MHz, distance R is measured in km, and gain G_{TX} (transmitting) and G_{RX} (receiving) are measured in dBi, the above equation transforms into Equation 3.8.

$$P_{Loss} (dB) = 20\log_{10} (f) + 20\log_{10} (R) + 32.44 - G_{TX} - G_{RX} \quad (3.8)$$

8: Equation 3.8: Path Loss

Using the path loss equation, it is conceivable to specify the signal power in the far-field area. Conversely, this equation does not indicate all the aspects that affect the propagation course, namely reflection, diffraction, absorption, etc. (Balanis, 2005).

Related to an antenna are common efficiencies such as: the antenna reference terminals (input and output), reflection, conduction, and dielectric losses. The overall antenna efficiency E_o is used to explain losses at the input terminals and is contained in the structure of the antenna. Equation 3.9 forecasts the efficiency of an antenna:

$$E_o = E_R E_{CD} = E_{CD} (1 - |\Gamma|^2) \quad (3.9)$$

9: Equation 3.9: Antenna Efficiency

Where:

$E_o = E_C E_D$ = antenna radiation efficiency used to relate the gain and directivity

E_o = total efficiency

E_R = reflection efficiency

E_C = conduction efficiency

E_D = dielectric efficiency

Γ = antennas input terminals voltage reflection coefficient

Gain is an additional measure relating to the performance of an antenna. Even though the gain of the antenna is strictly associated with the directivity, it is a measure that takes into account the efficiency of the antenna and its directional competencies. According to Balanis (2005), the gain

of an antenna in an assumed direction is the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π . Gain is presented as Equation 3.10:

$$G = 4\pi \frac{R_i}{P_i} = 4\pi \frac{U(\theta, \phi)}{P_i} \quad (3.10)$$

10: Equation 3.10: Gain

Where:

G = Gain

R_i = radiation intensity, $U(\theta, \phi)$

P_i = total input power

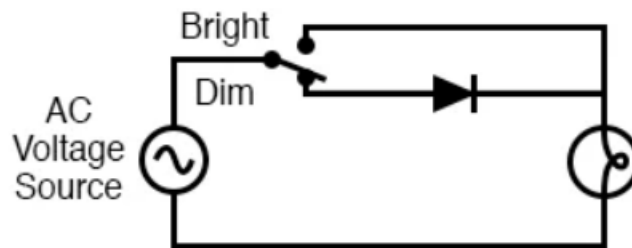
The Yagi-Uda antenna provides the most cost-effective option for gain and directivity, resulting in the most feasible antenna for this research. As a consequence of its ability to deliver antenna gain in a precise direction, the Yagi antenna has a tapered frequency range. Characteristically, the bandwidth is about 10% of the operating frequency, meaning that at an operating frequency of 400 MHz, the bandwidth is from 380 - 420 MHz (Kitchin and Counts, 2004). Yagi antennas possibly can function in the frequency range from about 3 – 3000 MHz, with the unsurpassed operational range below about 1500 MHz.

3.2.2 Voltage Rectifier (Full Bridge Rectifier Circuit)

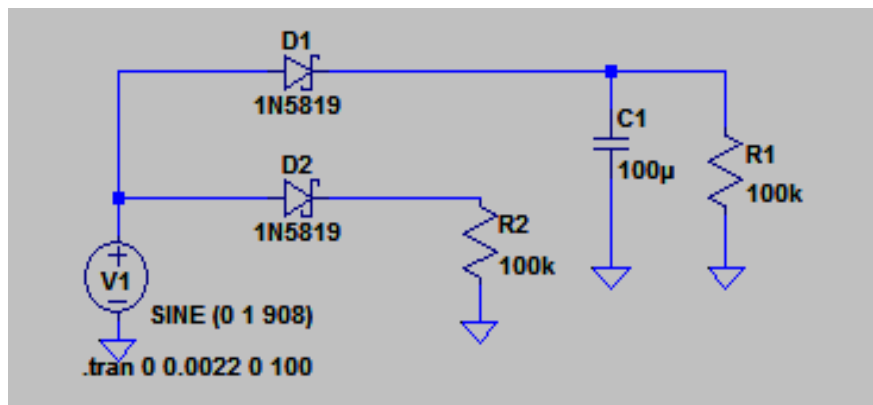
A rectifier is an electrical device that converts AC to DC. AC occasionally reverses direction and DC flows in one direction only (Lemmon, 2009). Rectifiers are generally used in circuits that require a stable voltage.

Rectification yields DC that incorporates active voltages and currents, which are then attuned into a form of persistent voltage DC. This differs depending on the current end-use. The current is permitted to flow continuously in one direction, and no current is permitted to flow in the opposite direction.

Rectifiers can comprise more than one diode in a definite arrangement. A rectifier can take on dissimilar waveforms, such as the half-wave rectifier (Figure 3.6), where the positive or negative wave is passed through, and the other wave is blocked. This is not efficient because only half of the input waveform reaches the output (Figure 3.7).

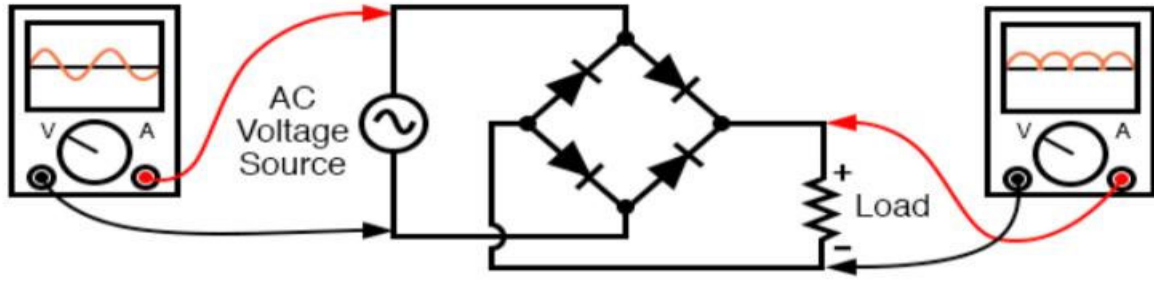


69: Figure 3.6: Half-Wave Rectifier (Kuphaldt, 2001)



70: Figure 3.7: LTspice schematic of the rectifier circuit simulation (Ramsaroop et al., 2017)

In order to rectify AC power to attain the complete use of both half-cycles of the sine wave, a dissimilar rectifier circuit alignment must be used, called a full-wave rectifier (Figure 3.8). The complete wave converts the negative part of the AC waveform and merges it with the positive part (Lemmon, 2009).



71: Figure 3.8: Full-Wave Bridge Rectifier Circuit (Lemmon, 2009)

Research conducted by Ramsaroop et al. (2017) on half-wave and full-wave bridge rectifier circuits demonstrated the full-wave rectifier circuit to be most feasible for the RF energy harvesting circuit. The average value, which is the value measured on a DC voltmeter, for a full-wave rectified sinusoidal voltage is twice that of the half-wave, as shown in Equation 3.11 (Hambley, 2011):

$$V_a = \frac{2V_p}{\pi} \quad (3.11)$$

where V_a is the average voltage and V_p is the peak load voltage divided by π .

11: Equation 3.11: Average Voltage

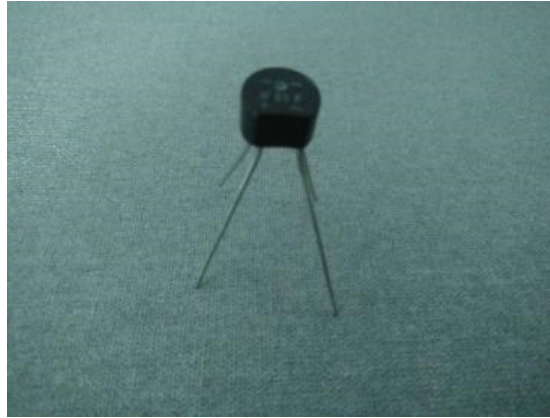
Electrical resistance is the opposite of the flow of voltage contained in the full wave rectifier circuit, calculated using Ohm's law (ElectronicsTutorials, 2019), depicted by Equation 3.12:

$$R = \frac{V}{I} \quad (3.12)$$

where R represents the resistance value in ohms (Ω), V is the voltage, and I resistors with current in amps (A).

12: Equation 3.12: Resistance

Currently, the researcher has discovered a more feasible component to be included in the WPT charging system, referred to as a voltage rectifier circuit (Figure 3.9).



72: *Figure 3.9: Photograph of the Voltage Rectifier Circuit*

The voltage rectifier circuit functions similarly to the full bridge rectifier circuit. The only difference is that this component comprises four pins. Two alternate pins connect to the antenna and ground, and the remaining two alternate pins connect to a positive and negative point (to connect to a charging device or a capacitor to store the harvested power). The rectifier circuit includes four assimilated silicon diodes in the arrangement, much like Figure 3.8. The rectifier circuit is a suitable component to include in the WPT charging system, as it eliminates the need to construct a complete full-bridge rectifier circuit separately.

3.2.3 Magnetic Wire

The magnetic resonance coupling circuit included copper coils. Figure 3.10 depicts the American Wire Gauge (AWG) magnetic wire used to create the copper coils.

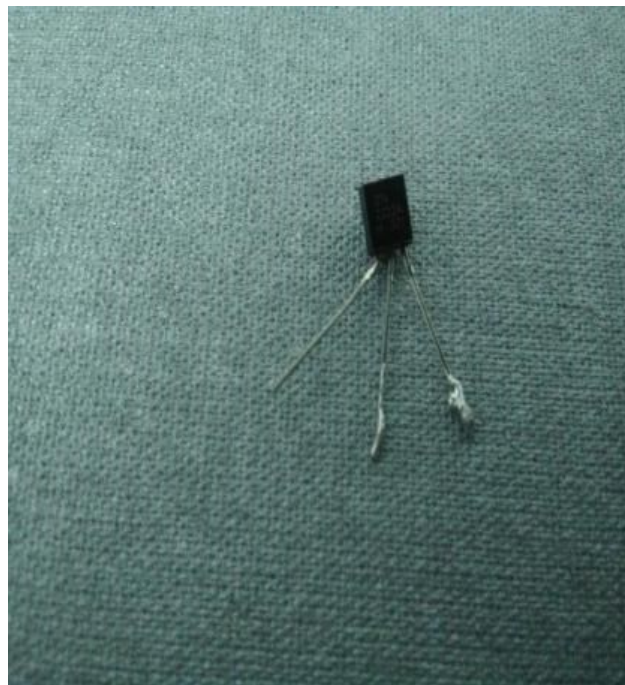


73: *Figure 3.10: Photograph of the 22 AWG Magnetic Wire*

Copper wire and magnetic wire are similar regarding conductivity, but the magnetic copper wire is layered with a thin, high heat-absorbing material. Thin, insulated material aids in making more turns (for the coils) in a small area, and it is adept at heat absorption. Customarily, copper wire is insulated with a thick material, which can entail more area for more turns; as a consequence, winding will not work efficiently and can melt the insulation in the heat. Magnet wire is coated with enamel insulation, which makes the insulation thinner and allows for a more compact winding and hence denser magnetic field in the coil (Xinyu, 2017). The WPT charging system used the 22 AWG magnetic copper wire to make the coils.

3.2.4 Transistor

A transistor is a minuscule electronic component that does two diverse tasks, working as an amplifier or a switch. During the task as an amplifier, it accepts a small electric current at one end (an input current) and yields a much superior electric current (an output current) at the other, referred to as a ‘current booster’. Furthermore, transistors can also operate as switches. A minuscule electric current flowing through one part of a transistor can make a much greater current flow through another part of it. The minuscule current switches on the larger one (Woodford, 2019).



