Sudan University of Science and Technology

College of Engineering

Electrical Engineering

Design and Implementation of Wireless Omnidirectional Power Transfer System using Inductive Coupling

تصميم و تنفيذ نظام نقل الطاقة لاسلكياً متعدد الاتجاهات باستخدام الاقتران الحثي

A Project Submitted In Partial Fulfillment for the Requirements of the Degree of B.Sc. (Honor) In Electrical Engineering (Control)

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الآية

بسم الله الرحمن الرحيم

قال الله تعالى :

(يَرْفَعِ اللّهُ الّذِينَ آمَنُوا مِنكُمْ وَالّذِينَ أُوتُوا الْعِلْمَ دَرَجَات)

صدق الله العظيم

سورة المجادلة ، الأية 11

DEDICATION

To our beloved, sainted mothers and fathers who supported us, to the hundreds of young men and women who are in our university in pursuit of an education; And to everyone who made a positive effect on us.

ACKNOWLEDGEMENT

We would like to express our special thanks of gratitude to our teacher **Dr. Awadallah Taifour Ali,** who gave us the golden opportunity to do this wonderful project, and also helped us in completing our project. Secondly we would also like to thank anyone who helped us a lot in finalizing this project within the limited time frame.

ABSTRACT

Wireless Power Transfer (WPT) through inductive coupling could be one of the next prominent technologies that is widely used in the near future. However most WPT systems used today involve flat spiral coils that are suitable only for power transfer in one direction which is impractical for most applications. This study develops a two-loop and three-loop omnidirectional WPT system. Experimental results of coil separation distance, lateral misalignment and angular misalignment have been obtained using the single loop, two-loop and three-loop WPT systems. The results have been displayed in graphs using MATLAB software. By comparing different results obtained it was found that omnidirectional WPT systems exhibit better efficiency in terms of the coil separation distance, lateral misalignment and angular misalignment.

المستخلص

ان نقل الطاقة لاسلكياً من خلال الاقتران الحثي يمكن أن تكون واحداً من التكنولوجيات البارزة و الشهيرة في المستقبل القريب. و لكن معظم أنظمة نقل الطاقة لاسلكياً المستخدمة حالياً تتضمن استخدام أسلاك ملفوفة ذات حلقة واحدة مناسبة لنقل الطاقة في اتجاه واحد فقط و الذي لا يعتبر عملياً في معظم التطبيقات. في هذه الدراسة يتم تصميم نظام نقل الطاقة لاسلكياً متعدد الاتجاهات باستخدام أسلاك ملفوفة ذات حلقتين و ذات ثلاثة حلقات. تم الحصول على النتائج العملية بالنسبة للمسافة الفاصلة بين الأسلاك الملفوفة؛ الازاحة الخطية و الازاحة الزاوية من أنظمة نقل الطاقة لاسلكياً ذات حلقة واحدة؛ ذات حلقتين و ذات ثلاثة حلقات. تم عرض النتائج في صورة رسومات بيانية باستخدام برنامج ماتلاب. بمقارنة النتائج المختلفة الذي تم الحصول عليها وجد أن انظمة نقل الطاقة لاسلكياً متعدد الاتجاهات تعرض كفاءة أفضل في حالات المسافة الفاصلة بين الأسلاك الملفوفة؛ الازاحة الخطية و الازاحة الزاوية.

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
EITS	Electronic Intelligent Tag System
EXT	External Trigger
EVs	Electric Vehicles
LED	Light Emitting Diode
LVAD	Left Ventricular Assist Device
PoWiFi	Power Over Wi-Fi
RF	Radio Frequency
RFID	Radio-Frequency Identification
SWER	Single-Wire Earth Return
WPT	Wireless Power Transfer
WSN	Wireless Sensor Networks

LIST OF SYMBOLS

Hz	Hertz
K	Kilo
M	Mega
G	Giga
λ	Wavelength
m	Meter
s	Second
n	Nano
mW/cm^2	milliwatts per square centimeter
L	Inductance
v(t)	Voltage for time
i(t)	Current for time
ω	Angular Frequency
C	Capacitance
V	Voltage
Volts/Div	Volts-per-Division
Sec/Div	Seconds-per-Division
mm	Millimeter
cm	Centimeter
deg	Degree

CHAPTER ONE

INTRODUCTION

1.1 General

Electrical power transmission is known as the bulk transfer of electrical energy using transmission lines directly connecting the source and the load. This is usually done using electrical cables, which are able to handle the relatively low frequency of the alternating current at 50-60Hz. However electrical cables are not able to carry alternating current in the radio frequency (RF) range, which is the range containing electromagnetic wave frequencies extending from around 3kHz to 300GHz, as the energy radiates off the cable as radio waves at such high frequencies causing power loss.

This radio frequency energy however can be transmitted wirelessly through the air via energy coupling, such as inductive or magnetic coupling, which occurs when an energy source has a means of transferring energy to another object. Inductive coupling occurs when the source drives a primary coil, creating a sinusoidally varying magnetic field, which induces the voltage across the terminals of a secondary coil, and thus transfers power to a load. Inductive coupling is the most widely used WPT technology for transferring power between two coupled coils that are adjacent to each other so that the magnetic field of one coil passes through the other coil [1, 2].

1.2 Problem Statement

Generally, WPT systems have the power flow either in one direction or two directions on the same plane, where the transmitter and receiver coils have to be placed close to each other on a common axis and facing each other in order to transfer power efficiently without any major losses. This means that the coils should be positioned directly face-to-face without any lateral, angular or rotational misalignment between them, since any misalignment between the coils will result in a considerable drop in the system's efficiency. An efficient orientation insensitive WPT system is important for a higher degree of freedom in movement [3].

1.3 Objectives

The main objective of this study is to design and implement a wireless omnidirectional power transfer system via inductive coupling that is not highly affected by lateral and angular misalignment between the transmitter and receiver coils as the traditional WPT systems. In addition to that, other objectives of this study are:

- Designing and implementing two-loop and three-loop multi-turn coils.
- Tuning the transmitter and receiver coils to resonate at the same frequency.
- Taking experimental results concerning coil separation distance along with lateral and angular misalignments between coils.

1.4 Methodology

The omnidirectional WPT system using inductive coupling would require:

- Study of all related previous works in the field .
- Using Radio Frequency to carry the remote signal.
- Using MATLAB software to display the experimental results.

1.5 Layout

This study consists of five chapters:

Chapter one covers the introduction of power transmission, as well as the problem statement, the objectives and methodology of this study.

Chapter two describes the theoretical background of WPT in terms of the history, the technologies, the applications of the future aspects of WPT.

Chapter three discusses the components and circuits used in this study. It also describes the operation of the circuit and the principles of inductive coupling.

Chapter four gives a general idea of system implementation and experimental results, in addition to the performance of the circuits being evaluated.
Chapter five provides the conclusion and recommendations of the study.

CHAPTER TWO

THEORETICAL BACKGROUND

2.1 General

Wireless Power Transfer (WPT) is the technology that enables the transmission of electrical energy from the power source to an electrical load without the need for a medium of interconnecting wires, but rather through the air medium. Wireless power transmission technologies generally use time-varying electric, magnetic, or electromagnetic fields. A block diagram of the wireless power transmission is shown in Figure 2.1 [1].

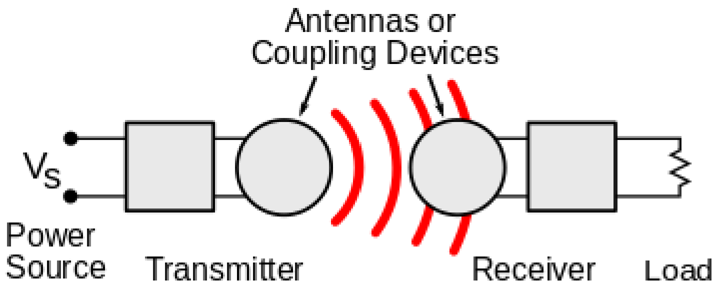

Figure 2.1: WPT system

There has been a variety of approaches and technologies developed over the years when it comes to WPT, which mainly fall into two categories, non-radiative or near field techniques involving the transfer of power using inductive or capacitive coupling and radiative or far field techniques where power is transferred by beams of electromagnetic radiation, also called power beaming.

Historically, The discussion of wireless power transmission as an alternative to transmission line power distribution alongside other practical applications started in the late 19th century. Both Heinrich Hertz and Nicolai Tesla theorized the possibility of wireless power transmission [4].

In terms of applications, WPT could gradually and perhaps eventually eliminate traditional charging systems, in which wireless power can be harnessed and implemented such that any device or load can be charged continuously and wirelessly without the need for plugging anything in. Higher level applications include charging of electric vehicles (EVs), and future and theoretical applications include a potential solution to renewable energy for the planet, by means of satellites collecting sunlight and sending power back to earth [5].

2.2 History of WPT

The early history of wireless power transfer involves two main figures: Heinrich Hertz and Nikola Tesla.

Hertz proved that electricity can be transmitted in electromagnetic waves. In 1889 Hertz created an experiment to generate high-frequency power and detect it at the receiving end. Hertz laid the foundation for wireless power and communication transfer.

Tesla's theory of the wireless transmission of power was a little different than today's vision; it was centered on his consideration of the earth as a giant conductor. Tesla transferred power directly through the earth's surface. Tesla held a firm belief that wireless power transfer was feasible, yet after considerable expenditures of time and money, he was unable to conclusively demonstrate its viability, and that was mainly due to insufficient funding [6].

2.3 Technologies of WPT

Wireless Power Transfer (WPT) is a collective term that refers to a number of different technologies for transmitting energy by means of electric, magnetic or electromagnetic fields. The technologies differ in the distance over which they can transfer power efficiently, whether the transmitter must be aimed or directed at the receiver, and in the type of electromagnetic energy they use: time-varying electric fields, magnetic fields, radio waves, microwaves, or infrared or visible light waves.

Accelerating electric charges, such as those found in an alternating current (AC) of electrons in a wire, create time-varying electric and magnetic fields in the space around them. These fields can exert oscillating forces on the electrons in a receiving antenna, causing them to move back and forth. These represent alternating current which can be used to power a load.

The oscillating electric and magnetic fields surrounding moving electric charges in an antenna device can be divided into two regions, depending on distance from the antenna. The boundary between the regions is somewhat vaguely defined. The fields have different characteristics in these regions, and different technologies are used for transferring power, which can be broadly classified into near field (non-radiative) coupling-based charging and far field (radiative) RF-based charging.

2.3.1 Near Field (Non-Radiative) Transfer

In near field or non-radiative techniques, power is transferred by magnetic fields using inductive coupling between coils of wire, or by electric fields using capacitive coupling between metal electrodes.

The Near-field or non-radiative region means the area within about 1 wavelength (λ) of the antenna. In this region the oscillating electric and magnetic fields are separate and power can be transferred via electric fields by capacitive coupling (electrostatic induction) between metal electrodes, or via magnetic fields by inductive coupling (electromagnetic induction) between coils of wire. These fields are not radiative, meaning the energy stays within a short distance of the transmitter. If there is no receiving device or absorbing material within their limited range to couple to, no power leaves the transmitter.

The range of these fields is short, and depends on the size and shape of the antenna devices, which are usually coils of wire. The fields, and thus the power transmitted, decrease exponentially with distance, so if the distance between the two antennas is much larger than the diameter of the antennas very little power will be received. Therefore, these techniques cannot be used for long range power transmission.

The range of near-field devices is divided into two categories, and they are short range (up to about one antenna diameter) which is the range over which ordinary non-resonant capacitive or inductive coupling can transfer practical amounts of power, and mid-range (up to 10 times the antenna diameter) which is the range over which resonant capacitive or inductive coupling can transfer practical amounts of power.

Some of the most common methods used for the wireless transmission of electricity in terms of the near-field region are:

A. Electromagnetic Induction

The electromagnetic induction or inductive coupling technology is used at distances of up to about one-sixth the wavelength. Near field energy is non-radiative but some radiative losses do occur. Furthermore, there are resistive losses. With electromagnetic induction electric current passes through a primary coil which generates a magnetic field that acts on a secondary coil generating a current therein. Coupling, has to be in order to achieve high efficiency.

The action of an electrical transformer is the simplest form of wireless power transfer. The primary and secondary circuit of a transformer are not directly connected. Energy transfer takes place through a process known as mutual inductance. Main functions are stepping the primary voltage either up or down and electrical isolation. Electric toothbrush chargers are an example of how this principle is used. Figure 2.2 shows a simple diagram of electromagnetic induction between two coils.

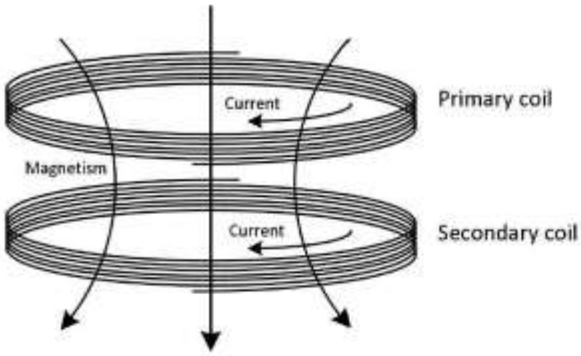

Figure 2.2: Electromagnetic induction

The main drawback of this basic form of short range wireless transmission is that the receiver needs to transmit directly to the induction unit or to couple efficiently to it. The application range of the resonance increases slightly. If resonant coupling is used, the transmitter and receiver are tuned to the same resonant frequency inductors.

