



Wireless Charging Of Batteries On Military Vehicles

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa and Academia Militar.

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Abstract

Recent developments, in the field of wireless charging, have led to increasing use of this technology across different areas of research. The search for improvement in Soldier Combat Systems has seen major investments in recent years, to find a standard architecture that can enhance military capabilities, such as in power management systems. This work is part of the C4I program of the Portuguese army, having had the primary objective of studying an alternative power supply option based on wireless technology, capable of charging man-portable devices in military vehicles.

On this dissertation, it was conducted a study on the behavior of the components of a wireless power transfer, focusing on different configurations and geometries of the charging coils, as well as the optimization of key parameters in a wireless power module. For this, key operating principles and charging methods were approached.

Using distance as a variable parameter, it was possible to study the variation in signal amplitude and compare the performances of each coil, reaching promising conclusions on which coil geometry is best suited in terms of shape, reach, and intensity of the generated magnetic field of the power transfer. Also, the matching outcomes from the theoretical deductions and the experimental work done in a controlled environment led to a strengthening of the obtained results.

After fabricating and testing prototype 3D structures for the coils, a proposal for a wireless charging system was conceived. This proposal includes architecture, protocols, and its implementation taking into account the characteristics of the charging environment.

Key-words: Coil Geometry, Inductive Coupling, Magnetic Field, Standardization, Wireless Charging

Resumo

Desenvolvimentos recentes, no campo do carregamento sem fios, levaram a uma utilização crescente desta tecnologia em diferentes áreas de investigação. A procura de melhorias nos Sistemas de Combate do Soldado tem sido objecto de grandes investimentos nos últimos anos, com o objetivo de encontrar uma arquitectura padrão que possa melhorar as capacidades militares, tais como nos sistemas de gestão de energia. Este trabalho faz parte do programa C4I do exército Português, tendo como principal objectivo o estudo de uma alternativa de fornecimento de energia baseada em tecnologia sem fios, capaz de carregar dispositivos portáteis em veículos militares.

Nesta dissertação, foram realizados uma série de estudos sobre o comportamento dos componentes de uma transferência de energia sem fios, focados nas diferentes configurações e geometrias das bobinas de carregamento, bem como a otimização dos parâmetros chave num módulo de fornecimento de energia sem fios. Para tal, foram abordados princípios chave de funcionamento e métodos de carregamento.

Utilizando a distância como parâmetro variável, foi possível estudar a variação da amplitude do sinal e comparar os desempenhos de cada bobina, chegando a conclusões promissoras sobre qual a geometria da bobina mais adequada em termos de forma, alcance e intensidade do campo magnético gerado pela transferência de energia. Além disso, os resultados coincidentes entre as deduções teóricas e os trabalhos experimentais realizados em ambiente controlado, levaram a um fortalecimento dos resultados obtidos.

Depois de fabricar e testar protótipos de estruturas 3D para as bobinas, foi concebida uma proposta para um sistema de carregamento sem fios. Esta proposta inclui arquitetura, protocolos, e a sua implementação tendo em conta as características do ambiente de carregamento.

Palavras-chave: Acoplamento Indutivo, Campo Magnético, Carregamento Sem Fios, Estandarização, Geometria da Bobina