74: Figure 3.11: Photograph of the 2N2222A Transistor

The WPT charging circuit comprised the 2N2222A transistor (Figure 3.11). The 2N2222A transistor consists of a base (access regulator device for the greater electrical supply), collector (the greater electrical supply), and emitter (the channel for that supply). One significant thing to note is the base resistor or the current-limiting resistor. This resistor limits the current flowing through the transistor to stop it from being destructive (Woodford, 2019). The significance of this resistor is evaluated using Equation 3.13:

$$R_{VB} = V_{BE} / I_{BR} \quad (3.13)$$

13: Equation 3.13: Base Resistor Value

where R_{VB} refers to the base resistor value, V_{BE} refers to the base-emitter voltage, and I_{BR} refers to the base resistor.

3.2.5 Capacitors

The WTP charging circuit used capacitors to smooth the rectified current and to accumulate charge. The electrolytic capacitor was used in the WPT charging circuit and the simulation. Capacitance is the ability of a circuit to store charge (Ramsaroop et al., 2017). The capacitance is calculated using Equation 3.14 below:

$$C_p = \frac{C_c}{V_a} \quad (3.14)$$

14: Equation 3.14: Capacitance

Where C_p is the capacitance and is expressed in Farads (F); C_c is the charge on the conductor; and V_a is the potential applied across the conductor.

Equation 3.15 below is used when capacitors are connected in series:

$$\frac{1}{C_{ps}} = \frac{1}{C_{p1}} + \frac{1}{C_{p2}} + \dots + \frac{1}{C_{pn}} \quad (3.15)$$

15: Equation 3.15 capacitors are connected in series

Equation 3.16 below is used for capacitors connected in parallel:

$$C_{pa} = C_{p1} + C_{p2} + \dots + C_{pn} \quad (3.16)$$

16: Equation 3.16 capacitors connected in parallel

As the capacitor charges or discharges, current flows through it. The current is restricted by the internal impedance of the capacitor. This internal impedance is commonly known as Capacitive Reactance and is given the symbol X_C in Ohms. Equation 3.17 (Shamieh, 2015) is used to calculate the capacitance reactance:

$$X_C = \frac{1}{2\pi fC} \quad (3.17)$$

17: Equation 3.17: Capacitance reactance

where X_C = Capacitive Reactance in Ohms, (Ω); π (pi) = 3.142 (decimal) or as $22 \div 7$ (fraction);

f = Frequency in Hertz, (Hz) and C = Capacitance in Farads, (F).

The previously stated equations in this section have been used to define the actual arrangement of the components to gain maximum charge. Capacitors have been used as storage for the harvested RF energy.

According to an article by Miret (2013), it is specified that energy storage is the foremost feature of creating environmentally friendly energy systems. The storage structure of a supercapacitor was matched to a standard mobile device battery. Currently, prominent energy storage is the battery, principally the lithium-ion battery. Lithium-ion batteries power nearly all portable electronic devices and are used in most electric cars, including the Tesla Model S and the Chevy Volt. Batteries store energy chemically, where chemical reactions release electrical carriers that can flow through a circuit when discharged. The charge and discharge process in batteries is gradual and can cause the chemical components inside the battery to degrade over time. As a result, batteries have low power density and a reduced lifespan due to damage to their materials.

The supercapacitor employs a different storage mechanism, where energy is stored electrostatically on the surface of the material, without involving chemical reactions. Supposedly, the vital mechanisms of supercapacitors are that they can be charged quickly, leading to an extremely high-power density, and they do not lose their storage abilities over time. Supercapacitors are able to last for millions of charge/discharge cycles, without losing energy storage capability.

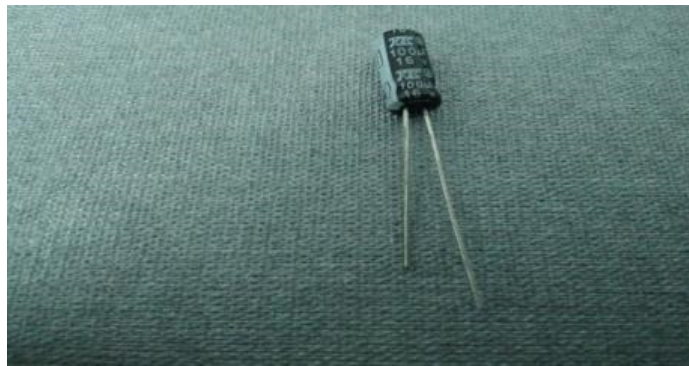
The primary drawback of supercapacitors is their cost—the materials used in supercapacitors are more expensive than those in batteries due to the greater challenges involved in developing new

supercapacitor materials. Advancements in material production methods will help close the energy density gap for certain commercial applications. Another drawback is their low energy density—the amount of energy supercapacitors can store per unit weight is significantly lower, especially when compared to batteries (Amperics, 2019).

According to Sciencing.com (2019), electrolytic capacitors have a superior capacitance per volume to any other type of capacitor. Due to their advanced capacitance values, electrolytic capacitors are frequently used in lower-frequency applications, such as in power supply filters. The high capacitance values related to electrolytic capacitors act as shorts or low impedance lines for higher-frequency applications. Shamieh (2015) summarises the characteristics of capacitors and their related applications (Figure 3.12):

Type	Typical Range	Application
Ceramic	1 pF to 2.2 μ F	Filtering, bypass
Mica	1 pF to 1 μ F	Timing, oscillator, precision circuits
Metalized foil	0.01 to 100 μ F	DC blocking, power supply, filtering
Polyester (Mylar)	0.001 to 100 μ F	Coupling, bypass
Polypropylene	100 pF to 50 μ F	Switching power supply
Polystyrene	10 pF to 10 μ F	Timing, tuning circuits
Tantalum (electrolytic)	0.001 to 1,000 μ F	Bypass, coupling, DC blocking
Aluminum electrolytic	10 to 220,000 μ F	Filtering, coupling, bypass, smoothing

75: Figure 3.12: Capacitor Characteristics (Shamieh, 2015)



76: Figure 3.13: Photograph of an Electrolytic Capacitor

The WPT charging circuit used electrolytic capacitors with 100 μ F of capacitance and a 16 V rating (Figure 3.13) based on the high capacitance values. As per Figure 3.11, electrolytic capacitors are used for coupling.

3.2.6 Voltage Regulator

The purpose of a voltage regulator is inevitably to normalise voltage levels. The voltage regulator steps down the input voltage to the anticipated level and maintains it at a similar level during the supply. This makes sure that even when a load is applied, the voltage does not drop. A voltage regulator is used for two reasons, namely, to regulate or vary the output voltage of the circuit and to keep the output voltage constant at the desired value, despite variations in the supply voltage or the load current (Figure 3.14).



77: Figure 3.14: Photograph of the Voltage Regulator Circuit

According to Poly Technic Hub (2019), the following table (Table 3.2) summarises the advantages of an integrated voltage regulator circuit.

12: Table 3.2: Advantages of a Voltage Regulator Circuit

Advantages of a Voltage Regulator
Conveniently used for local regulation.
It is easy to use
Efficient and reliable
Versatile
Cheap due to mass production and easily available
Compact, rugged, and light in weight
Power supply design becomes easy and quick.

Easily manufactured with features such as built-in protection, programmable output, current or voltage boosting, internal protections such as thermal shutdown, floating operation to facilitate higher output voltage, etc.
Has a fast, transient response

3.3 CONCLUSION

This chapter explained the theoretical foundation for this research. The components that make up the entire WPT circuit are the Yagi-Uda antenna, magnetic wire (22 AWG), voltage rectifier, transistor (2N2222A), electrolytic capacitor (100 μ F, 16V), and voltage regulator.

The WPT circuit comprises two sections, namely, the RF energy harvesting circuit (to capture RF signals from the antenna and convert them to DC) and the magnetic resonance coupled circuit (to transfer the DC wirelessly to the mobile device battery for charging). This chapter also includes the advantages and disadvantages of using the mentioned components in the WPT circuit, thereby explaining the decision to include these components in the final WPT circuit. Table 3.3 summarises the key components explained in this chapter and used in the WPT prototype.

13: Table 3.3: Summary of Key Components for the WPT Charging System

Component	Description	Specifications / Type	Function in WPT System
Antenna	Yagi-Uda directional antenna designed for high gain and directivity within 30 MHz – 3 GHz.	- Operating range: VHF/UHF - Components: Boom, reflector, directors, folded dipole - Gain: ~20 dB max	Captures RF energy efficiently and directs electromagnetic waves to the rectifier.
Voltage Rectifier	Converts an AC signal from the antenna into usable DC power.	- Full-bridge rectifier - 4-pin package - Contains 4 silicon diodes	Converts the RF signal into DC and outputs to charging/storage components.
Magnetic Wire	22 AWG magnet wire is used to wind	- Thin enamel insulation	Forms inductive coils for efficient magnetic resonance

	coils for magnetic resonance.	- Heat resistant - High turn density	coupling and energy transfer.
Transistor	2N2222A NPN transistor used as a switch or amplifier.	- Terminals: Base, Collector, Emitter - Requires a base resistor for protection	Amplifies or switches signals to control energy flow in the circuit.
Capacitor	Electrolytic capacitors for energy storage and signal smoothing.	- 100 μF, 16 V rating - High capacitance per volume - Used in parallel/series configurations	Stores harvested energy; smoothens rectified current to prevent voltage drops or spikes.
Voltage Regulator	Maintains a constant DC voltage regardless of load variations.	- Integrated circuit regulator - Built-in protection features	Stabilises and regulates output voltage to prevent damage to the load or charging device.

CHAPTER 4

STUDY METHODOLOGY

This chapter explores a key aspect of magnetic resonance coupling and RF energy harvesting in WPT circuits through mathematical modelling and simulation. The study concentrates on developing a mathematical model for the components based on the WPT charging circuit. The chapter also describes the simulation software used for testing the circuit layout during this research.

4.1 MATHEMATICAL MODELLING AND SIMULATION

Modelling and simulation (M&S) involve using models—whether physical, mathematical, or otherwise—as accurate representations of a system, entity, phenomenon, or process. This provides a foundation for simulation methods, applying a model either statically or over time, to generate data that serves as the basis for administrative or practical decision-making. M&S contributes by providing information that allows an entity to be evaluated without the need for real-life testing (Department of Defence, 2009).

The use of M&S in engineering is widely recognized. Simulation technology is an integral part of the engineer's toolset across various applications and is often incorporated into the assumptions underlying engineering regulations. M&S helps reduce costs, enhance the quality of products and systems, and document and store shared knowledge and insights (Department of Defence, 2007).

The reason for adopting the mathematical modelling method is that this research falls within the field of engineering. Mathematics can demonstrate broad results; the form of an equation used critically governs these results. Mathematical models can accommodate small deviations in the equation without significantly affecting the entire system (Marion and Lawson, 2008).

Mathematical models are abridged depictions of some actual world object, represented as equations, and they can be projected to imitate vital structures while separating the inessentials. Mathematical models are characterised by conventions about variables (the things that change), parameters (the things that do not change), and functional forms (the relationship between the two).

It is practical to consider factors such as the type of mobile device, the RF energy harvesting system, the circuitry of the magnetic resonant system, the signal strength of the receiving antenna, and the size of the battery.

The aspects affecting the effectiveness of wireless power systems include coil formation and design, broadcast distance, and coupling. A less effective system will produce additional emanations and result in a reduced amount of power passing through to the receiver device or load (mobile device battery) (Powerbyproxi, 2013).