B. Electrostatic Induction

Electrostatic induction or capacitive coupling is the passage of electric energy by a dielectric. In practice, there is an electric field gradient or differential capacitance between two or more insulated blocks, plates, electrodes, or nodes, which are elevated above a conductive ground plane. The electric field is generated by feeding the sheets with a high potential, high-frequency AC power supply. The capacitance between two terminals and a higher powered device form a voltage divider. The electrical energy which is transmitted through electrostatic induction is then used by a receiving device.

Nikola Tesla demonstrated the illumination of wireless lamps by energy that is coupled into them through an alternating electric field using the Tesla coil shown in Figure 2.3.

Figure 2.3: Tesla coil

C. Electrical Conduction

There are two approaches for this method. The first type is the disturbed charge of ground and air approach. The wireless transmission of alternating current through the earth with an equivalent electrical displacement obtained by the air above long areas that are higher than the resonant electrical induction methods and low compared with the electromagnetic radiation methods. Electrical energy can be transmitted through earth with low loss because the net resistance between earth antipodes, which are two points in the earth that are opposite to each other, is less than 1 ohm.

The electrical adjustment takes place by electrical conduction through the oceans, metallic ore bodies and similar subsurface structures. Recipients are attracted by currents through the earth while an equivalent electric displacement is carried out in the atmosphere. This energy transfer process is suitable for the transmission of electric energy in industrial quantities and also for wireless broadband telecommunications.

The Wardenclyffe Tower project shown in Figure 2.4 was an early commercial venture for a wireless telephone network and proof-of-concept demonstrations of global wireless power transmission using this method. The plant was not completed due to insufficient funding. A global system for "the transmission of electrical energy without wires" called the world wireless system, dependent upon the high electrical conductivity of the plasma and the high electrical conductivity of the earth, was proposed in 1904.

Figure 2.4: Wardenclyffe tower

The second approach to this method is the terrestrial transmission line with atmospheric return approach involving Single-wire earth return (SWER) electrical power transmission systems. SWER is a single-wire transmission line which supplies single phase electric power from an electrical grid to remote or rural areas at low cost. Its distinguishing feature is that the earth (or sometimes a body of water) is used as the return path for the current, to avoid the need for a second wire (or neutral wire) to act as a return path.

SWER transmission systems rely on electricity, which is insulated by the earth and a single line from the earth to complete the circuit. In emergencies high-voltage DC power transmission systems can also operate in the SWER mode. Removal of the insulated wire, and the transmission of alternating high potential through the earth with an atmospheric return line is the base of this method for the wireless transmission of electrical energy.

This approach depends on the atmospheric line passage of electric current through the earth and the lower regions of the atmosphere. This flow is caused by electrostatic induction up to a height of about 3 miles.

2.3.2 Far Field (Radiative) Transfer

In far-field or radiative techniques, also called power beaming, power is transferred by beams of electromagnetic radiation. These techniques can transport energy for longer distances but the beam must be aimed at the receiver. Far field methods achieve longer ranges, often several kilometers ranges where the distance is much greater than the diameters of the devices, since electromagnetic radiation in the far-field can be made to match the shape of the receiving area (using high directivity antennas or laser beams).

The most common methods used for the wireless transmission of electricity in terms of the far-field region are:

A. Radio Waves and Microwave

Since directional transmission using radio waves is long distance, power transmission are at shorter wavelengths of the electromagnetic radiation, typically in the microwave range. A rectenna, which is a rectifying antenna used for converting electromagnetic energy into DC power, converts the microwave energy into electricity. Rectenna efficiencies have been realized in excess of 95%.

Power beaming using microwaves used for the transfer of energy from solar power satellites orbiting the earth has been considered. However it has been proposed that power beaming by microwaves has the difficulty that for most space applications the required transmitting antenna and receiving rectenna sizes are very large due to the limited antenna directivity. For example, the 1978 NASA study of solar energy requires satellite a 1 km diameter transmitting antenna, and a 10 km diameter receiving rectenna for a microwave beam at 2.45 GHz.

These sizes can be reduced by using shorter wavelengths, although short wavelengths may have difficulties with atmospheric absorption and beam blockage by rain or water droplets. For earthbound application a 10 km diameter receiving array is used in the low power density level for human electromagnetic exposure safety. A human safe power density of 1 mW/cm^2 over a 10 km diameter which corresponds to a total of 750 megawatts. This is the power found in many modern power plants.

B. Laser

In the case of electromagnetic radiation closer to the visible region of the spectrum, power can be transmitted by converting electricity into a laser beam, which is then pointed at a solar cell receiver. This mechanism is generally known as power beaming because the power is beamed at a receiver that can convert it into electrical energy.

The laser power beaming technology has been studied primarily in military weapons and space applications and it could be developed for commercial and consumer electronics applications. However WPT systems using laser for consumer electronics applications have to satisfy Laser safety requirements [7].

2.4 Applications of WPT

There are numerous WPT applications that could be used in various fields. For example, WPT could remove traditional charging systems that are in place today. Instead of plugging in a mobile phone or laptop via a power charger to charge the battery, wireless power can be harnessed and implemented in a home such that a laptop and phone charge continuously and wirelessly without the need for plugging anything in. Some applications of wireless energy transfer are described in this section.

2.4.1 Battery Charging

Electronic portable devices (LED lighting, low power radio, media remotes, audio headsets, game controllers, cell phones, laptops, tablets, smart watches, etc.) are found all over the world and are owned and used by billions of people. What these devices all have in common is the need to recharge their internal battery so that the device can be used while mobile.

Such is the issue of portable devices, as they run using internal power which means they can be used anywhere, however eventually they must be connected to a power charger in order to charge. WPT has the ability to disable and revolutionize the traditional mobile device, not only by making mobile devices more convenient by removing the need for physical power supplies, but also being more secure (as power chargers bear the risk of shock and can cause fires) as well as low cost to consumers [5].

2.4.2 Medical Equipment

Using WPT, systems can be designed to transfer power over distances up to several tens of centimeters safely and efficiently. The technology has the ability to enable a new generation of medical implants and could simplify the charging and sterilization process for many handheld, portable, and cart-based medical devices and instruments.

A. Wireless Charging for Implanted Medical Devices

In the medical device industry, researchers and engineers are developing next-generation medical implants which will harness the power of high resonance wireless power transfer. One example is a fully implantable left ventricular assist device (LVAD) which are implanted into patients who have heart diseases such as congestive heart failure to serve as a booster pump to improve the circulatory function of a weakened heart. A fully implantable LVAD would move the battery inside the body to be recharged wirelessly using highly resonant wireless power transfer.

B. Wireless Charging for Portable Medical Devices

Resonant wireless power transfer can be used with many portable medical devices that are used in hospitals and doctors' offices. For example, the technology can be used to charge surgical power tools, handheld diagnostic instruments, and portable infusion pumps.

2.4.3 Wireless Lighting Controls for Building Automation

Wireless lighting controls for high-end homes or classrooms have been around for a number of years, and wireless networking is now common for some applications, such as Internet access from hotel rooms.

Wireless controls are worth the consideration for lighting, fans, and other building-condition monitoring. Wireless sensors are used for monitoring security cameras, defense, vibration, air exchange and fans in amongst other applications.

2.4.4 Subsea Applications

Though subsea vehicles can self-navigate, human assistance is still required for power supply. Due to the rough terrain, as well as the distance, cabled conductors can prove to be a challenge. WPT comes in handy in these instances.

2.4.5 Other Applications

Other applications include Wireless Sensor Network (WSN) - based Electronic Intelligent Tag System (EITS) to provide intelligent management of the modern supermarkets, wireless motion sensors designed for general applications in homes and offices or commercial use as light, alarm and security applications and automatic wireless charging for low power camera and low power display [8].

2.5 Future Aspects in WPT

Wireless power transfer is an exciting new frontier, opening up new possibilities for manufacturers and consumers around the world. This new frontier will have a major impact on many significant market segments and create new ways to interact with the design of appliances and corresponding products, as shown in the following examples.

2.5.1 Energy saving in Wireless Sensor Networks

Wireless sensor networks (WSN) are one of the most trending and emerging technologies nowadays. They consist of a numerous number of nodes distributed over a particular area. Every node consists of 4 components sensor, a data processing unit, a transreceiver and most importantly a battery to supply the other three components with required power. The sensor first senses the data which is further processed by the data processing unit e.g. micro-controller. The processed data is further transmitted to the base station by the transreceiver.

There are many different parameters which reflect the efficiency of the WSN. One of the most important parameters of WSN is energy saving in batteries. This is because most of the sensor nodes in the network are placed at remote areas for environmental and military applications. These sensor nodes should be very small in size so as to reduce the cost and to make it more portable and advanced. Because of this the battery attached to the node is very small. This small battery has to be used for different processes like sensing, data processing and transmission.

After a certain amount of time these batteries may get completely exhausted and hence data in that region will never reach the base station. Hence it becomes really important to save the energy of the battery as one cannot replace it from time to time. Also wired charging of these batteries is almost impossible too as they are placed in remote areas.

The concept of WPT can be used here as it can be easily used to transmit power to the remote areas. Various primary stations can be constructed and these stations would have a particular area under their range. There may be large number of sensor nodes under this particular area.

An example of one scenario where this technology can be used is a field wherein water level and temperature variations are being sensed and there are around 1000 nodes installed, each node placed a few several feet away from each other. A huge primary coil can be installed which will be large enough to cover almost 50 sensor nodes and then 6-7 secondary coils are installed which can provide wireless power to 50 nodes when the battery decreases thus increasing the life and efficiency of the node to its maximum. Similarly we can extend the process and cover the entire geographical area. Huge coils with strong magnetic resonance will prove to be extremely useful for this purpose.

2.5.2 Power-Generating Solar Satellite

One of the more interesting WPT concepts is wirelessly transmitting energy from space to earth. Japan has already shown keen interest in this idea and it is planning to power up 3 million houses from this power. They have serious plans to send a solar powered satellite in space which will harness the energy of the sun, as shown figure 2.5. This harnessed energy will be sent to earth wirelessly through a beam that would be capable to transmitting giga-watts of power.

Figure 2.5: Japan’s wireless power transmitting satellite

However to overcome all the complications and remove all the flaws, it may take more than 3 decades for this setup to be actually implemented. Also one of the dangers of using this setup the microwave beam carrying giga-watts of power missing the intended target which could possibly cause severe damage or destruction [9].

2.5.3 Power Over Wi-Fi

The Power Over Wi-Fi (PoWiFi) system combines two elements; a Wi-Fi transmission strategy that delivers power on multiple Wi-Fi channels and energy-harvesting hardware that can efficiently harvest from multiple Wi-Fi channels simultaneously.

PoWiFi presents a power over Wi-Fi system that delivers power to low-power sensors and devices and works with existing Wi-Fi chipsets. Specifically it is shown that a Wi-Fi router can provide wireless power without significantly compromising the network's communication performance. It was also demonstrated that prototype battery-free temperature and camera sensors were powered with Wi-Fi at ranges of 20 and 17 feet respectively, alongside the ability to wirelessly trickle-charge lithium-ion coin-cell batteries at distances of up to 28 feet [10].

2.5.4 Architectural Point of View

Usage of WPT would also solve many problems related to construction of buildings. One example is the duct space which contains the electricity wires will no longer be needed. Hiding the transmitter coil in the ceiling or under the floor will serve the purpose. Also most of the causes for fires in the buildings are due to electricity wires getting short circuited. Wireless power transfer would solve this issue with ease [9].

CHAPTER THREE
SYSTEM DESIGN AND IMPLEMENTATION

3.1 Circuit Description

The main idea of this project is to design a wireless omnidirectional power transfer circuit via inductive coupling. The overall process requires a transmitter and a receiver using a 1MHz signal generator as a power supply in order to generate the specified resonant frequency of the coils. Then AC power is transmitted to the receiver coil depending on the distance between the transmitter coil and the receiver coil, and the output is measured using an oscilloscope connected to the terminals of the receiver coil as shown in Figure 3.1:

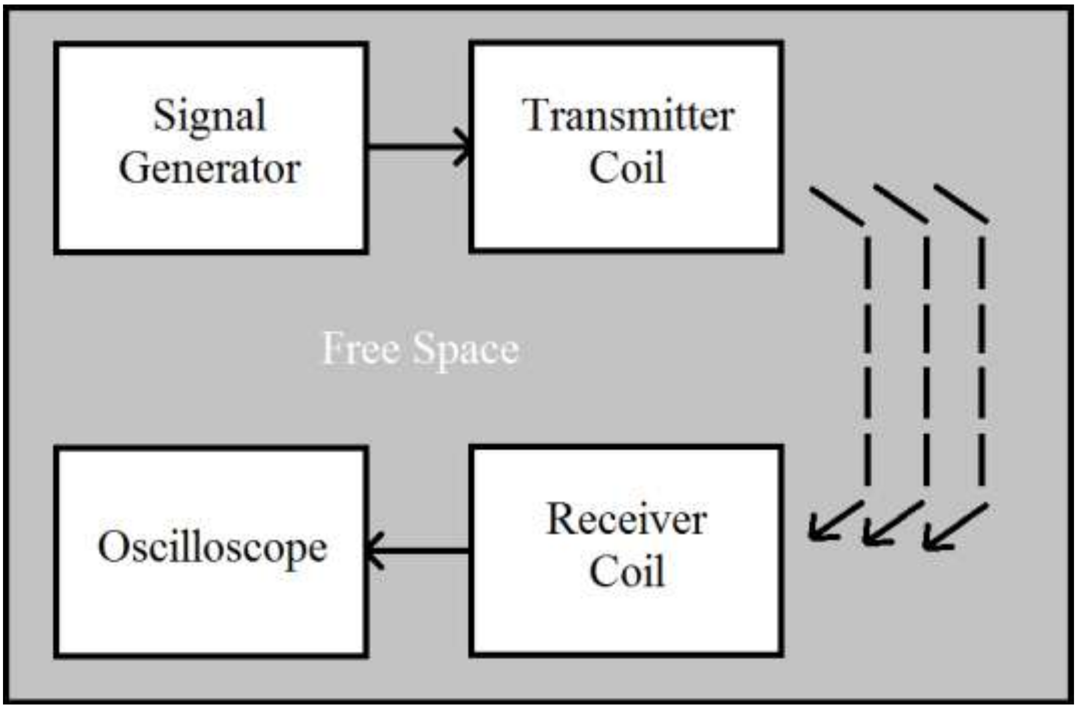

Figure 3.1: Circuit description

3.2 Transmitter Module

The transmitter module is made up of a signal generator as an AC power source and a transmitter coil.