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Acronyms

AC Alternating Current. 11, 20, 21, 28

AEP Allied Engineering Publication. 7

C4 Command, Control, Communications and Computers. 6

C4I Command, Control, Communications, Computers and Intel. iii, 2, 6

DC Direct Current. 11, 20, 21

DDS Data Distribution Service. 6

DSS Dismounted Soldier Systems. 2, 5–8

EDA European Defense Agency. 4, 5

EF Electromagnetic Fields. 22

EU European Union. 1, 4

FOD Foreign Object Detection. 18, 19, 21, 33, 66, 71

FSK Frequency Shift Keying. 20

GUI Graphical User Interface. 16, 27, 28, 32–34, 47, 71

IC Inductive Coupling. 3, 11, 12, 14, 16, 41, 42, 45, 73

ICNIRP International Commission on Non-Ionizing Radiation Protection. 22

IEEE Institute of Electrical and Electronics Engineers. 9

IoT Internet of Things. 21

IPT Inductive Power Transfer. 11, 12, 21, 34, 73

IRE Institute of Radio Engineers. 9

JDSSIN Joint Dismounted Soldier System Interoperability Network. 6

LAN Local Area Network. 21

MI Mutual Inductance. 14

MIT Massachusetts Institute of Technology. 17

MRC Magnetic Resonance Coupling. 16, 17, 42

NATO North Atlantic Treaty Organization. 1, 2, 4–8, 24, 25

OTP Open Telecom Platform. 33

PoE Power over Ethernet. 3, 4, 21, 71

RF Radio Frequency. 1, 10, 22, 23

RFID Radio Frequency Identification. 12

RX Receiver. 16, 17, 21, 27, 34, 41, 42, 45, 49–53, 59, 70–72, 75

STASS Standard Architecture for Soldier Systems. 1, 2, 4, 25

TX Transmitter. 14, 16, 17, 21, 26, 32, 34, 41, 42, 45, 49–53, 58, 59, 70–72

WHO World Health Organization. 22

WPC Wireless Power Consortium. 12, 18

WPT Wireless Power Transfer. 1–4, 9–12, 17, 22, 34, 35, 46–48, 70–73, 75

Chapter 1

Introduction

Standardization, interoperability, and interchangeability of soldier systems has been a long-fought problem of European Union (EU) member states which, in recent years, rallied their efforts in order to enhance military effectiveness, improve capability development and support the competitiveness of the European defense industry [1]. In order to tackle this problem, North Atlantic Treaty Organization (NATO) has launched a program, Standard Architecture for Soldier Systems (STASS), which focuses on finding a standard architecture for all participant member states in order to avoid differences in military potential between allies and, simultaneously, find the most reliable and practical solution [2].

Wireless power is rapidly evolving from theories toward standard use across different research areas. According to a study conducted by Allied Market Research¹, was valued at \$6.51 billion in 2018, and is expected to reach \$40.24 billion by 2027. The most recent developments in this field of research have brought a new and promising alternative way to address the energy bottleneck felt on battery-powered devices [3].

This technology has seen some setbacks over the years, mainly in terms of complexity and power management. But, on the other side, WPT has become a grand contributor to benefits on the user experience side of things, such as ease of handling and mobility, making it one of the more popular products among the general public [3]. Devices that are suited for wireless charging do not require a charging cable, which prevents the degradation of power and data interfaces and makes them considerably more durable than wired devices. Also, the coils required for wireless charging are never exposed to air, which reduces the oxidation and corrosion of the charging unit [4].

Wireless charging approaches can be classified into non-radiative coupling-based charging, and radiative Radio Frequency (RF)-based charging [5]. The former method can be decomposed into three different techniques: inductive coupling, magnetic resonance coupling, and capacitive coupling. These techniques are mostly used on near-field applications, due to the lack of intensity of the generated electromagnetic field for larger distances, and, as a result, a lower efficiency, associated with the latter [5].

Recent studies have tried to appropriate the shape and dimensions of the coils used in WPT modules in order to accommodate the needs of the equipment that is being charged, facilitate the power transfer in

¹View of an Allied Market Research study on the Wireless charging Market outlook towards 2027 Adapted from: <https://www.alliedmarketresearch.com/wireless-charging-market>

terms of user experience and reduce loss of energy [6]. Aspects such as inductance, coupling coefficient, quality factor, and parasitic resistance between transmitter and receiver are important parameters to consider when working with wireless power transmission, in order to guarantee a high-performing system. These variables can significantly impact the power transfer efficiency by simply changing the size or the geometry of the coils [7].

1.1 Problem Definition and Motivation

NATO's joint forces program has been present in several military conflicts since the Balkans, its first major crisis-response operation [8]. This type of allied cooperation between different armed forces has made possible several military, economic and political benefits to the scenario of international confrontations, but has also brought up major problems in terms of standardization, interoperability, and interchangeability between armed forces equipment and *modus operandi* [2]. The necessity to deal with this issue has, for long, been one of the top priorities of NATO's armed forces.