This research method formed the basis for employing a prototype to test the practicality of the WPT circuit. M&S aided in obtaining information about the behaviour of the WPT prototype model via simulation and mathematical equations, before physically building and testing it. The simulation software, LTspice, was used to analyse the test results of the WPT prototype circuit.

The research method used for this study is based on quantitative research, focusing on mathematical modelling and simulation. The experimental test results of the WPT prototype were quantified to offer a practical solution for the wireless transfer of power. Variables measured for the energy harvesting circuit were distance, device, and amount of energy harvested based on the viability of the circuit model, and variables considered for the magnetic resonance coupling circuit were the resistance and conductivity of the copper wire.

4.1.1 Reasons to Use Mathematical Modelling

Mathematical models assist in understanding and exploring the meaning of equations or functional relationships. After developing a conceptual model of a physical system or circuit, it is accepted to develop a mathematical model that assists in permitting an estimate of the quantitative behaviour of the system or circuit before the prototype circuit is created. Quantitative output from mathematical models can be compared with observational results that assist in identifying a model's strengths and weaknesses. Mathematical models are a vital component of the overall model of a circuit (Sousa, Vieira, and Vieira, 2017).

4.2 SIMULATION SOFTWARE

SPICE (Simulation Program with Integrated Circuit Emphasis) is an all-purpose circuit simulator created at the Electronics Research Laboratory at the University of California, Berkeley, by the

doctoral student Laurence W. Nagel. The benefits of LTspice over other available SPICE-based programs are that it is free, and its proficiencies are unhindered (Assad and Piñón, 2012).

One of the most promising SPICE-based curricula in academia available currently is LTspice IV, by Linear Technology Corporation. LTspice IV is a high-performance, general-purpose SPICE simulator that comprises a built-in schematic capture interface and a waveform viewer tool. In addition, it is possible to compose a SPICE level reliably in the program or an alternative text editor and run your simulations employing this program. One of the advantages of this latter feature is that LTspice IV can be used as a SPICE engine to conduct analyses using SPICE levels produced mechanically by further schematic capture software, a PCB, or a corporate design tool (Assad and Piñón, 2012).

LTspice contains all the analyses accessible in most SPICE-based simulation tools. For an enhanced understanding of the proficiencies of the SPICE analyses conducted in this research, Table 4.1 (Assad and Piñón, 2012) displays the most common applications for each analysis type and a brief narrative on each.

14: Table 4.1: Main applications for each type of SPICE analysis

Analysis	Application
DC operation point	Define the DC situations of a biased transistor (i.e., the task region). DC node voltages and loop currents of an electrical network.
Transient	The time response of any circuit.
DC sweep	Transference function of an amplifier, DC-specific curves of a transistor.
AC	Frequency response (gain and phase) of a passive or active filter. Bandwidth of an amplifier.
Noise	Assess the response of an audio amplifier in noise conditions.
DC transfer	Input and output resistance of an electrical network. Output impedance of an amplifier. The output voltage of a network is given for a resolute input value.

4.2.1 Reasons to use LTspice for simulation

The main reason for using LTspice for the simulation of the circuit is to follow the industry standard. Simulating the circuit with LTspice is the industry-standard way to verify circuit operation before committing to manufacturing or building the physical circuit. For example, it will draw out circuits and simulate what happens when the circuits are powered up/ and behave under different emergency conditions. This does save cost and prevents wastage of components before building the circuit. Based on these reasons, the LTspice software was used for simulating the circuit design before building the prototype (Sousa, Vieira, and Vieira 2017).

To ensure quantitative rigor in the simulation and experimental analysis, each simulation scenario and circuit prototype test was repeated a minimum of three times under the same test conditions. Results were recorded and averaged, with the standard deviation (SD) calculated to reflect the variability in output voltage and power transfer efficiency. This approach reduced the impact of transient fluctuations and external interferences.

For example, voltage readings across the load during RF harvesting were averaged across repeated runs, and standard deviations (mean $\pm$ SD) were used to assess the stability of harvested energy at fixed distances. Error margins were calculated based on the variance in repeated readings, especially when altering critical parameters like coil distance and wire material. These statistical protocols helped substantiate claims of performance consistency and informed the decision to consider the results as “promising.”

Additionally, simulation conditions were carefully controlled. Environmental factors such as electromagnetic interference were kept minimal, and consistent component values were maintained during circuit modelling in LTspice. These steps ensured reproducibility and reduced systematic bias in performance evaluation.

4.3 CONCLUSION

This chapter explained the research paradigm (mathematical modelling and simulation) used and the formulas that were considered to measure the voltage, voltage loss, impedance, and voltage gain of the passive components and the antenna. The main application focusing on SPICE analysis was explained.

The integration of repeated measurements, statistical summaries (mean $\pm$ SD), and controlled simulation parameters enhances the reliability of the findings. This quantitative foundation not only validates the use of mathematical modelling and simulation in this research but also supports the credibility of the results discussed in the subsequent chapter.

CHAPTER 5

EXPERIMENTAL RESULTS

This chapter presents the implementation and the experimental results of the WPT prototype circuit with RF energy harvesting and magnetic resonance coupling to charge mobile device batteries, with the related results. The implementation utilises the prototype circuit to test the feasibility of magnetic resonance coupling and showcases the harvesting of RF energy with an increase in voltage. The experimental results are presented using the LTspice IV simulation application to assess the feasibility of the components and determine the optimal circuit layout for maximizing charge. The simulation application helped evaluate circuit components, identify the most effective layout, and facilitated the use of third-party SPICE models, allowing for the prediction of RF harvesting circuits and the efficiency of the coils in the magnetic resonance system.

To enhance the quantitative credibility of the simulated and experimental results, additional protocols were adopted. All LTspice IV simulations were conducted under standardised and repeatable test conditions. Parameters such as voltage sources, coil dimensions, and load resistances were held constant during each simulation cycle to ensure consistency.

For each simulation stage (magnetic resonance coupling, RF energy harvesting, and WPT charging), three to five repeated simulation runs were performed, and key metrics such as output voltage and current were averaged. Standard deviation (SD) was calculated where relevant to reflect output stability. For example, during Stage 2 simulations of the RF harvesting circuit, repeated measurements of output voltage yielded consistent values with low variance (e.g., mean = 5.1 V, SD = ± 0.14 V).

These statistical summaries were used to validate claims of ‘promising results.’ In addition, error analysis was incorporated by comparing simulations with and without key components (e.g., capacitors), thereby assessing component-level impact on output reliability.

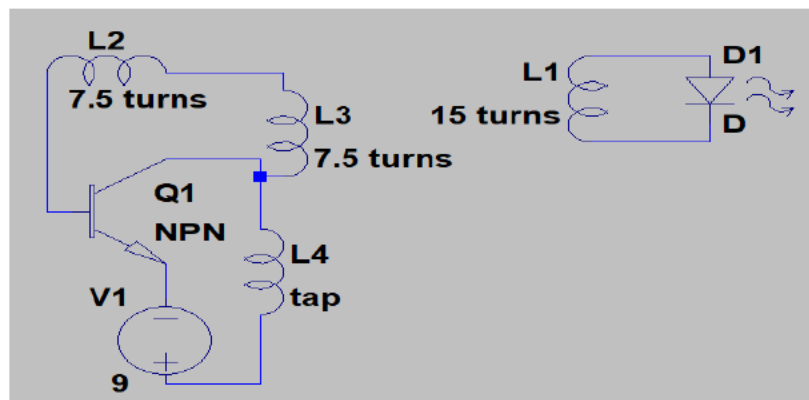
Physical limitations such as minor electromagnetic interference, simulation tool modelling constraints, and component tolerances (e.g., diode forward voltage drop) were acknowledged, and their impact was minimised through iterative simulation design and repeated measurements.

The repeated simulations and error consideration provide a stronger empirical foundation for the prototype's performance, increasing the reliability and reproducibility of the findings discussed throughout this chapter.

5.1 MAGNETIC RESONANCE COUPLING – STAGE 1

The simulated experiments were conducted on the WPT prototype circuit. LTspice was used to simulate the prototype circuit design, and the results were compared to improve the physical WPT circuit. This simulated experiment was conducted to test for the possibility of wireless power transfer.

Figure 5.1 depicts the magnetic resonance coupling circuit diagram in LTspice. The simulated circuit included two coils of wire for the receiver coil and transmitting coil. The receiver coil consisted of 15 turns of magnetic wire, a looped tap 3 cm, and another 15 turns of magnetic wire. The diameters of the coils were approximately 5 cm.



78: Figure 5.1: Magnetic resonance coupling circuit diagram

5.1.1 Equations for the Magnetic Resonance Circuit

The resistivity of the copper wire is a measure of how intensely the copper wire coils oppose the flow of electric current through the copper coils (Electronic Tutorials, 2019; Hambley, 2011). This is calculated using Equation 5.1:

$$p = \frac{R \times A}{L} \quad (5.1)$$

18: Equation 5.1: Resistivity

where p is the resistivity, A is the area of the copper wire, L is the length of the copper wire, and R is the resistance. Generally, the resistivity of pure copper is $1.7 \times 10^{-8} \Omega\text{m}$.

The voltage resistance of the copper wire is the opposition to voltage flow through the copper wire coils (Electronic Tutorials, 2019; Hambley, 2011). This is given using Equation 5.2:

$$R = \frac{pL}{A} \quad (5.2)$$

19: Equation 5.2: Resistance Value in Ohms

where R represents the resistance value in ohms (Ω); p is the resistivity; L is the length of the copper coils; and A is the area.

The conductance of the copper wire determines the amount of voltage that flows through the copper wire (Electronic Tutorials, 2019; Hambley, 2011). Conductance was evaluated with Equation 5.3:

$$C = \frac{A}{pL} \quad (5.3)$$

20: Equation 5.3: Conductance Value

where C represents the conductance value; A is the area of the copper wire; p is the resistivity; and L is the length of the copper wire.

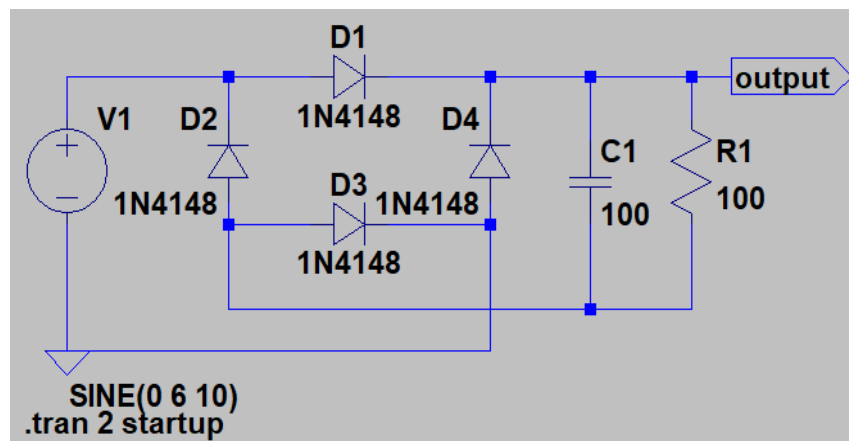
The conductance was affected by the resistivity of the copper wire, and is the total resistance the copper wire has. The larger the resistivity of the copper wire, the less conductance it possesses in a circuit. The lower the resistivity, the greater the conductance it possesses.

5.2 RF ENERGY HARVESTING CIRCUIT – STAGE 2

Stage 2 comprises the results of the simulated RF energy harvesting circuit and the implementation and testing of the actual RF energy harvesting circuit. The results displayed indicate an increase in the voltage acquired.