The signal generator supplies the transmitter coil with high frequency AC power and the coil, energized by the high frequency AC current, produces an alternating magnetic field. Figure 3.2 gives a general idea of the transmitter module:

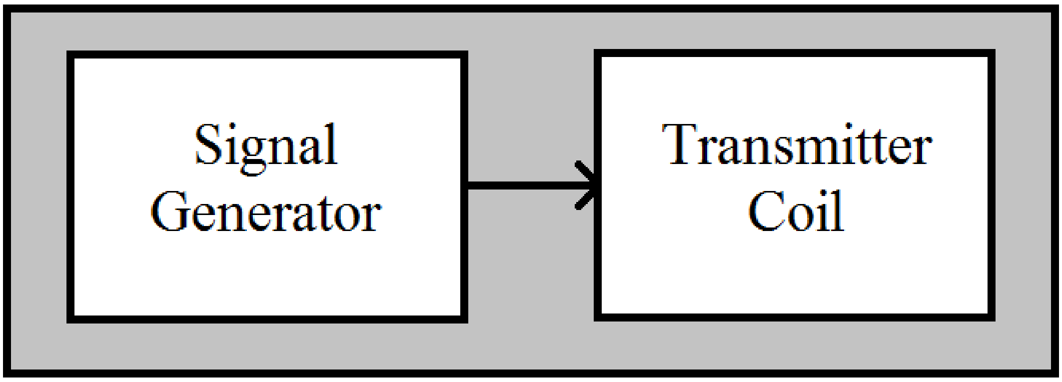

Figure 3.2: Transmitter module

3.2.1 The Signal Generator

The power source used is a Kenwood AG-203A signal generator capable of supplying signals at frequencies of up to 1MHz. The signal generator is set at the specified resonant frequency and at a signal amplitude of 10V.

Figure 3.3: Kenwood AG-203A signal generator

3.2.2 Operation of The Signal Generator

A signal generator is an electronic device that generates repeating or non-repeating electronic signals in either the analog or the digital domain. It is generally used in designing, testing, troubleshooting, and repairing electric and electronic devices.

The most basic signal created from a signal generator is the continuous wave signal, or sine wave, as shown in Figure 3.4:

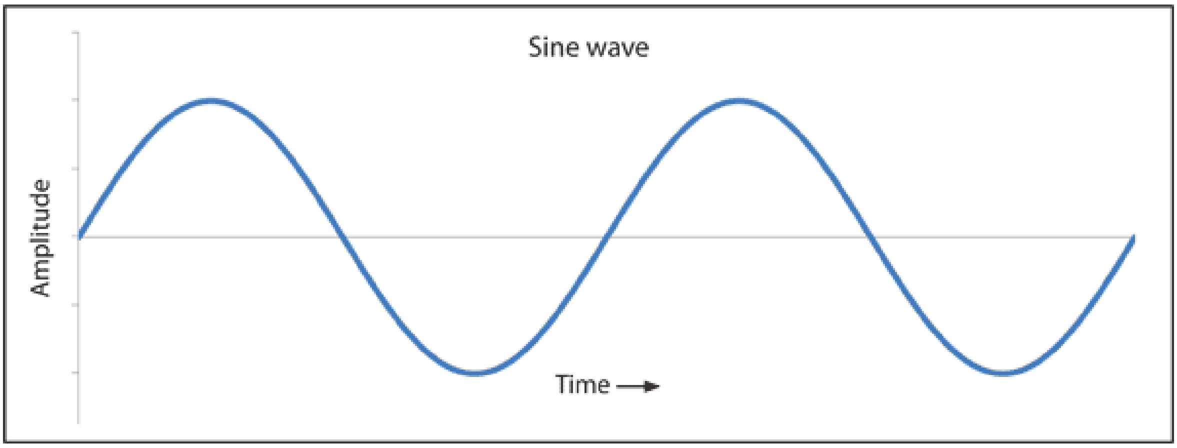

Figure 3.4: Sine wave

3.3 Receiver Module

The receiver module of this system consists of a receiver coil and an oscilloscope. An AC Voltage is induced in the receiver coil, and it is measured using an oscilloscope. The following block diagram shown in Figure 3.5 gives a general idea of the receiver module:

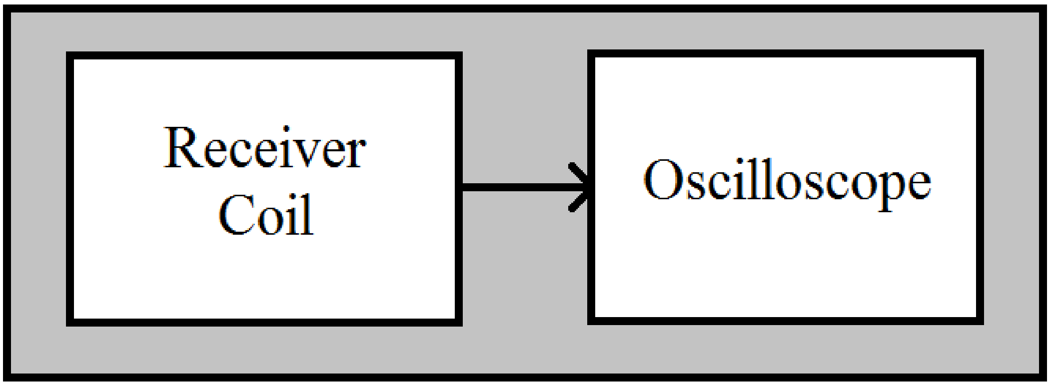

Figure 3.5: The receiver module

3.3.1 The Oscilloscope

The oscilloscope used is the Anshuman AN102 oscilloscope as shown in Figure (3.6), capable of displaying signals at frequencies of up to 20MHz. The oscilloscope's frequency scale was set to 1μsec and the voltage per square scale was varied according to the measurement to display it as clearly as possible.

Figure 3.6: The Anshuman AN102 oscilloscope

3.3.2 The Operation of The Oscilloscope

The oscilloscope is a type of an electronic test instrument that allows observation of constantly varying signal voltages, usually as a two-dimensional plot of one or more signals as a function of time.

Oscilloscopes are used to observe the change of an electrical signal over time, such that voltage and time describe a shape which is continuously graphed against a calibrated scale. The observed waveform can be analyzed for such properties as amplitude, frequency, rise time, time interval, distortion and others. Modern digital instruments may calculate and display these properties directly. Originally, calculation of these values required manually measuring the waveform against the scales built into the screen of the instrument.

The basic oscilloscope, as shown in Figure 3.7, is typically divided into four sections: the display, vertical controls, horizontal controls and trigger controls. In addition to the screen, most display sections are equipped with two basic controls: a focus knob and an intensity knob.

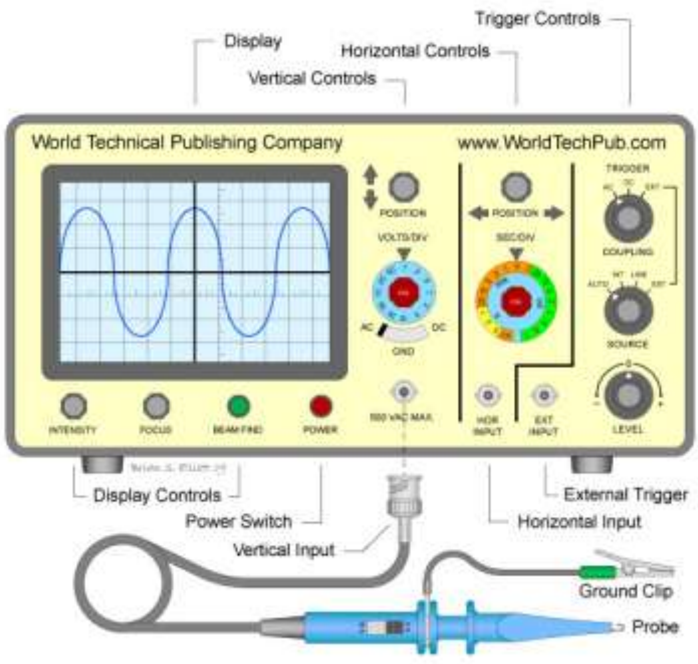

Figure 3.7: Basic oscilloscope

The vertical section controls the amplitude of the displayed signal. This section carries a Volts-per-Division (Volts/Div) selector knob, an AC/DC/Ground selector switch and the input port for the instrument.

The horizontal section controls the time base or "sweep" of the instrument. The primary control is the Seconds-per-Division (Sec/Div) selector switch. Also included is a horizontal input for plotting dual X-Y axis signals. The horizontal beam position knob is generally located in this section.

The trigger section controls the start event of the sweep. The trigger can be set to automatically restart after each sweep or it can be configured to respond to an internal or external event. The principal controls of this section will be the source and coupling selector switches. An external trigger input (EXT Input) and level adjustment will also be included.

3.4 The Transmitter and Receiver Coils Formation

The coil used in both the transmitter and the receiver modules is a long thick wire made of copper that is turned into a series of turns that could take any required shape. The coil used, consists of 22 turns at a diameter of 22 cm and 10 turns at a diameter of 15 cm. The coil has a thickness of 3 mm and is insulated using a coating.

There are three differently shaped coils made, the first one is the single-loop (flat spiral) multi-turn coil, the second one is the two-loop multi-turn coil, and the third one is the three-loop (spherical) multi-turn coil.

3.4.1 The Single Loop (Flat Spiral) Multi-Turn Coil

The single loop coil consists of a series of circular turns and is the traditionally used coil shape for WPT systems. The coil in Figure 3.8 is a single-loop multi-turn coil:

Figure 3.8: The single loop (flat spiral) multi-turn coil

3.4.2 The Two-loop Multi-Turn Coil

The two-loop consists of a series of circular turns where the coil turns are divided and two loops or flat spiral shapes are made, the first lies horizontally and the second lies vertically, perpendicular to the first shape. The coil in Figure 3.9 is a two-loop multi-turn coil:

Figure 3.9: The two-loop multi-turn coil

3.4.3 The Three-Loop (Spherical) Multi-Turn Coil

The spherical coil consists of a series of circular turns where the coil turns are divided and three flat spiral shapes are made, the first lies horizontally, the second lies vertically, perpendicular to the first shape and the third also lies vertically, but perpendicular to the second shape. This type of coil is used for the wireless omnidirectional power transfer system. The coil in Figure 3.10 is a three-loop multi-turn coil:

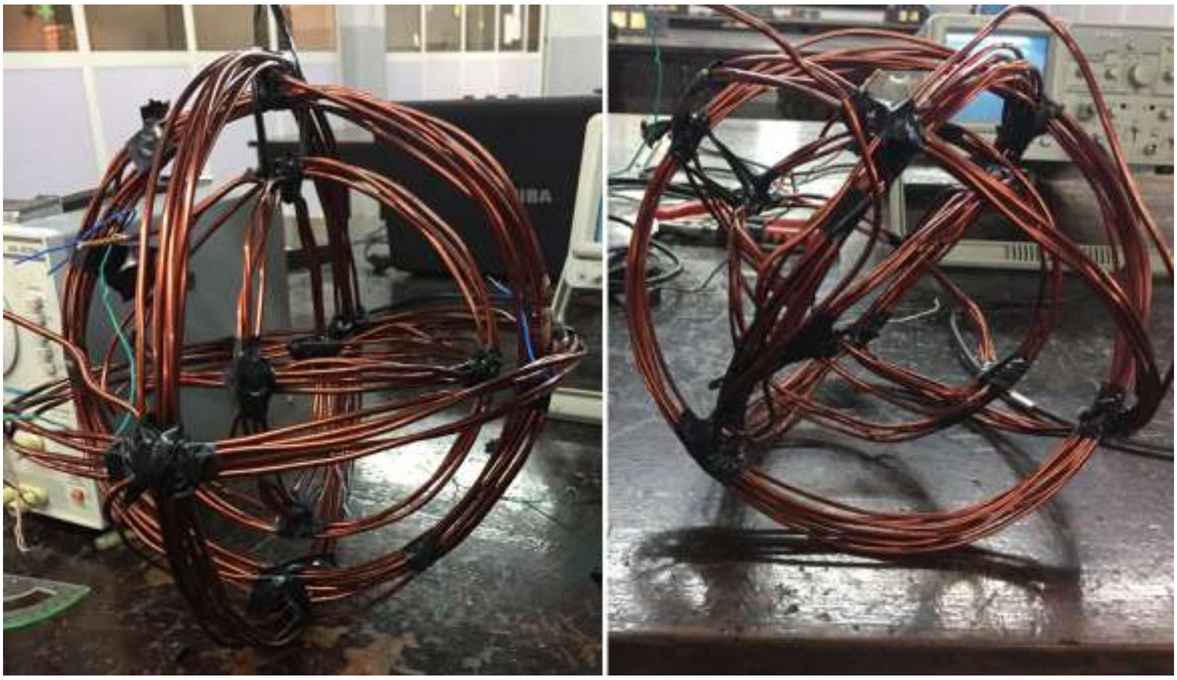

Figure 3.10: The three-loop (spherical) multi-turn coil

3.5 The Operation of The Transmitter and Receiver Coils

Electric power can be transferred from one point to another without the use of connecting cables but using loosely coupled coils as shown in Figure 3.10.