This thesis is part of the Soldier's Combat Systems project, which is an initiative of the Portuguese army, that aims to improve the Command, Control, Communications, Computers and Intel (C4I) capabilities, with a special focus on the communication and Intel systems [9]. The motive behind this initiative comes as a response to the STASS program, which searches for a reference architecture for all soldier systems, and that has propelled the creation of the Dismounted Soldier Systems (DSS) program with the objective of conducting a thorough assessment of the data distribution, power, and system architecture of dismounted soldier systems across NATO's member states, where Portugal is included [2, 10].

It is of the utmost importance for this study to go forth and accomplish promising results so that it can be an important contribution to the Portuguese army's initiative. The right contributions will help lead the Soldier's Combat Systems project to a concise and well-documented architecture, that can be positively compared to other nations' implementations, showing that the dedication and vision of the Portuguese army are aligned with NATO's. This study's motivation also rests on the premise of exploring the enormous potential surrounding WPT technologies, which, despite their rising popularity, were never implemented in military charging systems.

1.2 Objectives

This dissertation is focused on developing an alternative to the wired charging systems currently implemented in military vehicles to power electronic devices carried by soldiers in operational environments. The core of this work is the study of a wireless charging system capable of powering a Central Power and Data Hub, the DSI-104, which is currently under development and will be the center of the man-portable charging system of the Portuguese army. This study targets a thorough examination of current military charging methods and reference architectures, that are, as of today, in use by NATO member states. Current near-field WPT systems, their applications, operating mechanics, and safety considerations of this technology must also be documented in this work.

The behavioral study of Inductive Coupling (IC)-based systems using referenced equipment, and related works are the foundation for the theoretical and practical component of this project. This study comprises rigorous research on the performance, functionalities, capabilities, shape, and altering parameters of wireless power transmission with results comparison, in order to better understand which approach better suits the problem at hand. The theoretical and practical results served as the base for the system's architecture and implementation that was proposed, which is the final product of this work.

The desirable outcome from doing this present work is the elaboration of a suitable wireless power system architecture that can be the basis for a successful implementation in military vehicles, leading to other studies in this area, culminating in the improvement and advancement of charging technologies in the military.

1.3 Dissertation Structure

The first chapter of this dissertation presents an introduction to this thesis, the context of the problem, and its definition, namely, wireless charging of man-portable equipment inside military vehicles, the motivation behind the resolution of this issue, and the objectives that were set to be accomplished.

The second chapter includes the state of the art of various subjects that are key to this work, such as power transfer systems in military applications, WPT systems, and their different approaches, theoretical concepts, Power over Ethernet (PoE) methods and applications, and health and safety considerations on wireless charging.

The third chapter is comprised of a detailed equipment analysis. These devices were used during the practical component of this dissertation, and are the foundations of the dissertation's results.

The fourth chapter includes related studies presented by other authors, as well as the theoretical deductions that the author achieved during the course of this work.

The fifth chapter presents the assessment of the tested wireless charging systems, as well as a detailed study of the practical works done during the dissertation. It incorporates, results, achievements, and system development details.

The sixth chapter focuses on the essential requirements, characteristics, architecture, main approach, and implementation of the proposed wireless charging system for man-wearable devices, which are based on the theoretical and practical results of this dissertation.

The seventh chapter presents the conclusions drawn from this study, as well as the fulfilled achievements, and future work for this project.

Chapter 2

State of the Art

This chapter covers the subjects upon which the present work will be based. It includes the current state of the art of power supplies in soldier systems, the development and approaches throughout the years of WPT, the current market applications of this technology, its theoretical background, and the correlations between them. Other topics that are connected to wireless power such as Power over Ethernet (PoE), and health and safety considerations are also addressed through the course of this chapter.

2.1 Power Transfer in Soldier Systems

The technological advances in recent years are well known to be at their highest and the investments made by the armed forces worldwide in terms of technological applications are enormous. The European Defense Agency (EDA) Annual Defence Data Report¹ has stated that its 26 member states have spent, roughly, 186 billion euros as of 2019, increasing 5 % in comparison to 2018, making it the highest level ever recorded by EDA since it began collecting data in 2006. Although the Covid-19 number impact doesn't yet reflect in this data, it is clear that investment in the military is growing in the EU [11].