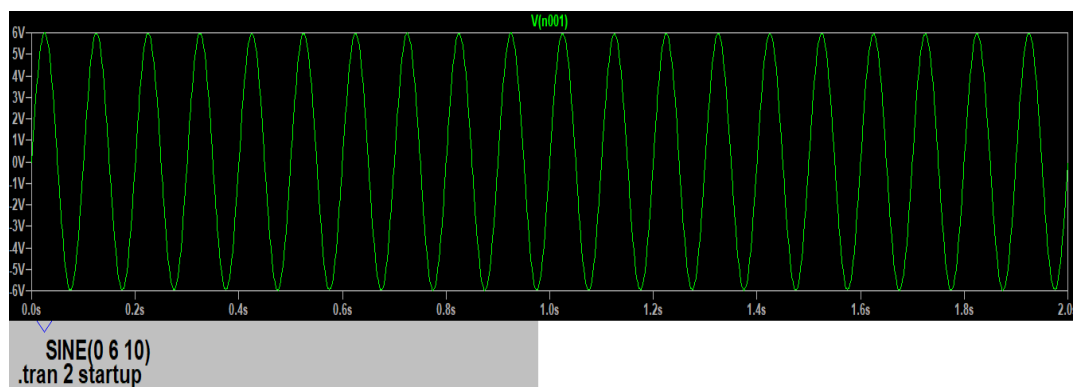
5.2.1 Simulated RF Energy Harvesting Circuit

The simulated RF energy harvesting circuit comprised a full-wave rectifier circuit with the following components: a capacitor (100 μF), 4 diodes (1N4148), and a resistor (100 $\text{k}\Omega$). The simulated circuit diagram is depicted in Figure 5.2 below:



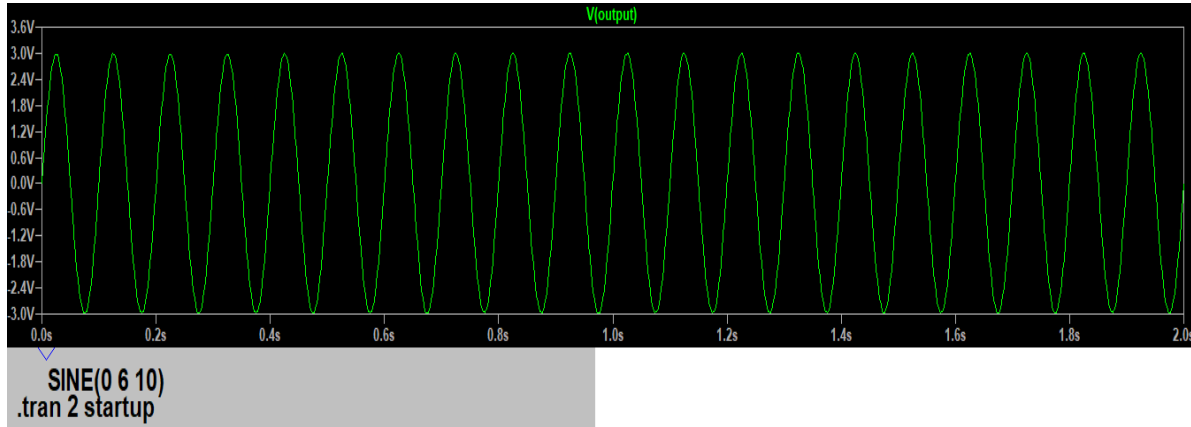
79: Figure 5.2: Full-wave rectifier circuit in LTspice

Transient analysis was conducted over a two (2) second timeframe. According to Assad and Piñón (2012), a time domain transient analysis is where a parameter, such as a voltage or current, is plotted against time. The output of this type of analysis displays the behaviour of a circuit over a specified length of time. Input voltage is set at 6 V (since this is the target voltage intended to be acquired by the actual RF energy harvesting circuit to initiate the charging of a mobile device battery) and is represented by a constant sine wave from start-up to the 2-s timeframe, which is depicted in the trace analysis in Figure 5.3.



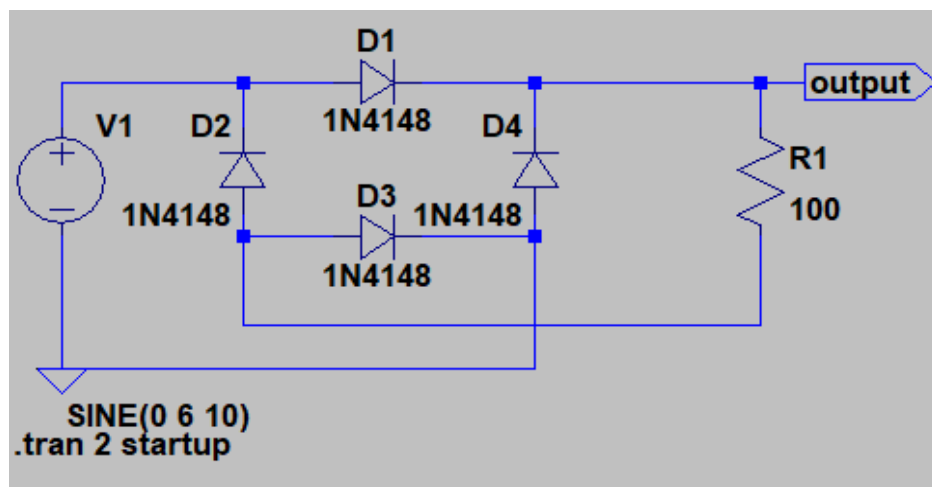
80: Figure 5.3: Input voltage sine wave

The output voltage after the transient analysis was conducted is depicted in Figure 5.4 and represents 3.0 V, which is half of the input voltage.



81: Figure 5.4: Output voltage sine wave

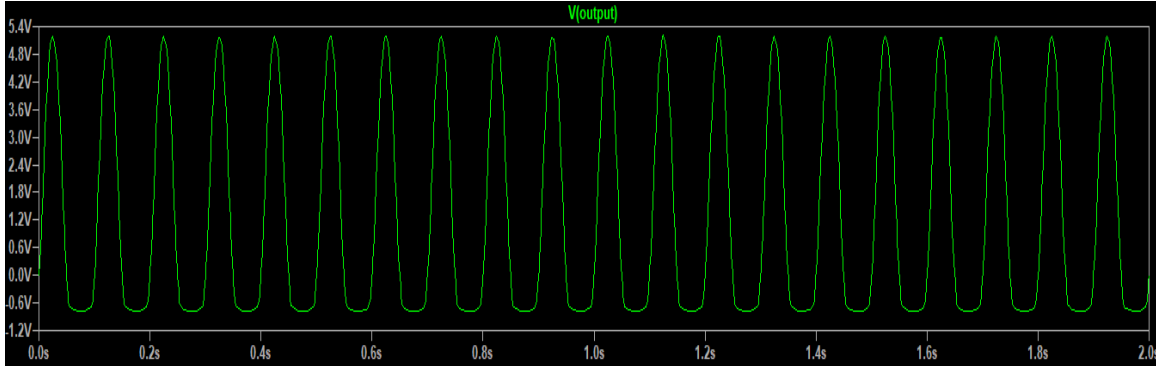
When the capacitor was removed from the initial simulated circuit (Figure 5.5), there was a drastic change in the output voltage.



82: Figure 5.5: Full-wave rectifier without the capacitor

The output voltage of the full-wave rectifier circuit once the capacitor was removed (Figure 5.6) is seen to be between 4.8 V and 5.4 V, which is more than the voltage seen in Figure 5.4. The voltage required to start the charge of a mobile device battery is 5 V. The results of the simulation

prove that this method of charging a mobile device battery is possible and further that the capacitor stores some of the power moving through the circuit.



83: Figure 5.6: Voltage output without a capacitor

5.2. Equations for the RF Energy Harvesting Circuit

The average DC output voltage across the sine wave in the full-wave rectifier circuit was calculated using Equation 5.4 (Agcal, Ozcira, and Bekiroglu, 2016):

$$Va = \frac{2Vp}{\pi} \quad (5.4)$$

where Va is the average voltage and Vp peak load voltage divided by π .

21: Equation 5.4: Average voltage

Electrical resistance is the opposition to the flow of voltage within the full wave rectifier circuit, and this was calculated using Ohm's law (Humbley, 2011), depicted by Equation 5.5:

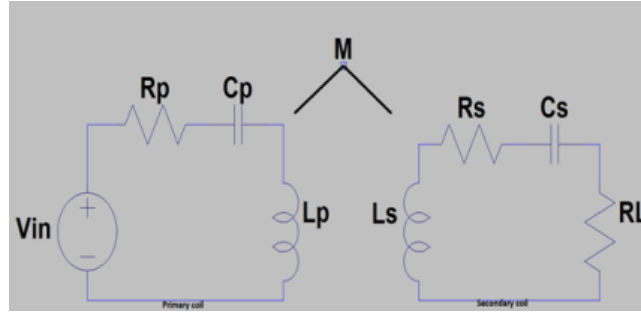
$$R = \frac{V}{I} \quad (5.5)$$

22: Equation 5.5: Resistance

where R represents the resistance value in ohms (Ω); V is the voltage; and I represents resistors with current in amps (A).

5.3 WPT CHARGING CIRCUIT – STAGE 3

Mutual inductance, represented in Figure 5.7, is the operating principle of all electrical components interacting with the magnetic field; in this case, all the components from the primary coil interact with the components of the secondary coil.



84: Figure 5.7: Mutual inductance of the primary and secondary coils

To analyse the WPT circuit, mutual inductance was taken into consideration by applying Equation 5.6

$L_p = L_s = L$ (where L_p and L_s represent the inductance in the primary and secondary coils, and L is the overall inductance)

$RL = \text{load}$

$M = \text{mutual inductance}; k = \text{coupling coefficient}; k \propto 1/\text{distance}$

$$M = \sqrt{L_p L_s}, \quad (5.6)$$

$$\therefore M = kL$$

23: Equation 5.6: Mutual Inductance

Magnetic flux (Φ) common to both the transmitting and receiving coils is represented by: $k \Phi T$, where ΦT is the total magnetic flux. Magnetic flux is only presented in one coil and is not included in the energy transfer; this is represented by: $(1-k) \Phi T$.

To further analyse the WPT circuit, it was necessary to separate the coupled circuit and include the dependent voltage sources of each coupling circuit. The dependent voltage sources are replacing the coupling between the two circuits.