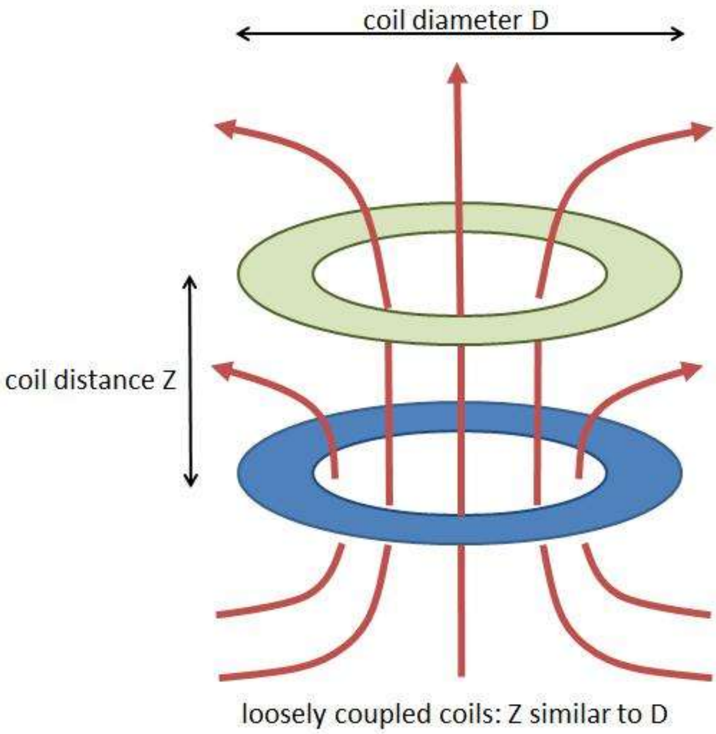

Figure 3.11: Loosely coupled coils

The operation of the transmitter and receiver coils depend on inductance, magnetic fields due to moving charges, inductive coupling and resonance. Each principle is explained on its own.

3.5.1 Inductance

In electromagnetism and electronics, inductance is the property of an electrical conductor by which a change in current through it induces an electromotive force in both the conductor itself and in any nearby conductors by mutual inductance.

An electronic component that is intended to add inductance to a circuit is called an inductor. Inductors are typically manufactured from coils of wire. This design delivers two desired properties, a concentration of the magnetic field into a small physical space and a linking of the magnetic field into the circuit multiple times.

The relationship between the self-inductance, L, of an electrical circuit, the voltage, v(t), and the current, i(t), through the circuit is:

$$v(t) = L * \frac{di(t)}{dt} \quad (3.1)$$

3.5.2 Magnetic Field Due to Moving Charges

All moving charged particles produce magnetic fields. Moving point charges, such as electrons, produce complicated but well known magnetic fields that depend on the charge, velocity, and acceleration of the particles.

Magnetic field lines form in concentric circles around a cylindrical current-carrying conductor, such as a length of wire. The direction of such a magnetic field can be determined by using the right hand grip rule as shown at Figure 3.11.

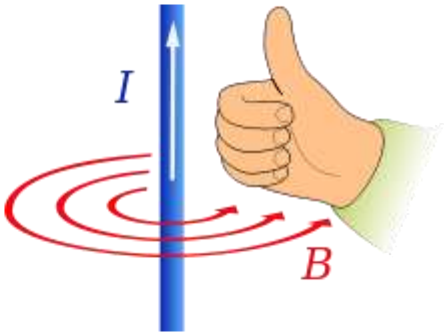

Figure 3.12: Right hand grip rule

Right hand grip rule is used at two applications of Ampere's circuital law. The first is that when an electric current passes through a solenoid, which results in a magnetic field. When wrapping the right hand around the solenoid with the fingers in the direction of the conventional current, the thumb points in the direction of the magnetic north pole.

The second application is that when an electric current passes through a straight wire. Grabbing the wire points the thumb in the direction of the conventional current (from positive to negative), while the fingers point in the direction of the magnetic flux lines.

The strength of the magnetic field decreases with distance from the wire. For an infinite length wire the strength is inversely proportional to the distance.

3.5.3 Inductive Coupling

In electrical engineering, two conductors are referred to as inductively coupled or magnetically coupled when they are configured such that a change in current through one wire induces a voltage across the ends of the other wire through electromagnetic induction. The amount of inductive coupling between two conductors is measured by their mutual inductance.

The coupling between two wires can be increased by winding them into coils and positioning them on the same axis, so the magnetic field of one coil passes through the other coil. Coupling can also be increased by a magnetic core of iron or ferrite in the coils, which increases the magnetic flux. The two coils may be physically contained in a single unit, as in the primary and secondary windings of a transformer, or may be separated. Coupling may be intentional or unintentional. Unintentional inductive coupling can cause signals from one circuit to be induced into a nearby circuit, this is called cross-talk, and is a form of electromagnetic interference. Figure 3.12 shows the concept of inductive coupling in an electric circuit.

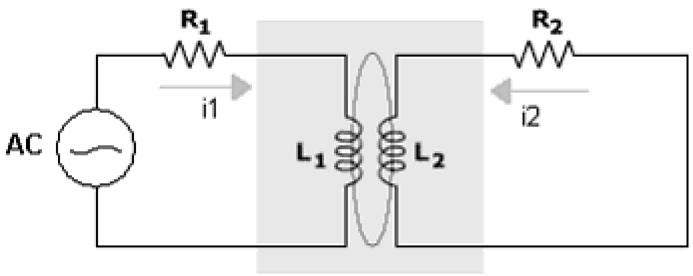

Figure 3.13: Inductive coupling

3.5.4 Resonance

In physics, resonance is a phenomenon in which a vibrating system or external force drives another system to oscillate with greater amplitude at a specific preferential frequency. Figure 3.13 gives an example of the amplitude at resonant frequency.

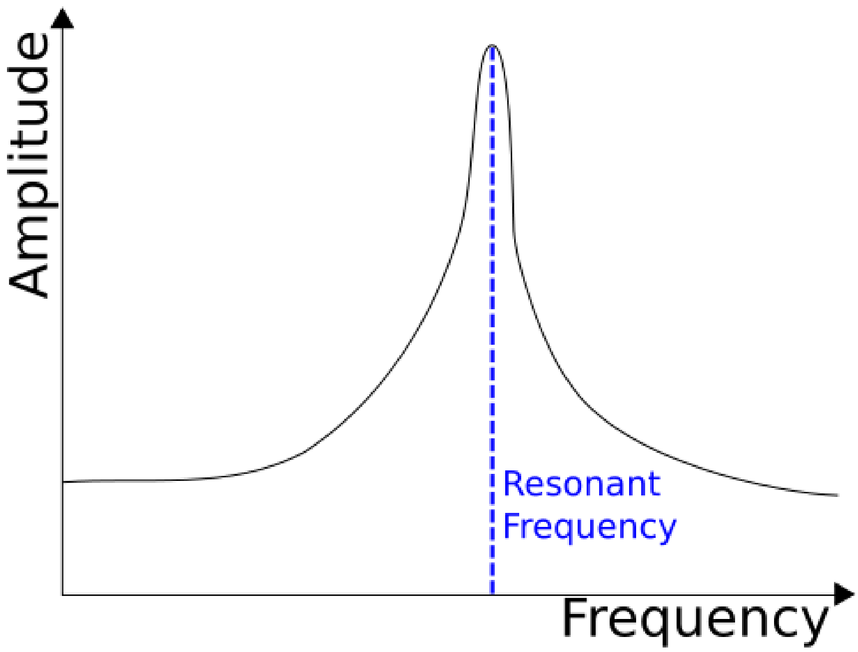

Figure 3.14: Resonant frequency

Resonance occurs when a system is able to store and easily transfer energy between two or more different storage modes. However, there are some losses from cycle to cycle, called damping. When damping is small, the resonant frequency is approximately equal to the natural frequency of the system, which is a frequency of unforced vibrations.

Resonance of a circuit involving capacitors and inductors occurs because the collapsing magnetic field of the inductor generates an electric current in its windings that charges the capacitor, and then the discharging capacitor provides an electric current that builds the magnetic field in the inductor. This process is repeated continually. An analogy is a mechanical pendulum, and both are a form of simple harmonic oscillator.

At resonance, the series impedance of the two elements is at a minimum and the parallel impedance is at maximum. Resonance is used for tuning and filtering, because it occurs at a particular frequency for given values of inductance and capacitance. It can be detrimental to the operation of communications circuits by causing unwanted sustained and transient oscillations that may cause noise, signal distortion, and damage to circuit elements.

Parallel resonance or near-to-resonance circuits can be used to prevent the waste of electrical energy, which would otherwise occur while the inductor built its field or the capacitor charged and discharged. As an example, asynchronous motors waste inductive current while synchronous ones waste capacitive current. The use of the two types in parallel makes the inductor feed the capacitor, and vice versa, maintaining the same resonant current in the circuit, and converting all the current into useful work.

Since the inductive reactance and the capacitive reactance are of equal magnitude, the resonant angular frequency is known as:

$$\omega = \frac{1}{\sqrt{LC}} \qquad (3.2)$$

Where L is the inductance in Henries and C is the capacitance in Farads.
Also the angular frequency is known to be larger than the natural frequency by a factor of 2π as follows:

$$\omega = 2\pi f \quad (3.3)$$

Where f is the resonance frequency in Hertz.

3.5.5 Resonant Inductive Coupling

Resonant inductive coupling is the phenomenon where the coupling is enhanced when the secondary side of the loosely coupled coils resonates.
When the resonant state on the secondary side is observed from the primary side of a circuit, two resonances as a pair are observed. One of them is called the resonant frequency (series resonant frequency), and the other is called the anti-resonant frequency (parallel resonant frequency). When the primary coil is driven with a resonance frequency (serial resonance frequency) of the secondary side, the phases of the magnetic fields of the primary coil and the secondary coil are synchronized. As a result, the maximum voltage is generated in the secondary coil due to the increase of the mutual flux, and the copper loss of the primary coil is reduced, the heat generation is reduced, and the efficiency is relatively improved. The resonant inductive coupling is the technology used in the near-field wireless transmission of electrical energy between magnetically coupled coils [1].

CHAPTER FOUR

SYSTEM IMPLEMENTATION AND EXPERIMENTAL RESULTS

4.1 System Implementation

The main idea is to develop a wireless omnidirectional power transfer system that is not as sensitive to positioning as the traditional WPT systems using single loop (flat spiral) multi-turn coils are, or developing a system that is not highly affected by lateral misalignment and angular misalignment between the transmitter and receiver coils.

Both of the traditional and omnidirectional WPT systems using inductive coupling were formed for the results and measurements to be compared. The overall process required a transmitter and receiver in both circuits.

The first circuit is the traditional WPT system using single loop multi-turn coils as shown in Figure 4.1.

Figure 4.1: The single loop coil WPT system

The second circuit is the WPT system using two-loop multi-turn coils as shown in Figure 4.2.

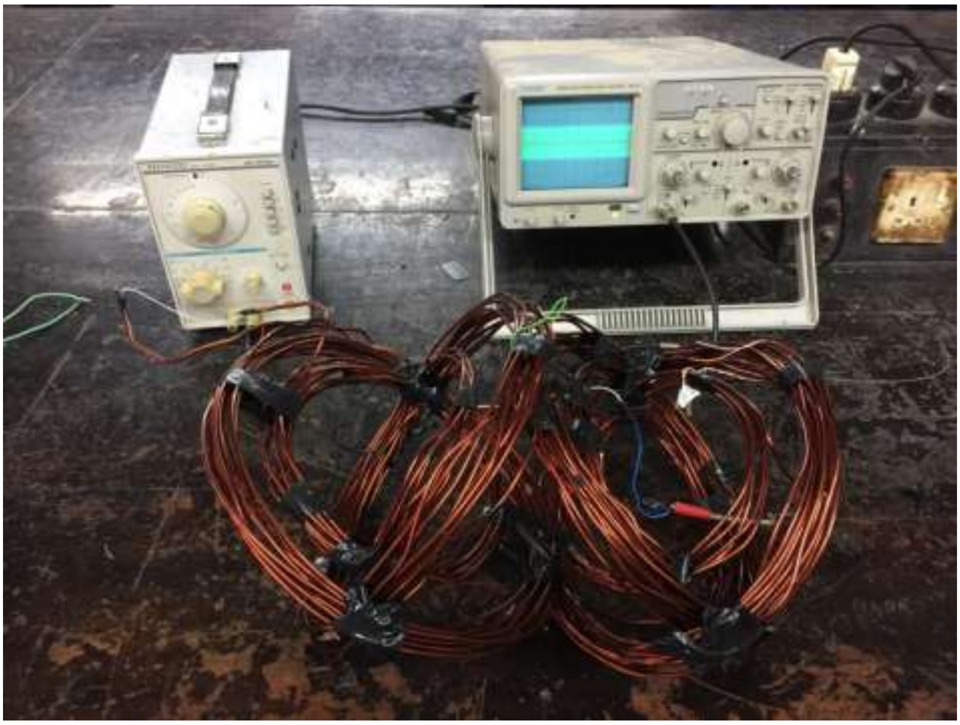

Figure 4.2: The two-loop coil WPT system

The third circuit is the wireless omnidirectional power transfer system using three-loop (spherical) multi-turn shaped coils as shown in Figure 4.3.