With major investments coming into this sector, there was the need to reformulate some key aspects of the currently implemented soldier systems. In order to develop new and more practical solutions for NATO's armed forces, a series of programs and architectures were proposed [8].

2.1.1 Current Military Programs

The STASS program is a proposed architecture by NATO that reflects the need and the search for standardization in soldier systems, mainly focusing on the data and power transfer aspect [2]. This program aims to promote standardization, interoperability, and interchangeability for dismounted soldier programs and reduce cabling efforts, all this while allowing innovation by upgrading existent sub-systems into new, more dynamic, and easy-to-use possibilities across all NATO's member states. Since most of these goals are far from being met, a new approach is needed [2]. This proposed plan focuses mainly on cable options to be used for power purposes, stressing the fact that there is not a common denominator,

¹Report of Annual Defense Data for 2019 by EDA Adapted from <https://eda.europa.eu/news-and-events/news/2021/01/28/european-defence-spending-hit-new-high-in-2019>

in this area, between allied forces, forcing soldiers to rely on power adapters or other methods when using allied forces charging equipment. Wireless power options are still under discussion in the soldier power community, mainly because safety and health considerations require a deeper understanding [2].

NATO's Sensors and Electronics Technology Task Group on "Energy Generation for Man-wearable/Man-portable Applications and Remote Sensors" (SET-206) is also focusing its efforts on improving data and power sources and management, and has made an assessment on various Dismounted Soldier Systems (DSS) across NATO's member states, both currently being used and in development [10]. This assessment includes different designs, functionalities, and approaches to the DSS program, including modular systems that strive to focus power on a specific point in the soldier's complex system of electronics and direct it to his various types of equipment [10]. This type of hybrid power system, seen in figure 2.1, has a distributed and centralized architecture, which relies on central batteries that decreases the logistic burden.

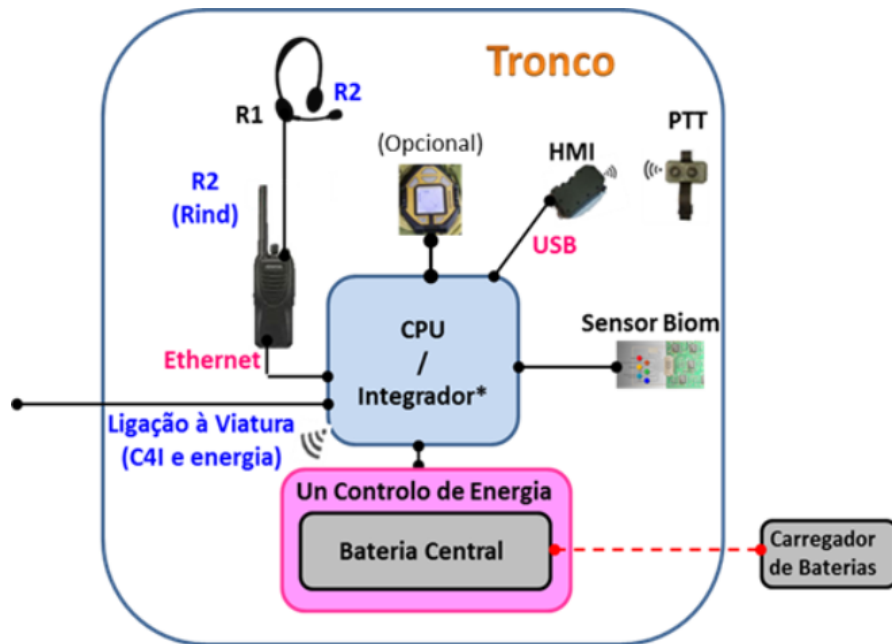


Figure 2.1: Centralized Battery DSS. Data gathered from [9].

EDA has yet to define the standard for the architecture of this power system, focusing a tremendous amount of resources on the development of this project. The energy component is the one that contributes the most to adding weight to the DSS program, and it is estimated that it will undergo considerable development in the coming years, helping to reduce the total weight of these systems [9].