$I_1 = \text{current running through the primary coil (transmitting)}$

$I_2 = \text{current running through the secondary coil (receiving)}$

Z_{Ri} = reflective impedance

$j\omega MI_2$ = dependent voltage (primary coil)

$j\omega MI_1$ = dependent voltage (secondary coil)

$$I_2 = \frac{-j\omega MI_1}{Z_s} \quad (5.7)$$

24: Equation 5.7: Current in Secondary Coil

$$Z_s = R_L + \frac{1}{j\omega C_s} + j\omega L_s + R_s \quad (5.8)$$

25: Equation 5.8: Impedance

$$\begin{aligned} j\omega MI_s &= \frac{\omega^2 M^2}{Z_s} + I_1 \\ &= Z_{Ri} I_1 \end{aligned} \quad (5.9)$$

26: Equation 5.9: Dependent Voltage (Primary Coil)

$$Z_{Ri} = \frac{(\omega M)^2}{Z_s} \quad (5.10)$$

27: Equation 5.10: Total Reflective Impedance

From Equation 5.10, we get Equation 5.11:

$$Z_{Ri} = \frac{[\omega k \sqrt{L_p L_s}]^2}{Z_s} \quad (5.11)$$

28: Equation 5.11: Total Reflective Impedance

The value at I_1 is at a maximum when Z_s is at a minimum. To get the total resistance (R_L') of the

circuit, we look at the total load (R_L) and the resistance at the secondary coil (R_s), and we get the following equations with $V_{in} = \omega_o$:

$$\omega_o = \frac{1}{\sqrt{L_p C_p}} = \frac{1}{\sqrt{L_s C_s}} \quad (5.12)$$

29: Equation 5.12: Total Reflective Impedance

$$\frac{(\omega_o M)^2}{R_L'} = \frac{k^2 \omega_o^2 L}{R_L'} \quad (5.13)$$

30: Equation 5.13: Total Reflective Impedance

$$R_L' = R_L + R_s \quad (5.14)$$

31: Equation 5.14: Total Resistance

where P = power

$$P = I_2^2 R_L \quad (5.15)$$

32: Equation 5.15: Power

Equation 5.15 is simplified into Equation 5.16:

$$P = I_2^2 \frac{(\omega_o M)^2}{R_L'} \cdot \frac{R_L}{R_L + R_s} \quad (5.16)$$

33: Equation 5.16: Power

The resistivity Equation 5.17 of the copper wire is a measure of how intensely the copper wire coils oppose the flow of electric current through the copper coils. This was calculated using the following equation:

$$p = \frac{RA}{L} \quad (5.17)$$

34: Equation 5.17 Resistivity

Where p is the resistivity, A is the area of the copper wire, L is the length of the copper wire, and R is the resistance. Generally, the resistivity of copper is 1.7×10^{-8} .

The voltage resistance (Yaghjian, 1986; Zhai, Yang, and Liu, 2017; Talaat, Metwally, and Arafa, 2018) of the copper wire is the opposition to voltage flow through the copper wire coils. This is given using Equation 5.18:

$$R = \frac{pL}{A} \quad (5.18)$$

35: Equation 5.18: Resistance Value

Where R represents the resistance value in ohms (Ω), p is the resistivity, L is the length of the copper coils, and A is the area.

The conductance of the copper wire determines the amount of voltage that flows through the copper wire. Conductance was evaluated with Equation 5.19 (Yaghjian, 1986) (Zhai, Yang and Liu, 2017) (Talaat, Metwally and Arafa, 2018) :

$$C = \frac{A}{pL} \quad (5.19)$$

36: Equation 5.19: Conductance Value

Where C represents the conductance value, A is the area of the copper wire, p is the resistivity, and L is the length of the copper wire.

The conductance was affected by the resistivity of the copper wire, that is, the total resistance the copper wire has. The larger the resistivity of the copper wire, the less conductance it possesses in a circuit. The lower the resistivity, the greater the conductance it possesses.

The coupling constant does not include the number of turns in a coil. The number of turns in a coil defines the magnetic field, which will be formed for a given current. The coupling constant includes how the lines of magnetic force created by one coil relate to the second coil, and hence the coupling constant between two air-spaced coils is dependent on physical size and the nature of the air space. Hence, to obtain the best coupling between transmitting and receiving coils in the WPT circuit, the size and spatial relationships of the coils can only be changed.

Average direct current (DC) output voltage in the energy harvesting circuit across the sine wave in the full wave rectifier circuit was calculated using Equation 5.20 (Yaghjian, 1986) (Zhai, Yang and Liu, 2017) (Talaat, Metwally and Arafa, 2018) :

$$Va = \frac{2Vp}{\pi} \quad (5.20)$$

37: Equation 5.20: Average Voltage

Where Va is the average voltage, and Vp peak load voltage divided by π .

Electrical resistance is the opposition to the flow of voltage within the full wave rectifier circuit, and this was calculated using Ohm's law (Yaghjian, 1986; Zhai, Yang, and Liu, 2017; Talaat, Metwally, and Arafa, 2018), depicted by Equation 5.21:

$$R = \frac{V}{I} \quad (5.21)$$

38: Equation 5.21: Resistance

Where R represents the resistance value in ohms (Ω), V is the voltage, and I resistor's current in amps (A).

5.4 CONCLUSION

The relevant equations and simulated circuit design were presented and explained. Various aspects regarding the three stages of this research were explained. For stage 1 (magnetic resonance coupling), resistivity, voltage resistance, and conductance of the copper wire were explained with the relevant formulas.

In stage 2 (RF energy harvesting circuit), a full-wave rectifier circuit was simulated in LTspice. Electrical resistance and average DC output voltage were presented using formulas and the sine wave.

Stage 3 (WPT charging circuit) looked at mutual inductance, magnetic flux, resistance, resistivity, voltage resistance, coupling constant, and average voltage. The overall voltage of the simulations

was between 4.8V and 5.4V, which meets the minimum requirements to initiate the charging process.

Overall, the integration of mathematical modelling and circuit simulation provided a rigorous and repeatable framework to evaluate the feasibility of the proposed WPT system. These findings form a solid foundation for subsequent physical implementation and optimization.

CHAPTER 6

DISCUSSION AND RESULTS

This chapter presents a discussion of the overall findings with the related results of the three stages for the creation of the WPT with a magnetic resonance circuit. The physical components are discussed with related limitations of the final prototype circuit.

6.1 MAGNETIC RESONANCE COUPLING – STAGE 1

Stage one comprises the creation of the magnetic resonance coupling coils. The diameter, turns, and type of wire are explained.

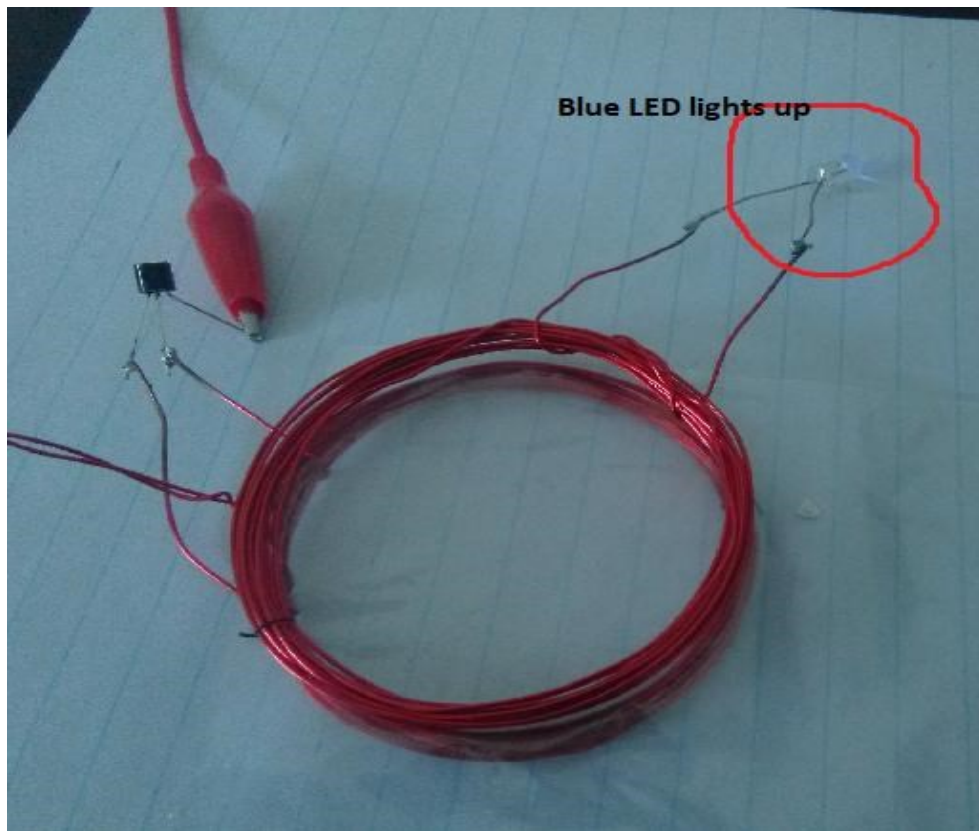
The following components comprised the initial magnetic resonance prototype circuit: 28 AWG magnetic wire and 2N222A transistor; 15 turns magnetic wire (receiver coil); 7.5 turns of the magnetic wire with a looped tap (3 cm) and then another 7.5 turns of magnetic wire (transmitting coil), each with a diameter of 5 cm (Figure 6.1). The resistivity, resistance, conductance, area (diameter in centimetres), and length were taken into consideration since they impacted the voltage flowing through the circuit. A 27K resistor can be added if the transistor overheats.



85: *Figure 6.1: Photograph of the transmitting (with transistor) coil and receiving coil*

The functionality of the magnetic resonance circuit prototype was tested using a blue LED and a 9 V battery (Figure 6.2). A blue LED was used in the testing stages due to its forward voltage

being between 3.2 V to 4.0 V, close to the start-up charge for a mobile device battery, which is about 5 V. Forward voltage is the required voltage to light up the blue LED. For this circuit, 22 AWG magnetic wire was used with a diameter of 5 cm and 15 turns for the receiver coil and 7.5 turns, then a 3 cm tap and 7.5 turns for the transmitting coil. This experiment was conducted to prove that power could be transferred wirelessly through an air gap. Figure 6.3 displays the colours of LEDs and their forward voltages.