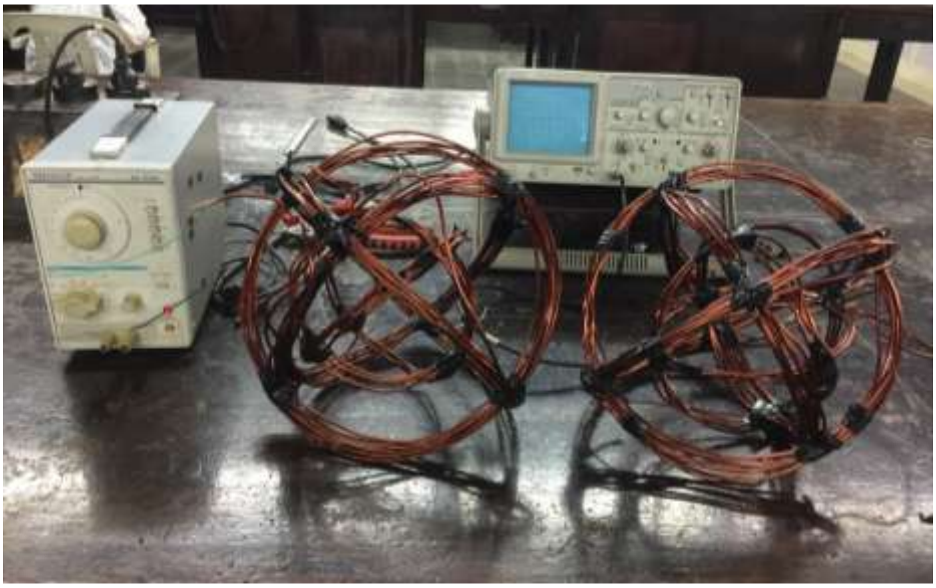

Figure 4.3: The three-loop coil WPT system

4.1.1 The Transmitter Module

There are three transmitter modules, the first using a single loop multi-turn coil, the second using a two-loop multi-turn coil and the third using a three-loop multi-turn coil.

Figure 4.4 shows the transmitter module of the first circuit as a whole, which belongs to the traditional WPT system using single loop multi-turn coils. The signal generator is connected to the transmitter coil via small copper wires.

Figure 4.4: The transmitter module of the single loop coil WPT system

Figure 4.5 shows the transmitter module of the second circuit as a whole, which belongs to the wireless omnidirectional power transfer system using two-loop multi-turn coil. The signal generator is connected to the transmitter coil via small copper wires.

Figure 4.5: The transmitter module of two-loop coil WPT system

Figure 4.6 shows the transmitter module of the third circuit as a whole, which belongs to the wireless omnidirectional power transfer system using three-loop multi-turn coil. The signal generator is connected to the transmitter coil via small copper wires.

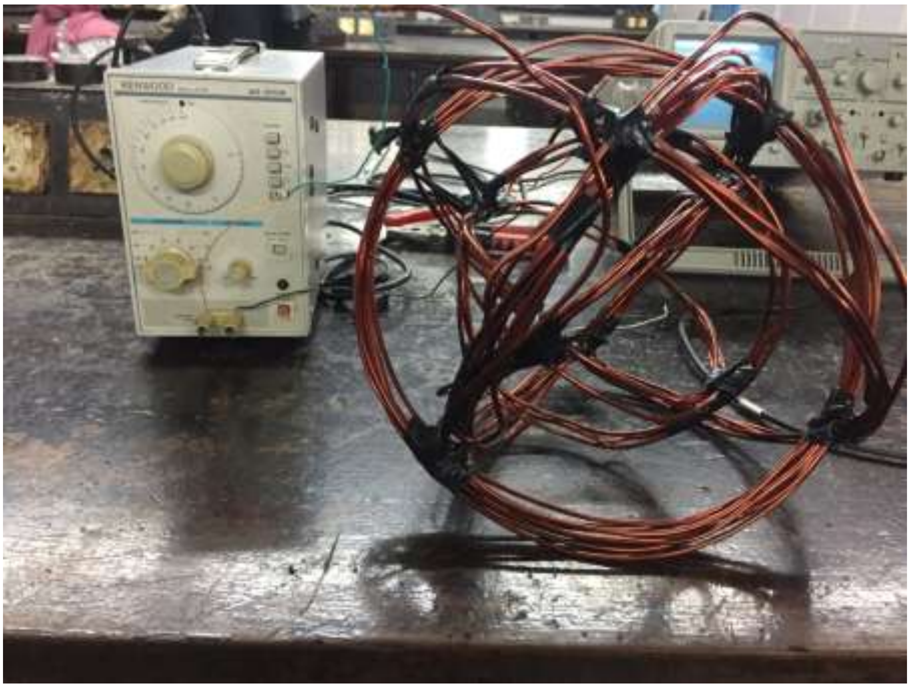

Figure 4.6: The transmitter module of three-loop coil WPT system

In all of the transmitter modules, the signal generator used is the Kenwood AG-203A capable of supplying signals at frequencies of up to 1MHz. The signal generator's amplitude dial was set to maximum amplitude output, which was measured using the oscilloscope by connecting them together using small copper wires and the maximum amplitude was found to be at 10V.

The signal generator was then connected to the terminals of the transmitter coil using small copper wires. The terminals were at both ends of the coil, where the coating was peeled off at that area and the small copper wires were wrapped around the peeled off area as shown in Figure 4.7, so that the signal generator was connected to the transmitter coil allowing AC current to flow through the coil.

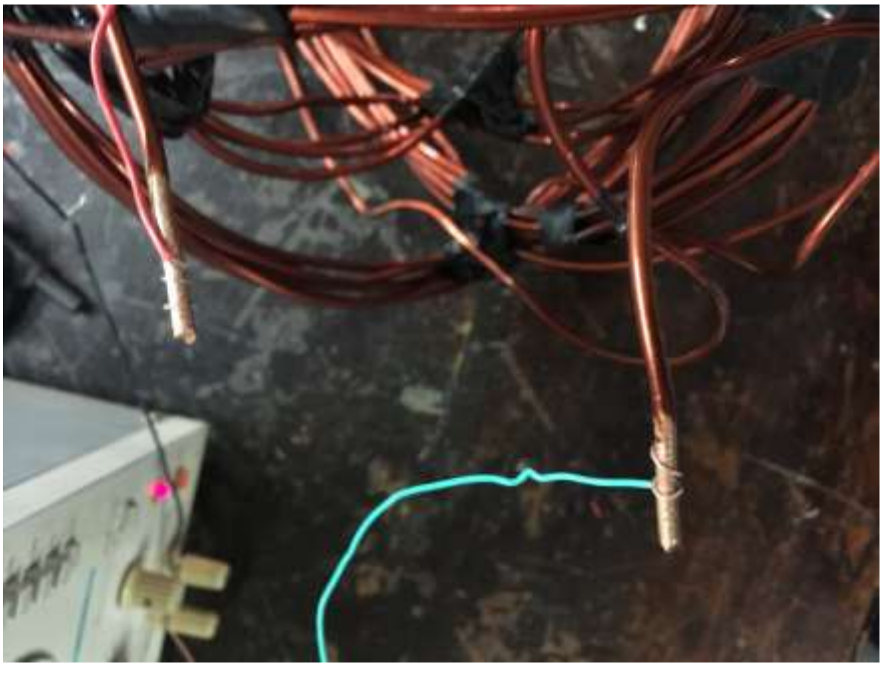

Figure 4.7: The transmitter coil terminals

4.1.2 The Receiver Module

There are three receiver modules, the first using a single loop multi-turn coil, the second using a two-loop multi-turn coil and the third using a three-loop multi-turn coil.

Figure 4.8 shows the receiver module of the first circuit as a whole, which belongs to the traditional WPT system using single loop multi-turn coils. The oscilloscope is connected to the receiver coil via small copper wires.

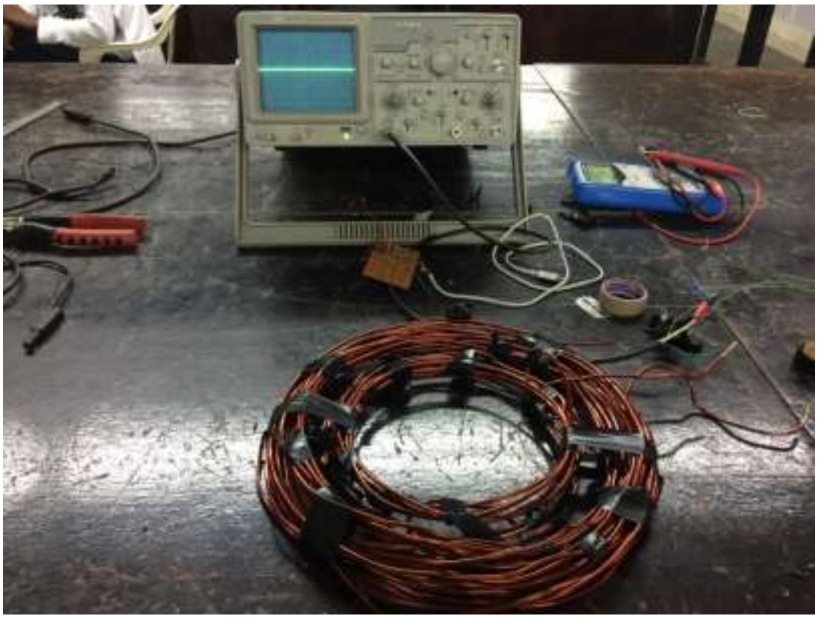

Figure 4.8: The receiver module of the single loop coil WPT system

Figure 4.9 shows the receiver module of the second circuit as a whole, which belongs to the traditional WPT system using two-loop multi-turn coils. The oscilloscope is connected to the receiver coil via small copper wires.

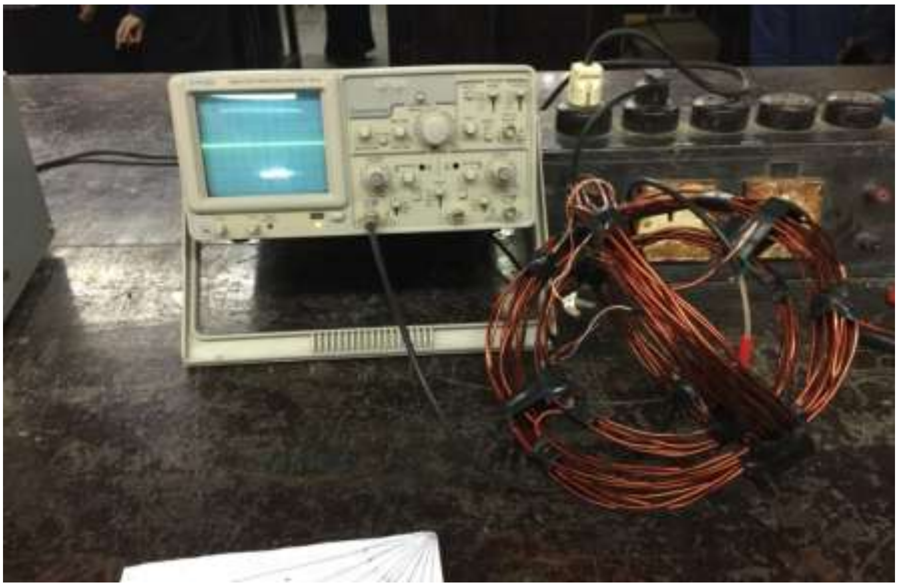

Figure 4.9: The receiver module of the two-loop coil WPT system

Figure 4.9 shows the receiver module of the second circuit as a whole, which belongs to the traditional WPT system using two-loop multi-turn coils. The oscilloscope is connected to the receiver coil via small copper wires.