As of now, power distribution on this system is achieved with cabling and connectors for the main power source and e-textiles with conductors that transport the power to all the other electronic devices [10]. In terms of NATO's focus, wireless power still has a long way to go but, in spite of that, this technology is steadily gaining a higher level of interest from government entities across the world, which may lead to a future without cables in the military.

2.1.2 Levels of Interoperability

The existent three levels of interoperability define the interconnectivity that exists for DSS. Each level is attributed to different equipment or situation [12].

Level 1 allows for a NATO DSS to utilize a vehicle power source and is the basis of the interoperability levels [13]. **Level 2** Interoperability is defined as a connector installed on the DSS power modules which refers mainly to the battery and central power systems to guarantee a direct exchange of portable power sources among NATO allies is possible. **Level 3** of Interoperability defines a standardized connector and form factor that allows for an exchange of both power and C4I data among NATO Data Distribution Service (DDS) [12].

In figure 2.2 there is a representation of the different options in terms of electrical connection between DSS components where “C” refers to a connector, “D” refers to a data interconnection and “E” denominates an energy interconnection. In terms of “a”, “b” and “c” subtypes, they represent the connection between the DSS power sources to the DSS, the connection between the DSS to the DSS central system, and the connection between the DSS to the DSS platform system, respectively.

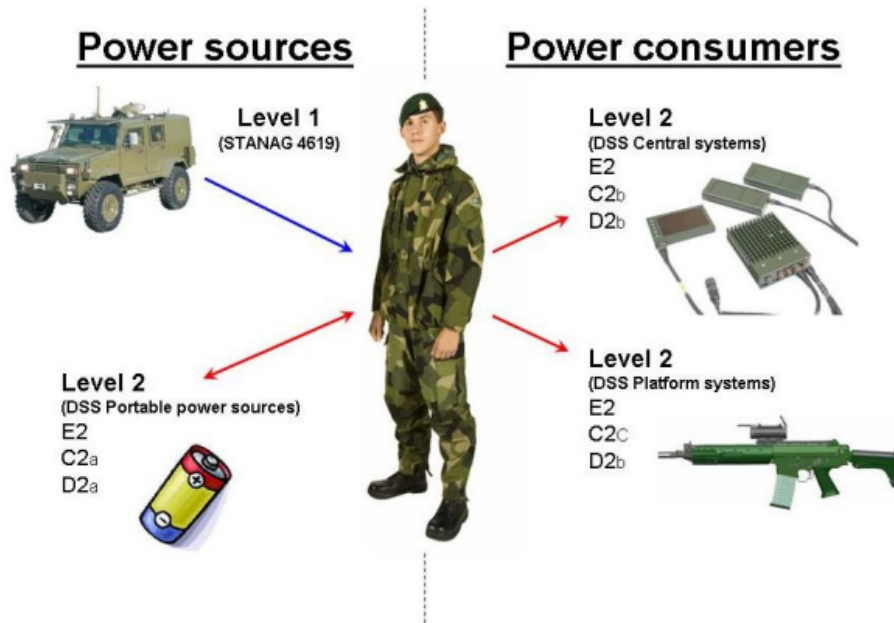


Figure 2.2: DSS Connections. Data gathered from [12].

2.1.3 STANAG 4677

The STANAG 4677 - Dismounted Soldier Systems Standards and Protocols for Command, Control, Communications and Computers (C4) Interoperability (DSS C4 Interoperability) is a document that was released by NATO in 2014, with the purpose of enabling interoperability through a standardized exchange of information between C4 systems, carried and used by dismounted soldiers [14]. By following the regulations and norms presented in this document every nation can be up to date in terms of the Joint Dismounted Soldier System Interoperability Network (JDSSIN) with other member states. Data and power exchange must comply with the communication protocol stack and interoperability interface

(connector) seen in figure 2.3.