86: Figure 6.2: Initial MR Coupling Circuit with Blue LED

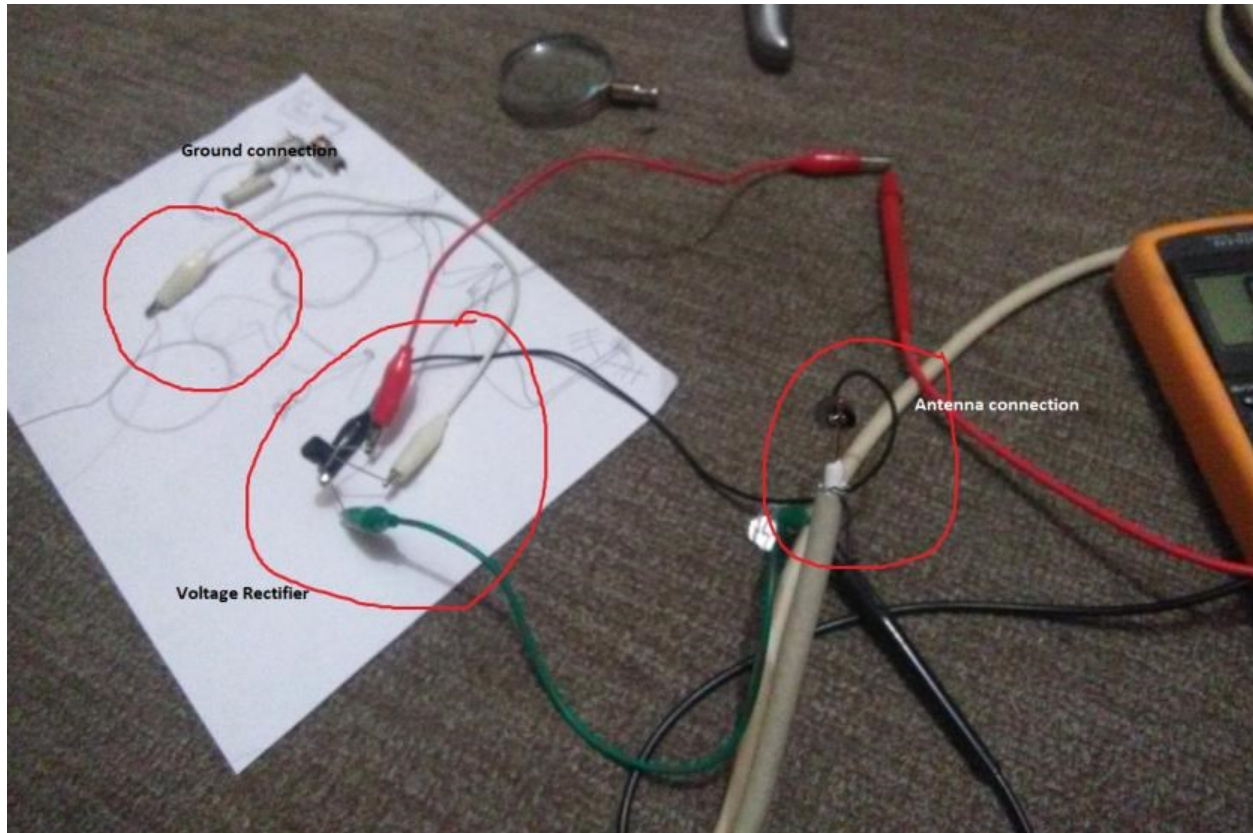
		LED Chip Code	Peak Wave length (nm)	Dominant Wave length (nm)	Color Name	Nominal Fwd Voltage (V _f @20ma)	Intensity (mcd) 5mm LEDs (For Reference)	Radiant Power mW/sr	LED Die Material
851	IR	IR851	843	N/A	Infrared	1.7	N/A	86mW@50mA	GaAlAs/GaAs
0UR		R3KF/R6	654	641	Ultra Red	1.9	1000mcd@20mA	13mW@20mA	GaAlAs/GaAlAs
00R		R3/R4/R5	640	625	HE Red	2.0	220mcd@20mA	1.8mW@20mA	GaAsP/GaP
0ER		E3K	634	624	Super E.Red	2.2	8000mcd@20mA	45mW@20mA	InGaAlP
0UO		O3KF	616	610	Super Orange	2.0	2000mcd@20mA	7mW@20mA	InGaAlP
00O		O4/O5	609	604	Orange	2.0	220mcd@20mA	0.7mW@20mA	GaAsP/GaP
0UY		Y3KF	598	593	Super Yellow	2.0	5000mcd@20mA	10mW@20mA	InGaAlP
0PY		Y3KH	592	589	Super P.Yellow	2.3	4000mcd@20mA	8mW@20mA	InGaAlP
00Y		Y3/Y4/Y5	582	584	Yellow	2.1	170mcd@20mA	0.3mW@20mA	GaAsP/GaP
0IW			3000K	N/A	Warm White	3.3	5500mcd@20mA	17mW@20mA	InGaN
XPW			6000K	N/A	Pale White	3.3	5500mcd@20mA	17mW@20mA	InGaN
0WW			8000K	N/A	Cool White	3.3	5800mcd@20mA	23mW@20mA	InGaN
0UG		G1K	575	573	Super L.Green	2.0	1800mcd@20mA	3mW@20mA	InGaAlP
00G		G3/G4/G5	563	569	HE Green	2.3	210mcd@20mA	0.03mW@20mA	GaP/GaP
UPG		PG350	563	564	Super P.Green	2.1	400mcd@20mA	0.6mW@20mA	InGaAlP
0PG		PG5	557	560	Pure Green	2.2	140mcd@20mA	0.2mW@20mA	GaP/GaP
0AG		AG10K	522	528	Aqua Green	3.4	15,000mcd@20mA	30mW@20mA	InGaN
0BG		BG7K	501	502	Blue Green	3.4	4300mcd@20mA	16mW@20mA	InGaN
0PB		PB4KB	455	460	Super Blue	3.2	3000mcd@20mA	61mW@20mA	InGaN
00B		UB500	425	447	Ultra Blue	4.0	250mcd@20mA	5mW@20mA	SiC/GaN
405	UV	UV405	402	420	Ultra Violet	3.8	39mcd@20mA	53mW@20mA	SiC/GaN

87: Figure 6.3: Forward Voltages for LEDs (kithub.cc, 2019)

6.2 RF ENERGY HARVESTING CIRCUIT – STAGE 2

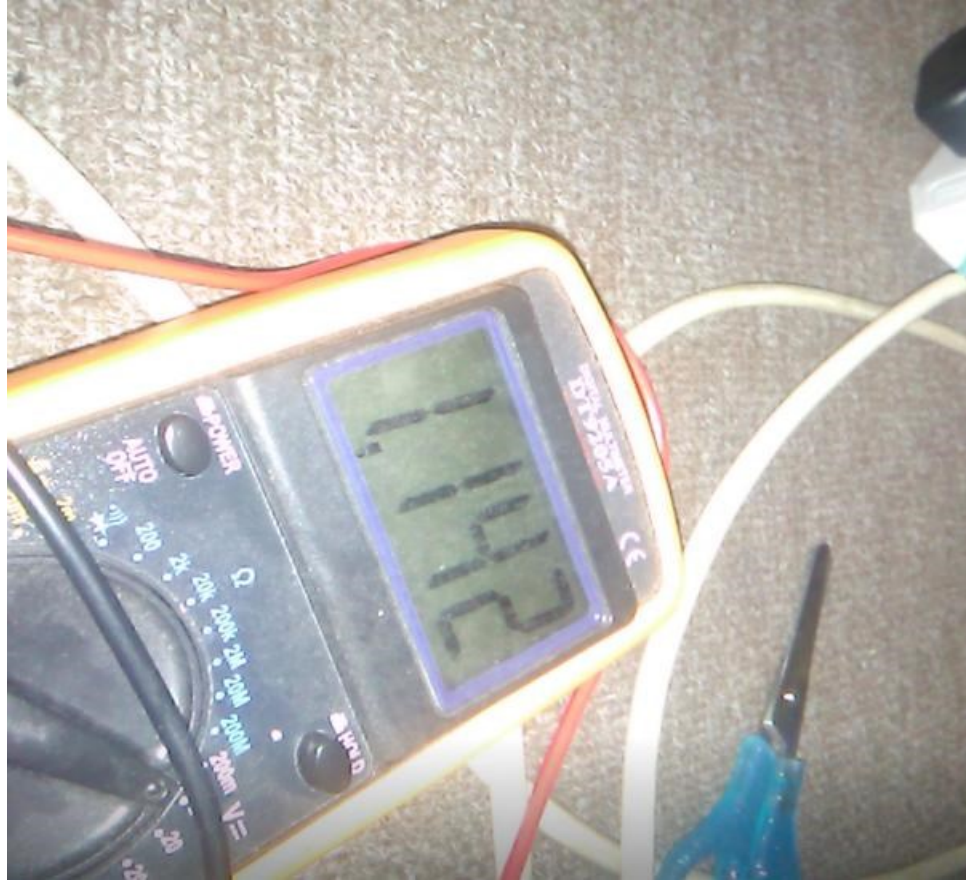
Concerning the results revealed in the simulated circuit, the RF energy harvesting circuit comprised a voltage rectifier component. This integrated passive component is similar to the full-wave rectifier circuit. Instead of building a full-wave rectifier circuit from scratch and using more components (four diodes and a resistor), the voltage rectifier seemed more convenient to use based on the mobility of the circuit and the reuse of components, since constant reworking of the circuit was done. This prevented the wastage of the components. The researcher chose not to solder the components together during this research to allow for the reworking of the circuit and for the changing placement of the circuit to check voltage gain (indoors and outdoors).

The RF energy harvesting circuit consisted of the voltage rectifier circuit (full-wave), the Yagi-Uda antenna connection (RG-5 coaxial cable), and the ground connection (straight copper cable attached to a metal pole inserted 6 m into the ground) (Figure 6.4).



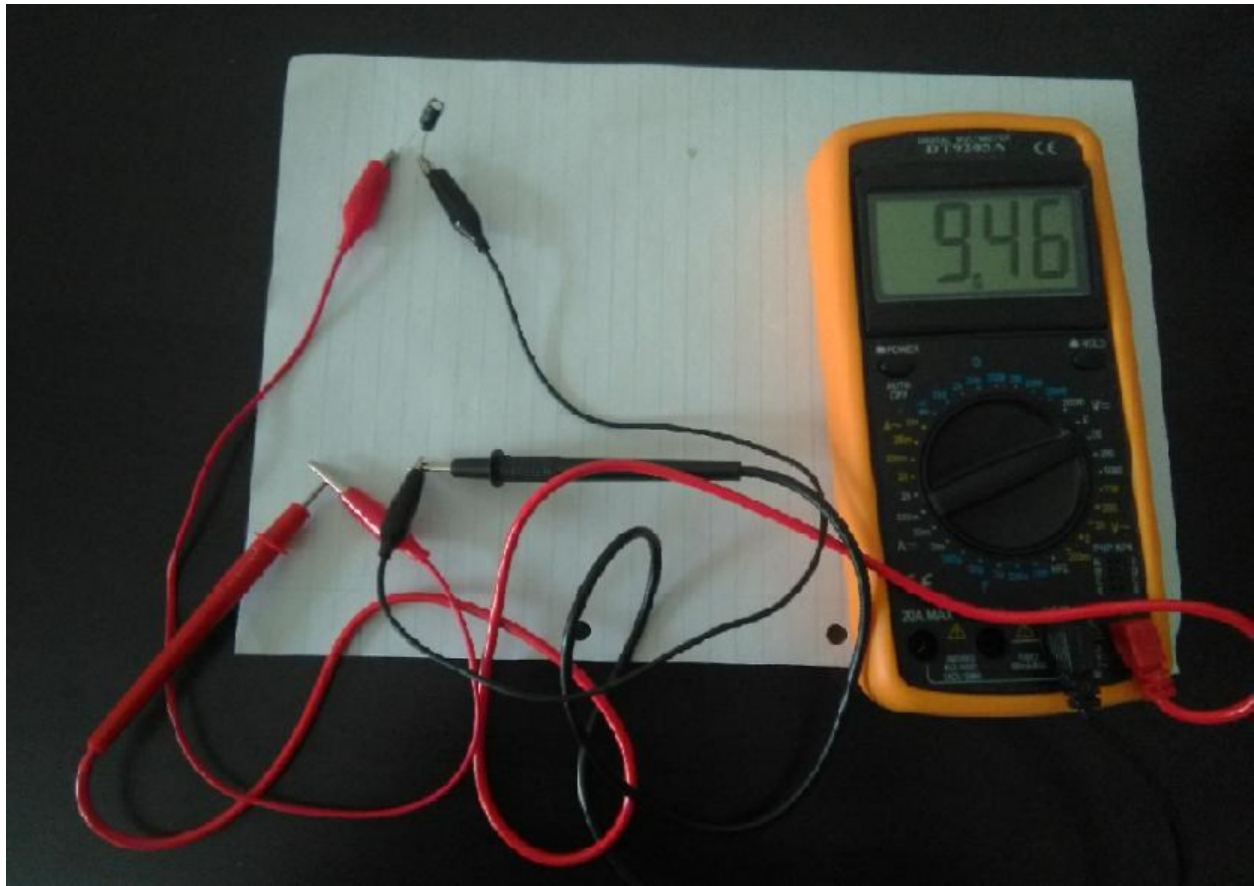
88: Figure 6.4: Experimental setup of the RF Energy Harvesting Circuit

The voltage rectifier component had four pins: one for ground connection ($\sim$), one for antenna connection ($\sim$), a positive (+), and a negative (-). A multi-meter attached to the voltage rectifier component via the positive and negative pins checked for the acquired voltage converted from the Yagi-Uda antenna via the voltage rectifier. Figure 6.5 displays the voltage of 1.142 V for 56 seconds.