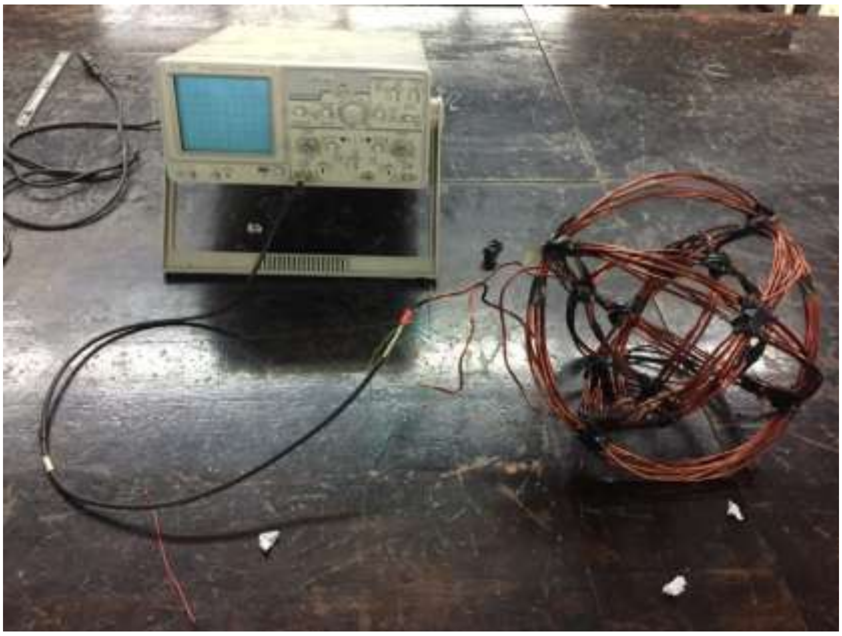

Figure 4.10: The receiver module of the three-loop coil WPT system

The oscilloscope was then connected to the terminals of the receiver coil using small copper wires. The terminals were at both ends of the coil, where the coating was peeled off at that area and the small copper wires were wrapped around the peeled off area as shown in Figure 4.11, so that the oscilloscope was connected to the receiver coil to read the needed measurements.

Figure 4.11: The terminals of the receiver coil

In both of the receiver modules, the oscilloscope used is the Anshuman AN102 oscilloscope, capable of displaying signals at frequencies of up to 20MHz. The oscilloscope's horizontal time per division dial or the frequency scale was set to 1μsec since most of the signals that required measurement were at frequencies in the range of 0.9-1MHz. The oscilloscope's volts per division dial or the voltage per square scale was varied according to the measurement to display it as clearly as possible.

4.2 The Experimental Results

The coils' resonant frequency has been measured and was found to be 0.97MHz, which was the frequency used for the measurements. The coil separation distance, lateral misalignment and angular misalignment have been measured in both of the traditional and omnidirectional WPT systems, with the measurements taken at various points, and the results have been displayed in the form of graphs of voltage per distance.

The coil separation distance in the WPT systems is as shown in Figure 4.12:

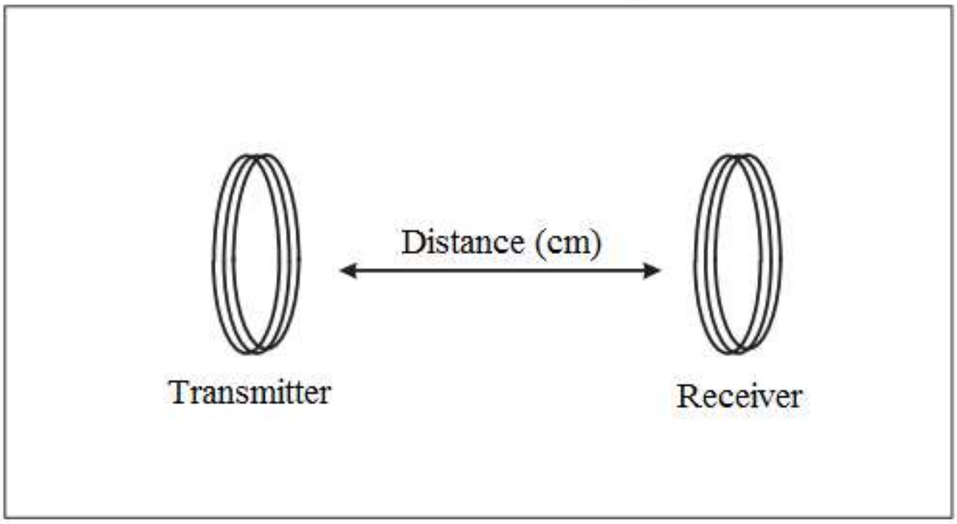

Figure 4.12: The coil separation distance in the WPT systems

The lateral misalignment is as shown in Figure 4.13:

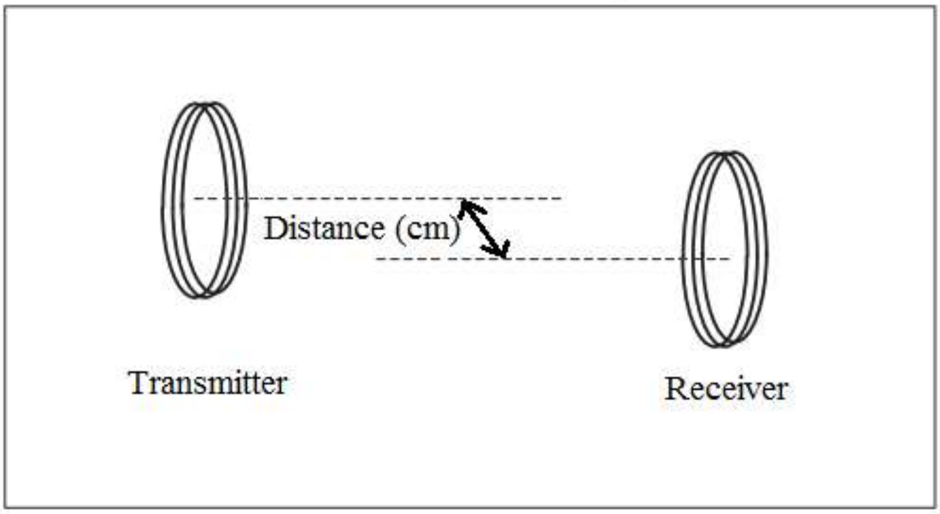

Figure 4.13: The lateral misalignment in the WPT systems

The angular misalignment is as shown in Figure 4.14:

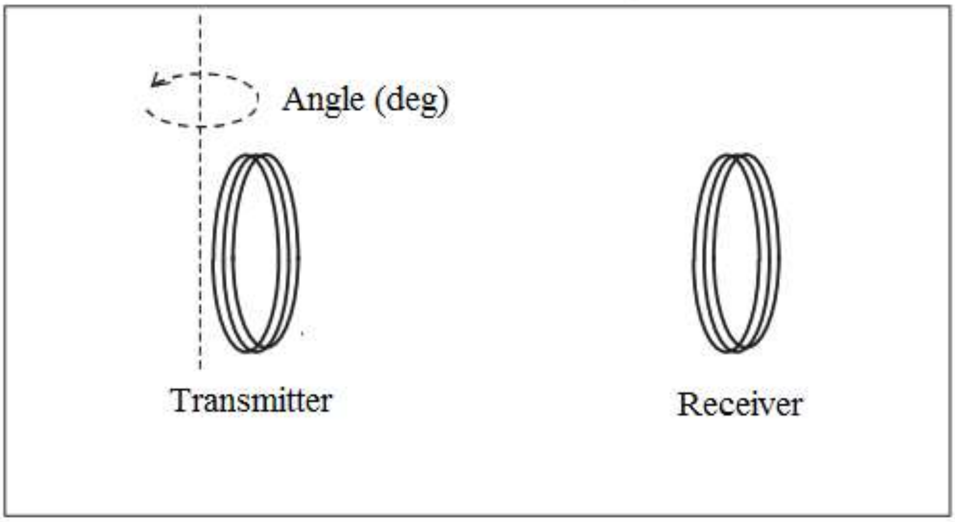

Figure 4.14: The angular misalignment in the WPT systems

4.2.1 The Single Loop (Flat Spiral) Coil WPT System

Figure 4.15 shows the coil separation distance from 0-35 cm measured every 5 cm. There is a sharp decrease in the voltage from 0 cm to 5 cm as it goes down from 5V to 3V, and it decreases by the same amount from 5 cm to 15 cm as it goes down from 3V to 1V, followed by a slower decrease in voltage from 15 cm to 35 cm as it goes down from 1V to 0.2V.

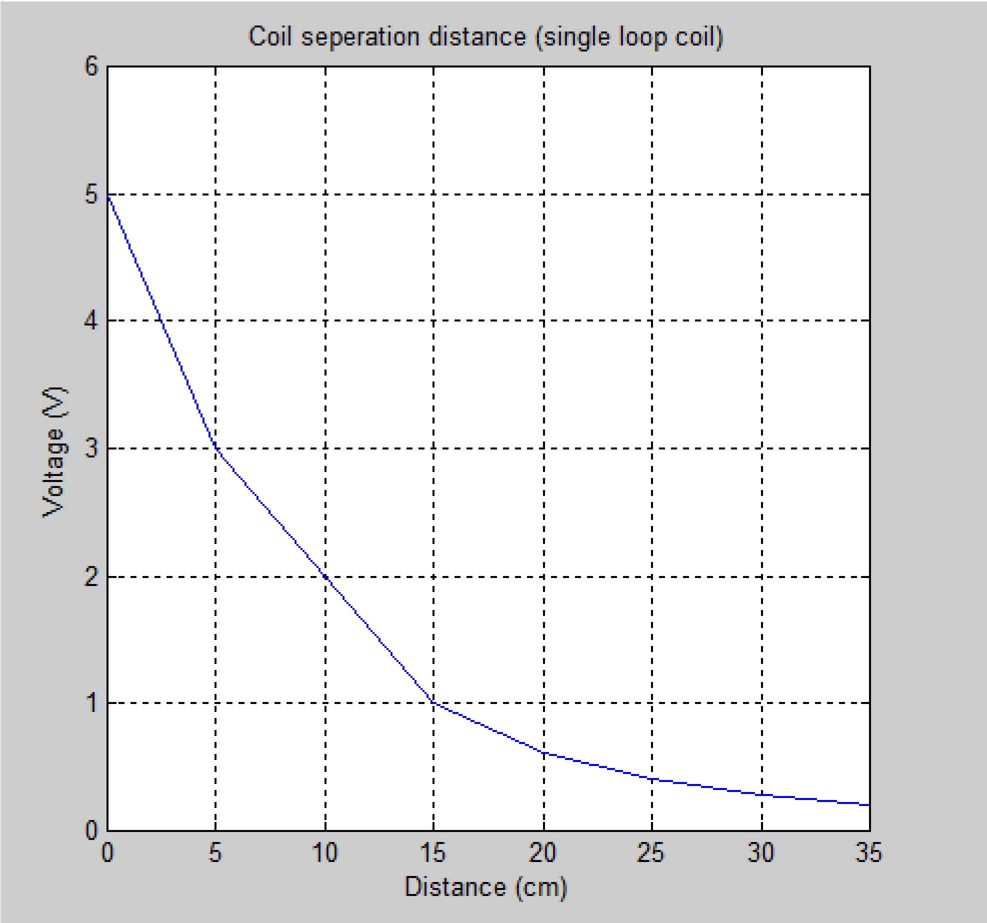

Figure 4.15: Coil separation distance (single loop coil)

Figure 4.16 shows the lateral misalignment between the coils from 0-20 cm measured every 5 cm. The measurements have been taken at a coil separation distance of 5 cm. There is a decrease in the voltage from 0 cm to 10 cm as it goes down from 3V to 2V, and a similar decrease in the voltage from 5 cm to 15 cm as it goes down from 2V to 1V, followed by a very slight change in voltage from 15 cm to 20 cm as it goes down from 1V to 0.99V.

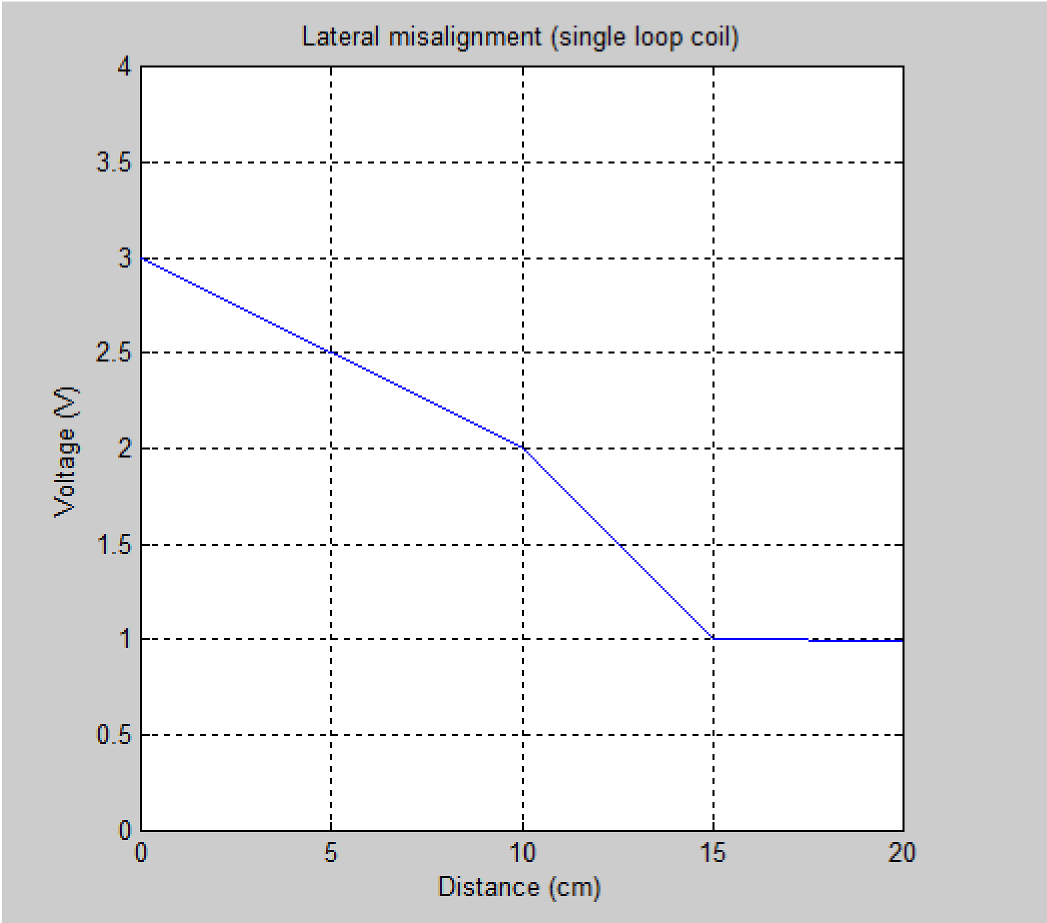

Figure 4.16: Lateral misalignment (single loop coil)

Figure 4.17 shows the angular misalignment between the coils from 0-90 degrees measured every 10 degrees. The measurements have been taken at a coil separation distance of 5 cm. There is a decrease in the voltage from 0 degrees to 10 degrees as it goes down from 3V to 2V, and a similar decrease in the voltage from 10 degrees to 50 degrees as it goes down from 2V to 1V, followed by a slower decrease in voltage from 50 degrees to 90 degrees as it goes down from 1V to 0.5V.