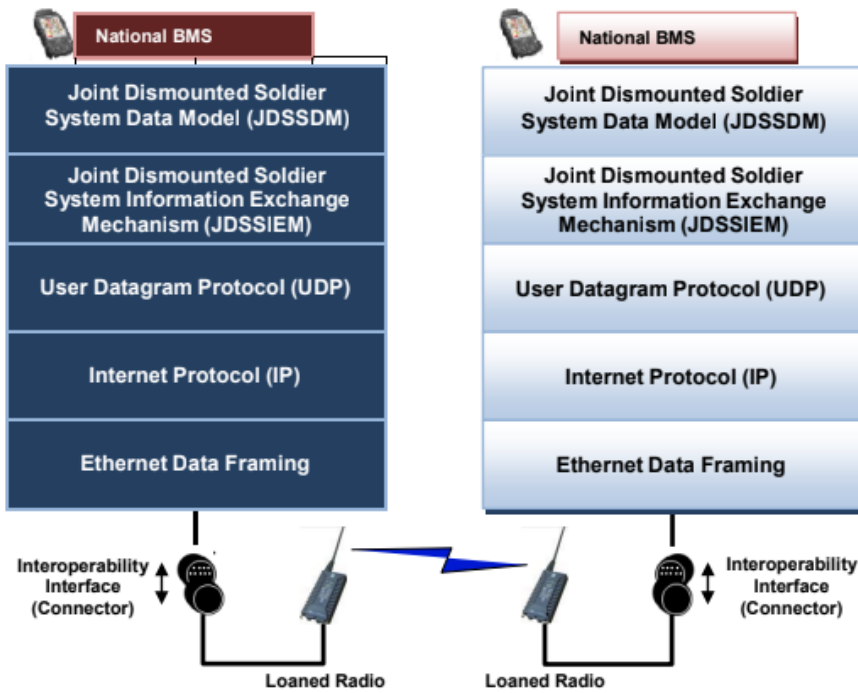


Figure 2.3: Proposed Solution for power and data exchange by STANAG 4677. Data gathered from [14].

This document also represents the different systems that a soldier can operate classified by energy levels of 1 or 2. Energy level 1 refers mainly to vehicles and energy level 2 depicts portable power sources, DSS Central Systems, and DSS platform systems. The system to be developed in the Soldier's Combat Systems project is of energy level 2 in terms of consumption and must comply with NATO standards [14].

2.1.4 STANAG 4695

The STANAG 4695 - Electrical Interface Specifications For Dismounted Soldier Systems (DSS) Level 2 Power Interoperability was released in June of 2016 and it is the current wired charging specification at use by NATO. This standard is very useful in terms of understanding how electrical connectivity is processed in the allied armed forces since there are not any systems implemented that make use of wireless charging, thus there are no standards for this technology. This document focuses on the connectivity between DSS power sources and power consumers, allowing interoperability to both of these between different allied nations. Level 2 power sources are a requirement so that the output of the DSS is met by other nations' power modules as defined by Allied Engineering Publication (AEP) - 95 [12].

The STANAG 4695 energy source should provide DC power at a voltage between 8 and 32 V, supplying up to 50 W in this voltage range, and must be set to provide over 1 A. When it comes to energy sources with limited output power, there should be a safety mechanism for whenever a peak in current is detected, limiting the voltage to below 8 V and be self-protected by a fuse. A STANAG 4695 compliant input port is set to work with the voltage window of the energy source, it shall draw no more than 5 A from it and limit the power draw if the energy source is not capable of providing 5 A in order to prevent it from shutting down [12].

The way it is defined by NATO, the level 2 connector must be capable of interfacing a DSS to an external power module, such as a fuel cell, solar panel, or another nation's battery charger, for power. In figure 2.4 it is possible to see how the system must be designed.