89: Figure 6.5: Acquired voltage from the RF Energy Harvesting Circuit

The acquired voltage (1.142 V) was too limited for charging a mobile device battery, and transferring the power wirelessly would also result in some voltage being lost. A capacitor (100 μ F, 16 V) was included in the RF energy harvesting circuit to store the converted power. The capacitor was connected to the RF harvesting circuit for 7.5 hours. The accumulated voltage, according to the multi-meter reading, was 9.46 V (Figure 6.6). This was sufficient to commence the charging of a mobile device battery via wireless power transfer, and also was sufficient in the event of voltage loss across the air gap.

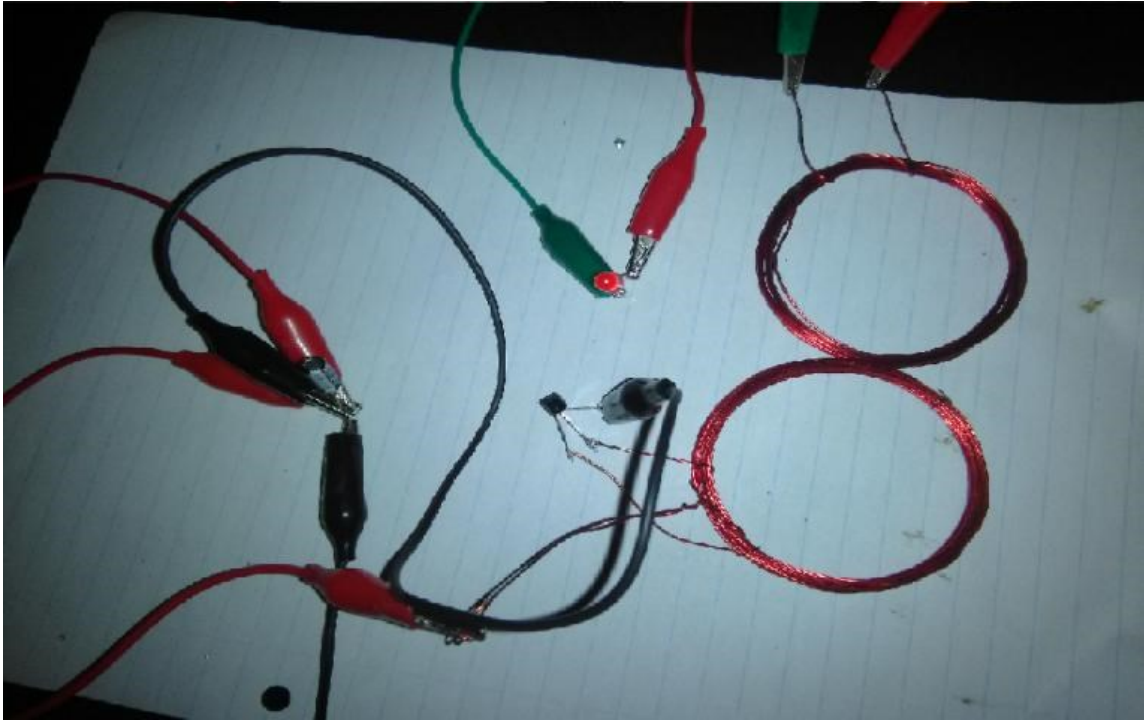


90: *Figure 6.6: Multi-meter Reading of Stored RF Harvested Energy in Capacitor 9.46 V*

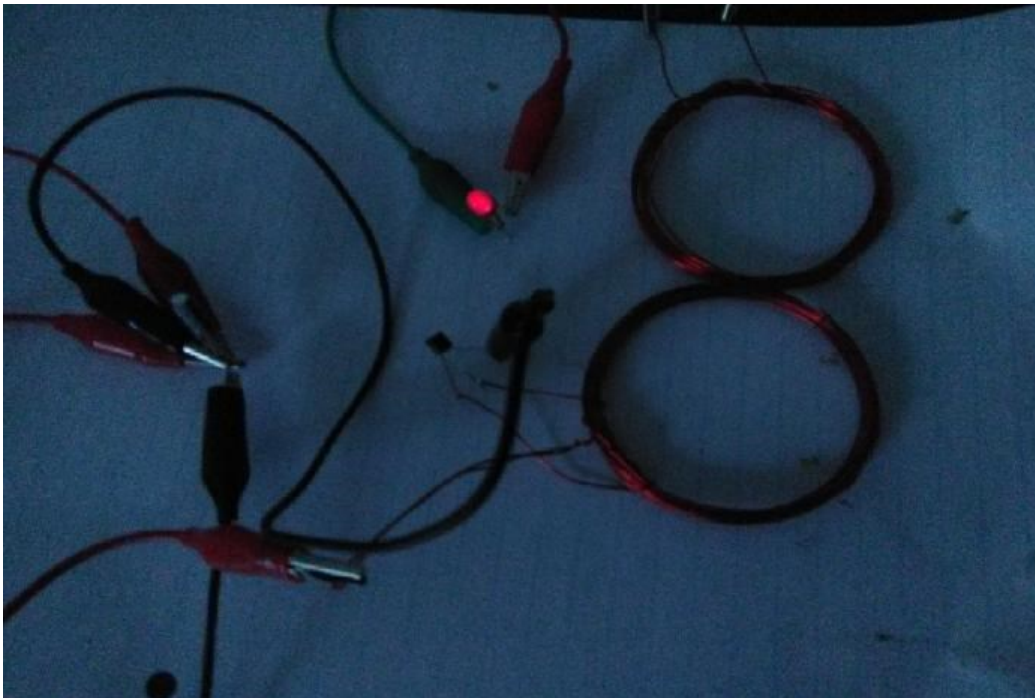
The voltage depicted by the multimeter seemed sufficient to initiate the charge on the mobile device battery since a mobile device battery requires 5V to initiate the charging process.

6.3 WPT CHARGING CIRCUIT – STAGE 3

The WPT charging circuit comprised the magnetic resonance coupling circuit and the capacitor (100 μ F, 16 V), containing the stored voltage from the RF energy harvesting circuit. The initial WPT charging circuit was tested by lighting up a red LED from the harvested energy stored in the capacitor. This yielded positive results. Figure 6.7 displays the circuit, and Figure 6.8 shows the lit-up red LED.



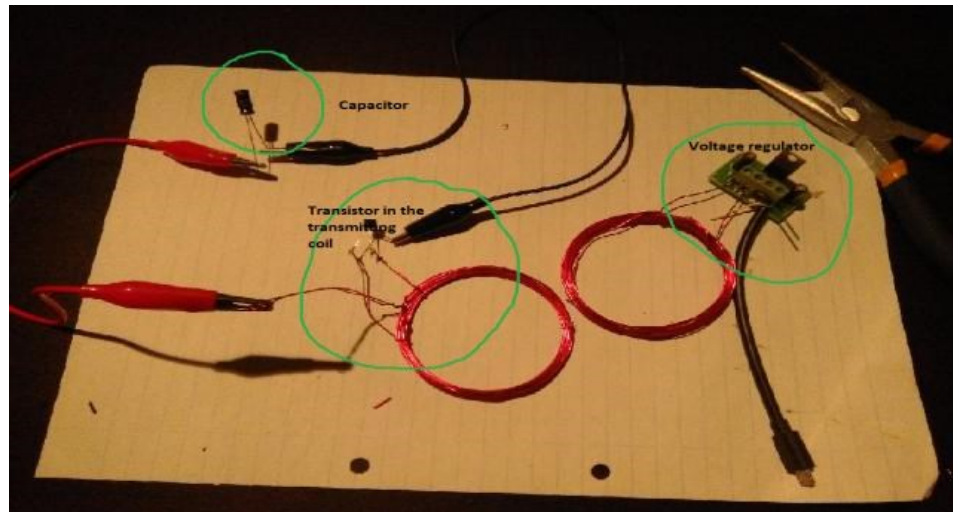
91: Figure 6.7: Capacitor joined to the MR circuit via crocodile clips



92: Figure 6.8: Lit-up LED in the MR Coupling Circuit

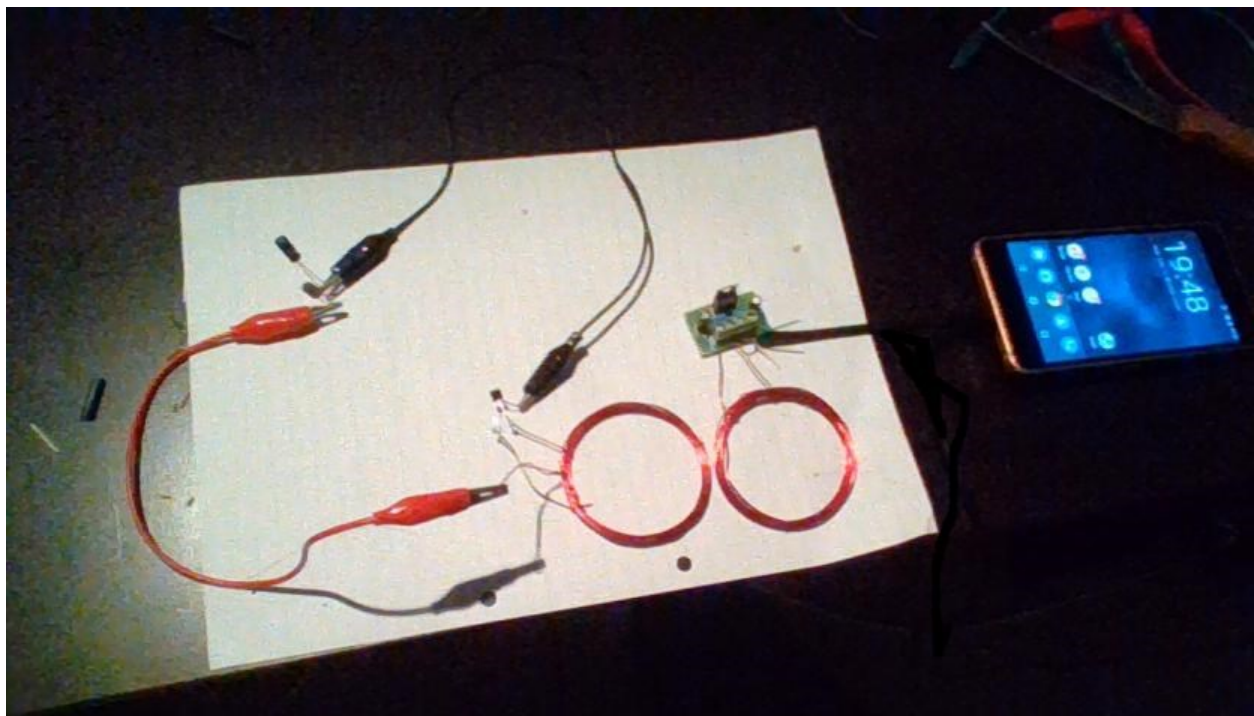
The copper coils were created using the 22 AWG (much thicker) magnetic wire; this was done to check the efficiency of the transferred power. The final WPT charging circuit included a voltage

regulator component to control the required voltage to the mobile device battery for charging, i.e., 5 V to initiate the charging process. The capacitor with the stored charge was connected to the WPT charging circuit (Figure 6.9).



93: Figure 6.9: WPT Charging Circuit

Figure 6.10 displays the charging process of the mobile device battery via the WPT charging circuit.



94: Figure 6.10: WPT Circuit Charging Mobile Device Battery

It can be concluded based on the results discussed in this chapter that WPT using an alternative form of energy is possible and is readily available in the presence of a rooftop (Yagi-Uda) antenna.