Figure 4.17: Angular misalignment (single loop coil)

4.2.2 The Two-Loop Coil WPT System

Figure 4.18 shows the coil separation distance from 0-35 cm measured every 5 cm. There is a sharp decrease in the voltage from 0 cm to 5 cm as it goes down from 0.8V to 0.3V, followed by a slower decrease in voltage from 5 cm to 15 cm as it goes down from 0.3V to 0.12V, followed by a slower decrease in voltage from 15 cm to 25 cm as it goes down from 0.12V to 0.06V, followed by a greater decrease in the voltage from 25 cm to 35 cm as it goes down from 0.06V to 0.015V.

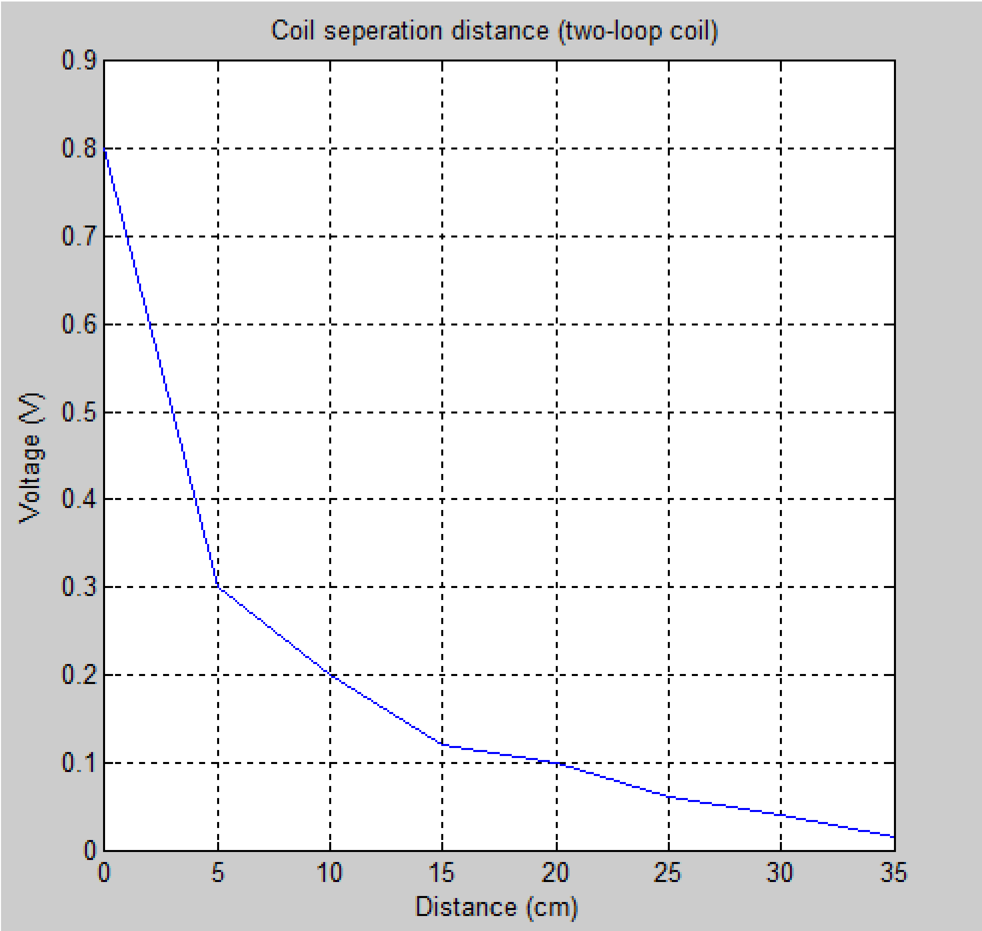

Figure 4.18: Coil separation distance (two-loop coil)

Figure 4.19 shows the lateral misalignment between the coils from 0-30 cm measured every 5 cm. The measurements have been taken at a coil separation distance of 5 cm. There is a decrease in the voltage from 0 cm to 10 cm as it goes down from 0.3V to 0.25V, followed a sharp decrease in the voltage from 10 cm to 25 cm as it goes down from 0.25V to 0.1V, followed by a very slight change in voltage from 25 cm to 30 cm as it goes down from 0.1V to 0.09V.

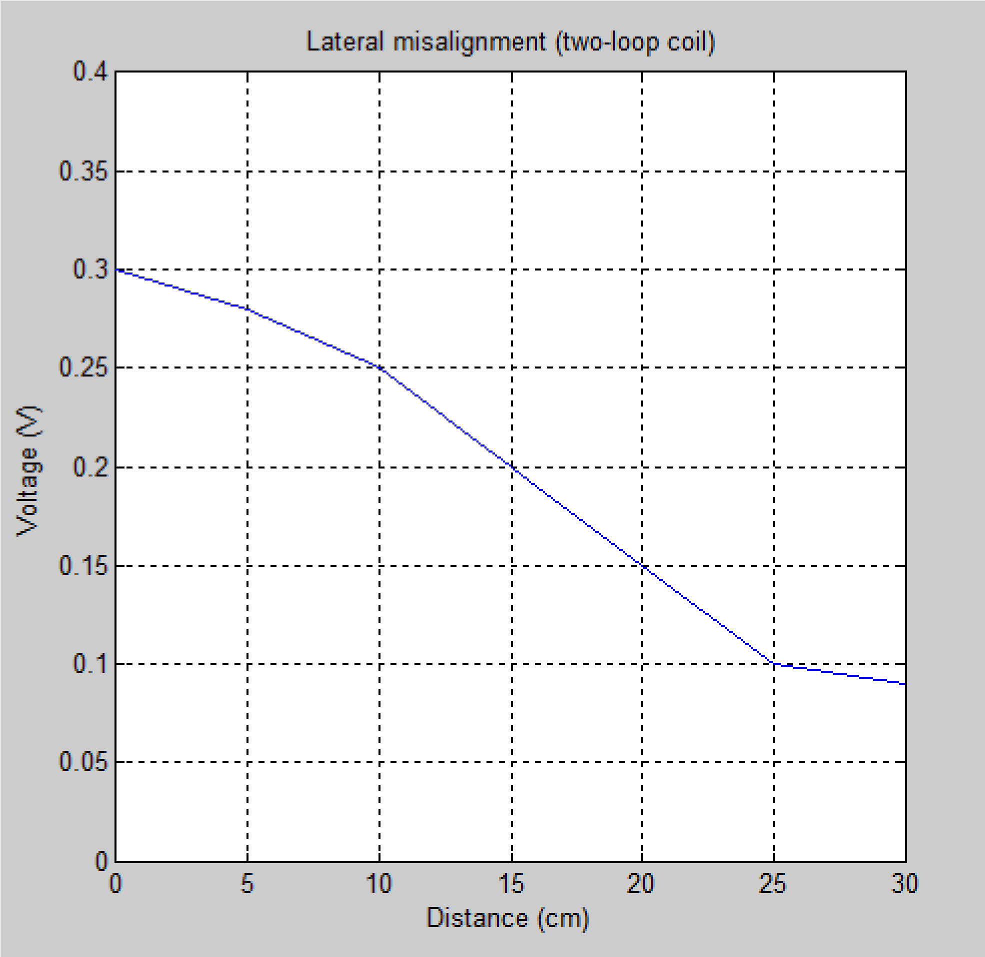

Figure 4.19: Lateral misalignment (two-loop coil)

Figure 4.20 shows the angular misalignment between the coils from 0-90 degrees measured every 10 degrees. The measurements have been taken at a coil separation distance of 5 cm. There is a decrease in the voltage from 0 degrees to 30 degrees as it goes down from 0.3V to 0.24V, then the voltage has no change from 30 degrees to 40 degrees as it stays at 0.24V, followed by a decrease in the voltage from 40 degrees to 60 degrees as it goes down from 0.24V to 0.2V, then the voltage has no change from 60 degrees to 70 degrees as it stays at 0.2V, then the voltage decreases from 70 degrees to 90 degrees as it goes down from 0.2V to 0.12V.

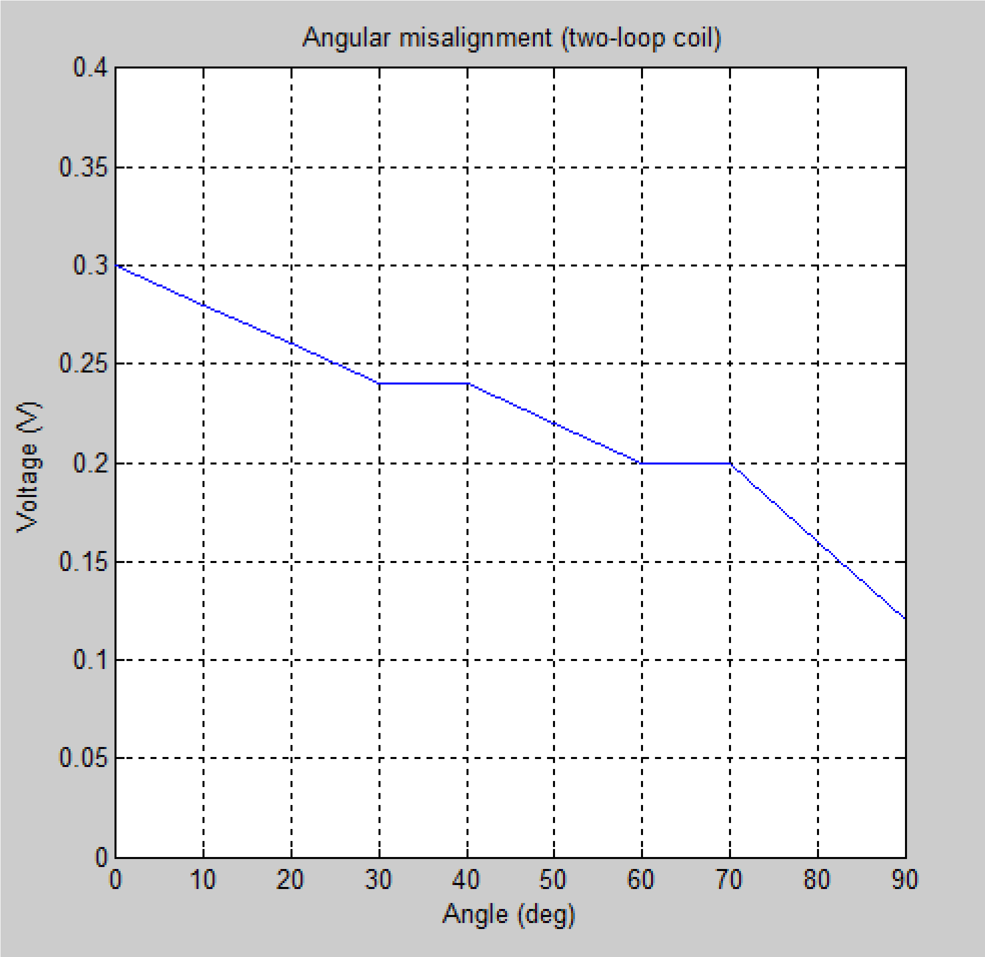

Figure 4.20: Angular misalignment (two-loop coil)

4.2.3 The Three-Loop (Spherical) Coil WPT System

Figure 4.21 shows the coil separation distance from 0-35 cm measured every 5 cm. There is a slight decrease in the voltage from 0 cm to 10 cm as it goes down from 2V to 0.8V, followed by a slower decrease in voltage from 10 cm to 15 cm as it goes down from 0.8V to 0.4V, then the voltage has no change from 15 cm to 20 cm as it stays at 0.4V, followed by a slight decrease in voltage from 20 cm to 35 cm as it goes from 0.4V to 0.1V.