This final stage demonstrates the successful integration of RF energy harvesting with magnetic resonance coupling, addressing a gap highlighted in prior studies (Section 2.10). While most existing research focused on charging wireless sensor nodes with limited power requirements (Jabbar et al., 2010; Liu et al., 2016), this prototype accumulated sufficient energy (9.46V) to initiate the charging of a mobile device battery, showing feasibility for higher-power applications.

6.4 LIMITATIONS OF THE WPT PROTOTYPE

This section explains the limitations experienced while conducting the experiments. The first limitation was sourcing the circuit components timeously for building the WPT circuit since most components were only obtainable from other countries and required online orders. This was time-consuming given the waiting period for the delivery of the components.

Secondly, the selection of a viable antenna to connect the RF energy harvesting circuit was an issue. Other antennas, such as the straight copper wire antenna (from clock radios), were tested but seemed to be inefficient. The most feasible and easily available antenna seemed to be the common roof-top TV antenna (Yagi-Uda). It took rigorous testing to select the correct antenna.

Finally, the demonstration of the complete WPT circuit required constant reworking for the most efficient circuit component layout and the selection of the most efficient components. This resulted in the researcher not soldering components together.

6.4.1 Practical Limitations of the WPT Prototype

Several practical challenges were encountered during the experimental phase of this study, which influenced the pace and scope of implementation of the proposed WPT system. These limitations are outlined below:

- **Component Availability and Procurement Delays:** A major limitation was the difficulty in sourcing essential components for the construction of the wireless power transfer (WPT) circuit. Many of the required parts, particularly those for RF energy harvesting and magnetic resonance coupling, were not readily available locally and had to be procured through

international suppliers. This dependency on overseas vendors led to significant delays due to extended shipping times and customs processing, ultimately prolonging the experimental timeline. Furthermore, the inability to obtain alternative or substitute components locally constrained the flexibility in the design and testing process.

- **Antenna Selection and Performance Optimization:** Another critical limitation was the identification and integration of a suitable antenna for the RF energy harvesting circuit. Several antenna types were tested, including simple wire antennas salvaged from old electronic devices such as clock radios. However, these were found to be ineffective for harvesting ambient RF signals with sufficient efficiency. After considerable experimentation, the most feasible and effective solution was determined to be a conventional rooftop TV antenna (Yagi-Uda). While this antenna type offered better performance, its size and directional properties introduced new challenges related to positioning and practical deployment. The process of selecting and tuning the antenna was time-intensive and required iterative testing under various conditions.
- **Circuit Configuration and Assembly Challenges:** The construction of a fully functional WPT circuit required repeated modifications to the circuit layout and the use of various component configurations to optimize performance. Achieving an efficient layout was not straightforward due to the sensitivity of the circuit to component placement and signal interference. This necessitated a flexible and modular approach to assembly. As a result, the final circuit was not permanently soldered, allowing for ease of adjustment but compromising mechanical stability and robustness. This limitation affected the consistency of the results and highlighted the need for a more finalised, soldered configuration for any long-term or field deployment.

These limitations underscore the complexity of implementing experimental WPT systems and the importance of considering logistical, material, and technical constraints during the design and prototyping phases. Future work should explore locally sourced alternatives, modular and scalable hardware designs, and more efficient assembly methods to streamline development and enhance system stability.

6.5 CONCLUSION

The three stages were explained. Stage 1 (magnetic resonance coupling) comprised two coupling coils adhering to the appropriate diameter and number of turns, tightly coupled. Functionality of the coils was tested with positive results before proceeding to Stage 2.

Stage 2 (RF energy harvesting circuit) comprised of a full-wave rectifier and the Yagi-Uda antenna. The accumulated voltage from the physical circuit returned a positive value of 9.4V which is more than the simulated circuit.

Stage 3 (WPT charging circuit) comprised the magnetic resonance couple portion, inclusive of a capacitor and the RF energy harvesting circuit. The circuit was tested and yielded positive results, thus proving the circuit to be successful in charging a mobile phone battery. The stored energy was successfully transferred through the magnetic resonance coupling circuit and used to power a red LED and eventually initiate the charging of a mobile device battery. The use of thicker (22 AWG) copper coils and the integration of a voltage regulator helped to maintain a stable output of $5.1 \text{ V} \pm 0.15 \text{ V}$ during charging attempts ($n = 3$), confirming that the harvested energy could be effectively transferred and regulated. However, more systematic measurements with proper load emulation and real-time data logging are recommended to reduce uncertainty and quantify energy transfer efficiency.

The findings of this study validate the possibility of combining ambient RF energy harvesting with wireless power transmission via magnetic resonance, a novel contribution not previously demonstrated in the reviewed literature (Brown, 1969; Bouchouicha et al., 2010; Mishra et al., 2015). While prior work typically used batteries or generators as energy sources for WPT systems, this study proves that harvested RF energy alone can serve as the energy source, thus supporting more sustainable and autonomous charging systems.

CHAPTER 7

CONCLUSION AND FUTURE WORK

This chapter provides a summary of the research study presented in this thesis. Various experiments at each stage of the WPT charging circuit were conducted. The outline of the research task and the concluding results are presented initially. Next, insights into potential future work and improvements are provided.

7.1 CONCLUSION

WPT is considered a promising advancement for charging mobile phones through magnetic resonance coupling and RF energy harvesting. This concept is seen as a green energy source since it includes the conversion of RF signals radiating from an antenna into useful voltage power and thus results in mobile devices becoming self-sustaining. Another reason for this concept being considered a green energy initiative is that the wireless transfer of power eliminates excessive use of cables. There is, however, limited research conducted on using both magnetic resonance coupling and RF energy harvesting. The simulated WPT prototype circuit provided promising results to consider for developments in battery design or technology, based on the use of a capacitor to store the converted RF energy.

This research study aimed to wirelessly charge mobile device batteries through RF energy harvesting and magnetic resonance coupling. Several research objectives emerged from this aim, for which literature was reviewed, and theories, models, formulae, and innovations in antenna design, RF energy circuits, and magnetic resonance coupling concepts in various fields were considered. Literature findings in magnetic resonance coupling for charging of mobile device batteries were seriously lacking, with only one literature study identified that was closely related to the charging concept.

Research in antenna designs and the feasibility of RF energy harvesting was reviewed, and the findings resulted in choosing the Yagi-Uda antenna as the most feasible and easily available due to the time constraints of this research. Further literature on the implementation of WPT in electric

vehicles was reviewed, and this seems to be the trend for WPT implementation. The majority of the reviewed research was based on WPT in the charging of electric vehicles, both stationary and moving. Further research in WPT within the medical field was reviewed – this seemed popular since WPT was first investigated in wireless sensor networks. WPT seems most useful in the medical field for the charging of pacemakers and endoscopic equipment, and concepts.

Results of the simulations and practical experiments revealed promising results towards a novel charging concept. Stage one of the research comprised testing the magnetic resonance coupling circuit using the 28AWG magnetic wire. This provided positive results by lighting up an LED wirelessly, with the energy source being a 9V battery. Stage two involved maximising the energy acquired from the RF energy harvesting circuit. The final WPT circuit consisted of a voltage rectifier, the Yagi-Uda antenna, and a capacitor to store the converted energy since the initial circuit had produced a voltage of 1.142 V. The limited voltage produced was not enough to initiate the charging process of a mobile device battery, which required 5 V to start the charging process. A total of 9.42 V of converted power was accumulated and stored in the capacitor. This was enough to commence the charging of a mobile device battery.

Finally, stage three was based on including the capacitor with the stored charge in the magnetic resonance coupling circuit to wirelessly charge mobile device batteries. This provided optimistic results and satisfied the aim of this research. WPT to charge mobile device batteries is indeed possible and should be considered for future charging mechanisms.

The experimental results aligned with and met the following key benchmarks:

- Minimum voltage benchmark: The target voltage of $\geq 5\text{V}$ —necessary to initiate mobile phone battery charging, was exceeded. Stage 2 successfully accumulated and stored 9.42V from the RF energy harvesting circuit in a capacitor, meeting and surpassing this performance threshold.
- No external power source requirement: The final system relied exclusively on ambient RF energy and magnetic resonance for energy transfer, confirming that a fully self-sustaining, battery-free system is feasible.
- Modular, practical design: Each stage was designed to be modular and reproducible, supporting future scalability and use in mobile or remote charging scenarios.

- Circuit validation through simulation and physical testing: The combination of simulated analysis and physical testing showed consistent results, validating the system's design under realistic conditions.
- Novelty and contribution: This is among the first experimental demonstrations (based on the reviewed literature) to integrate RF energy harvesting and magnetic resonance coupling into a single wireless charging system for mobile devices, moving beyond traditional reliance on batteries or wired generators.

Stage one demonstrated successful magnetic resonance energy transfer using a tightly wound 28AWG coil, confirmed through LED activation powered wirelessly from a 9V battery. In stage two, the rectifier circuit paired with the Yagi-Uda antenna initially yielded a low voltage of 1.142V, which was later enhanced to 9.42V after design adjustments. This voltage was sufficient to begin the charging process. Stage three involved integrating this stored energy into the resonance circuit to wirelessly charge a mobile device battery, completing the system's design cycle.

In conclusion, this research validates the technical feasibility and sustainability of using ambient RF energy as a viable input for wireless power transmission via magnetic resonance. The achievement of all performance benchmarks confirms the potential for real-world applications in self-powered charging systems. Future research could explore efficiency optimisation, miniaturisation of components, or integration with smart power management systems in mobile devices.

7.2 FUTURE WORK

Wireless Power Transfer (WPT) remains an evolving field of research, and the outcomes of this study provide a solid foundation for further investigation and development. While the current system successfully demonstrated the feasibility of magnetic resonance coupling and RF energy harvesting, several areas for future work have been identified to enhance performance, efficiency, and applicability.

One of the primary directions for future work involves combining the two core models explored in this research: the magnetic resonance coupling-based WPT system and the simulated RF energy harvesting circuit. A fully integrated hybrid system could offer a more robust and sustainable energy transfer solution, particularly for low-power applications and mobile devices.

The current implementation uses copper wire for coil construction. Future experiments should investigate the use of solid copper coils, which may reduce energy losses caused by spacing between wire turns. Solid coils could provide more stable voltage delivery and eliminate the inefficiencies associated with both strongly and loosely coupled wire-based coils.

The effect of the distance and alignment between transmitting and receiving coils requires further empirical analysis. Varying the separation and diameter of the coils could reveal optimal configurations for maximizing power transfer efficiency at different ranges. This will be essential for adapting WPT systems to real-world environments where perfect alignment cannot always be guaranteed.

The performance of the RF energy harvesting circuit is heavily dependent on the type and design of the antenna. While this study identified the Yagi-Uda antenna as a feasible option, future work should explore alternative antenna types, including printed antennas, patch antennas, or satellite-based antennas, which may offer higher gain and improved efficiency. Such antennas could significantly increase the harvested voltage, making the RF subsystem more viable for practical applications.

The current WPT system was able to charge a mobile device battery. Future developments should aim to scale up the system to charge other portable electronics with higher power demands, such as laptops, tablets, and power banks. This will require further refinement of the circuit design, power management systems, and safety considerations to ensure reliability across diverse device types.

This future work aims to bridge the gap between experimental validation and practical deployment by enhancing system efficiency, reliability, and scalability. Ultimately, the goal is to develop a comprehensive WPT solution capable of supporting a wide range of electronic devices in both personal and industrial settings.

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