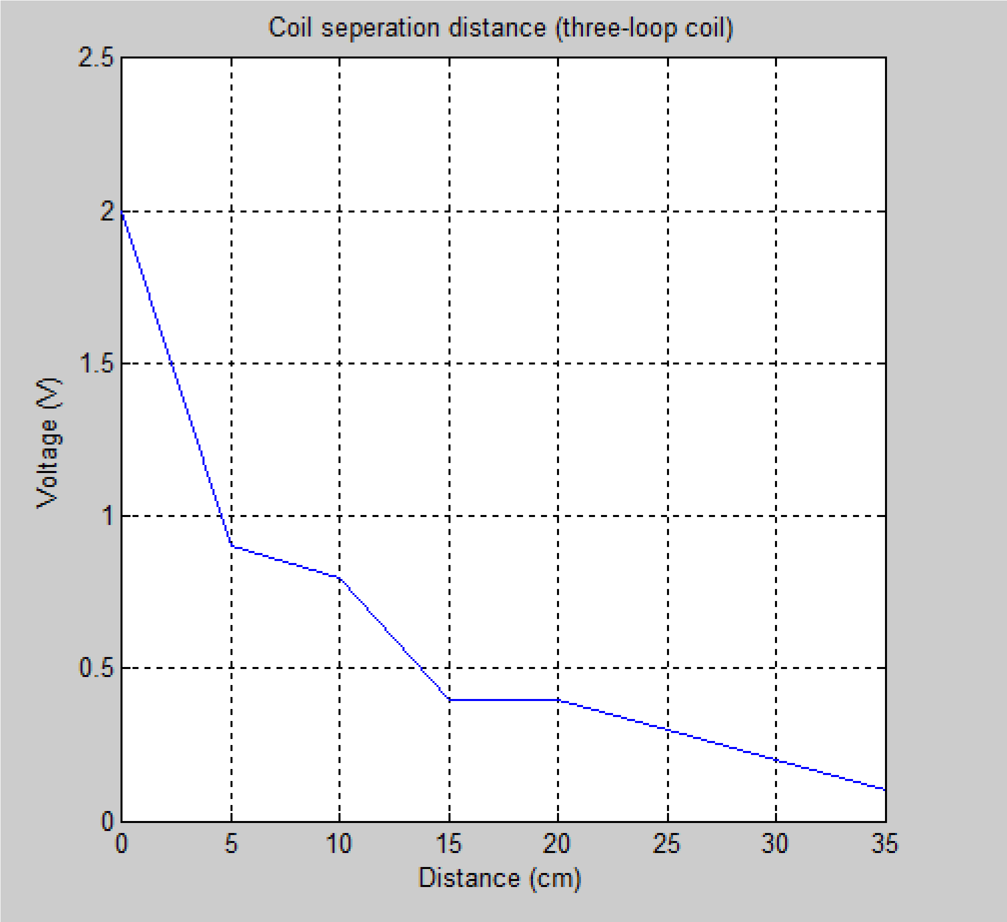

Figure 4.21: Coil separation distance (three-loop coil)

Figure 4.22 shows the lateral misalignment between the coils from 0-30 cm measured every 5 cm. The measurements have been taken at a coil separation distance of 5 cm. There is a decrease in the voltage from 0 cm to 5 cm as it goes down from 0.9V to 0.8V, followed by a bigger decrease in the voltage from 5 cm to 15 cm as it goes down from 0.8V to 0.4V, then the voltage has no change as it stays at 0.4V, followed by a decrease in voltage from 20 cm to 30 cm as it goes down from 0.4V to 0.2V.

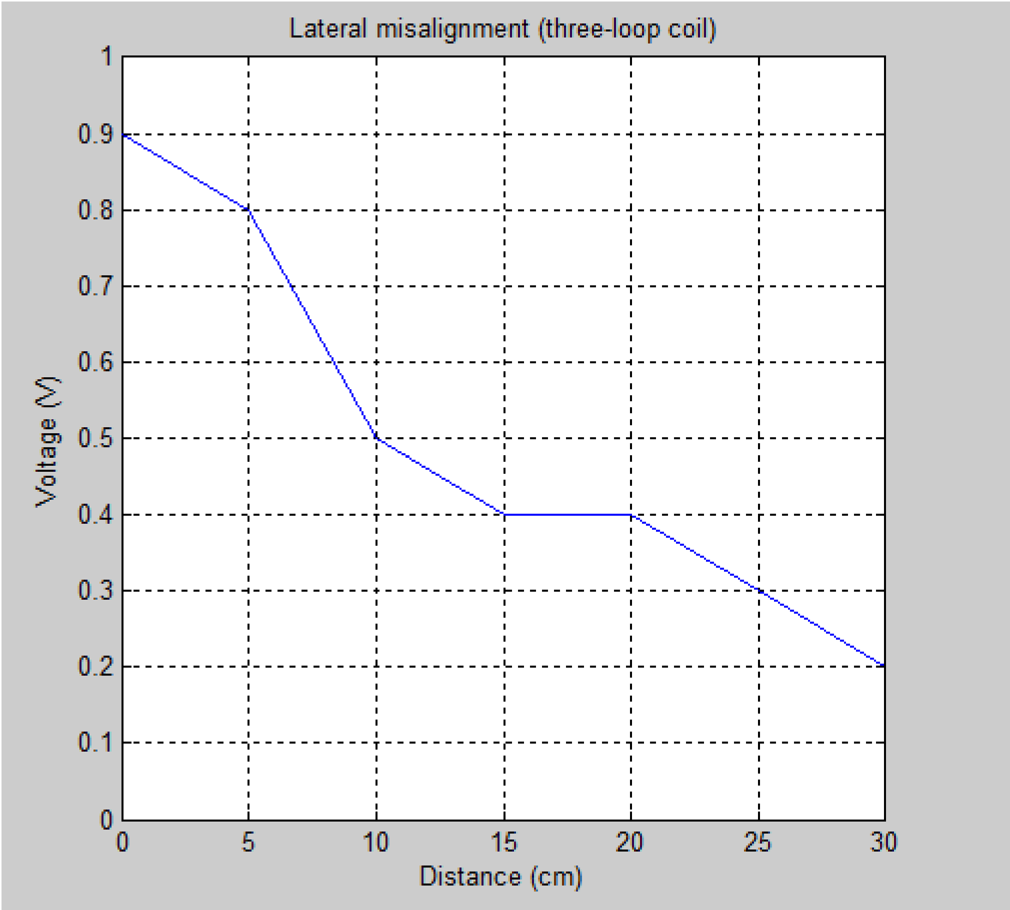

Figure 4.22: Lateral misalignment (three-loop coil)

Figure 4.23 shows the angular misalignment between the coils from 0-90 degrees measured every 10 degrees. The measurements have been taken at a coil separation distance of 5 cm. There is a slight decrease in the voltage from 0 degrees to 10 degrees as it goes down from 0.5V to 0.49V, followed by a decrease in the voltage from 10 degrees to 20 degrees as it goes down from 0.49V to 0.41V, then the voltage increases from 20 degrees to 30 degrees as it goes up from 0.41V to 0.45V, followed by a decrease in the voltage from 30 degrees to 50 degrees as it goes down from 0.45V to 0.4V,then the voltage has no change from 50 degrees to 70 degrees as it stays at 0.4V, followed by a decrease in voltage from 70 degrees to 90 degrees as it goes down from 0.4V to 0.3V.

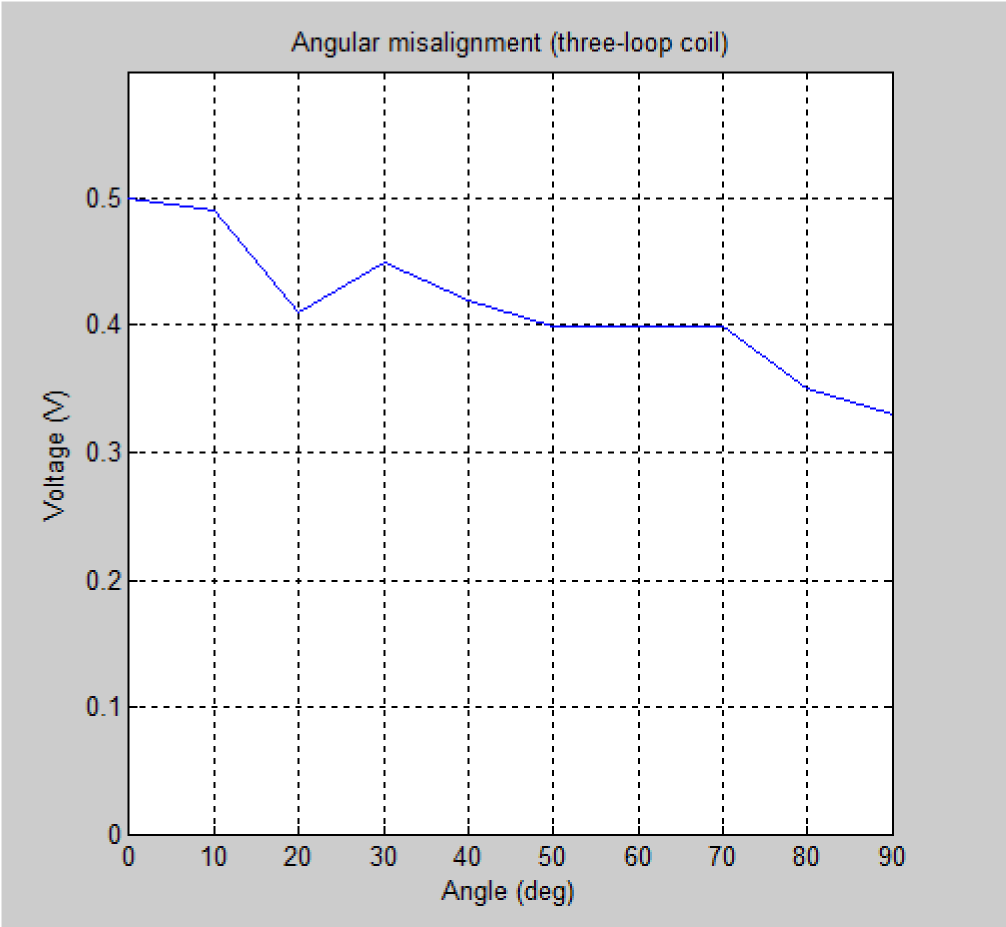

Figure 4.23: Angular misalignment (three-loop coil)

4.3 Performance and Analysis

The performance and analysis of this study is accomplished as shown in Table 4.1 in terms of coil separation distance, Table 4.2 in terms of lateral misalignment and Table 4.3 in terms of angular misalignment:

Table 4.1: Results of the coil separation distance measurements

Distance (cm)	Single Loop Coil System Voltage (V)	Two Loop Coil System Voltage (V)	Three Loop Coil System Voltage (V)
0	5	0.8	2
5	3	0.3	0.9
10	2	0.2	0.8
15	1	0.12	0.4
20	0.6	0.1	0.4
25	0.4	0.06	0.3
30	0.28	0.04	0.2
35	0.2	0.015	0.1

The measured voltage decreases with the increase of distance between coils. The single loop coil system has the highest voltage at the receiver coil, and that is due to the magnetic field being spread in an in more than one direction. However the rate of the voltage decrement in the single loop coil system is much higher than that of the two-loop and three-loop coil systems.

Table 4.2: Results of the lateral misalignment measurements

Distance (cm)	**Single Loop Coil System Voltage (V)**	**Two Loop Coil System Voltage (V)**	**Three Loop Coil System Voltage (V)**
0	3	0.3	0.9
5	2.5	0.28	0.8
10	2	0.25	0.5
15	1	0.2	0.4
20	0.99	0.15	0.4
25	-	0.1	0.3
30	-	0.09	0.2

The measured voltage decreases with the increase of distance between coils. The single loop coil system has the highest voltage at the receiver coil, and that is due to the magnetic field being spread in an in more than one direction. However the rate of the voltage decrement in the single loop coil system is much higher than that of the two-loop and three-loop coil systems.

Table 4.3: Results of the angular misalignment measurements

Angle (deg)	**Single Loop Coil System Voltage (V)**	**Two Loop Coil System Voltage (V)**	**Three Loop Coil System Voltage (V)**
0	3	0.3	0.5
10	2	0.28	0.49
20	1.8	0.26	0.41
30	1.5	0.24	0.45
40	1.2	0.24	0.42
50	1	0.22	0.4
60	0.75	0.2	0.4
70	0.7	0.2	0.4
80	0.6	0.16	0.35
90	0.5	0.12	0.3

The measured voltage decreases with the increase of angular misalignment between coils. The flat spiral coil system has the highest voltage at the receiver coil, and that is due to the magnetic field being spread in more than one direction. However the rate of the voltage decrement in the single loop coil system is much higher than that of the two-loop and three-loop coil systems.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The goal of this study is the design and implementation of a wireless omnidirectional power transfer system via inductive coupling. The system should be capable of transferring power without being heavily affected by the coils' orientation and positioning. After designing and implementing the traditional WPT system using single loop (flat spiral) multi-turn coil, the wireless omnidirectional power transfer system using the two-loop and three-loop (spherical) coils were designed and implemented and the experimental results were obtained for both systems and compared with each other.

The experimental results showed an improvement in terms of the sensitivity towards coil separation distance, lateral misalignment and angular misalignment in the wireless omnidirectional power transfer system using the two-loop and three-loop coils compared to the traditional WPT system using single loop multi-turn coil.

However the main disadvantage of the wireless omnidirectional power transfer system using the two-loop and three-loop coils is that the voltage produced is lower than that of the traditional WPT system using single loop multi-turn coil due to the magnetic field being spread in more than one direction.

5.2 Recommendations

- Increasing the power transfer efficiency by adjusting the number of turns of coils.
- Redesign the coil shape to get more uniformly distributed magnetic field.

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