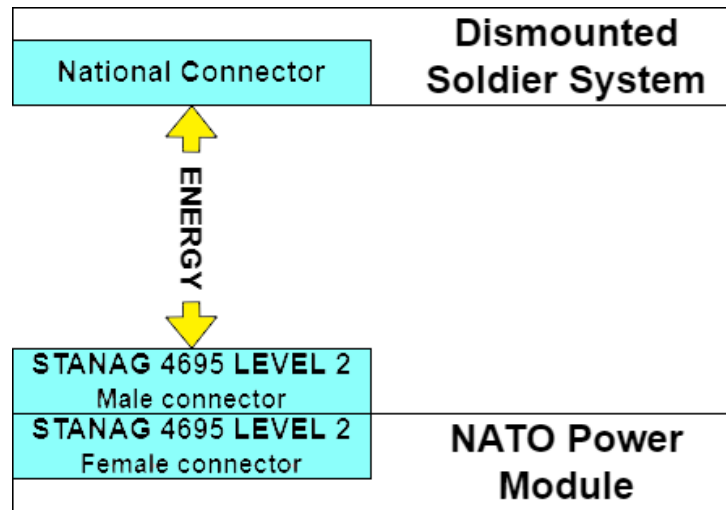


Figure 2.4: Connectivity of the DSS. Data gathered from [12].

The widely standardized 6-pin connector, shown in figure 2.5, must follow fabrication restrictions in terms of pin assignments, dimensions, electromagnetic compatibility, and environmental conditions [12].

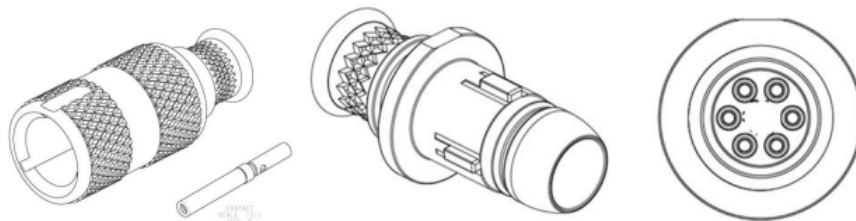


Figure 2.5: Receptacle, plug and 6 pin layout of the connector. Data gathered from [12].

Figure 2.6, depicts the mandatory pin assignments for the DSS for level 2 connectors without data transfer capabilities.

CONTACT LOCATION	DESCRIPTION	TERMINAL MARKINGS
1	V+ Battery Voltage	Batt +
2	V- Battery Ground	Batt -
3	Charge +	Charge +
4	SMBus Data	Data
5	SMBus Clock	Clock
6	SMBus ID (10K Thermister to Ground)	SB ID (*1)
7 (If Present)	No Connection or V+ Battery Voltage	Blank / NC / Batt + (*2)

Figure 2.6: Mandatory Pin Assignments for the 6 pin connectors. Data gathered from [12].

This pin assignment has seen different variations, such as the Mighty Mouse 807 QDC, and the MouseBud® connector, which can be seen in figures 2.7 and 2.8, respectively.



Figure 2.7: Mighty Mouse 807 QDC. Data gathered from [10].



Figure 2.8: MouseBud Connector. Data gathered from [15].

2.2 Wireless Power

Electrical power has always been associated with certain words such as energy, light, and wire, but as time went by and technological advances increased exponentially, the latter, which was once thought to be inseparable from power transmission is becoming undeniably more obsolete. Wired power is slowly being replaced by wireless transmission, which is gaining terrain and is now in the vanguard of electronic research, being highly regarded in terms of innovation, as it is in terms of possibility [16].

2.2.1 Historical Background

Although still taking its first steps, the transmission of electrical energy without wires dates back to the 19th century, with the appearance of the electromagnetic theory and the birth of Maxwell's equations, explained by the author in the theoretical paper, "A Dynamical Theory of the Electromagnetic Field", published in 1864 [17].

A few years later, in the late 19th century and early 20th century, Nikola Tesla first experimented with the object of perfecting a method of transmission of electrical energy through the natural medium [18], which was not achieved, at least to the extent that Tesla had in mind. In fact, he was able to create the Tesla Coil, a mechanism that creates a magnetic field capable of inducing an electric field on a nearby object thus creating a WPT. Despite this breakthrough that has found applications in multiple areas such as radio technology, medical and industrial X-rays, education, and even entertainment [19], his efforts didn't take into consideration molecular theory, a product of the lack of knowledge of the time, which led to the conclusion that the lack of electric conductivity in the atmosphere is not suited for wireless charging on a long distance scale [20].

In May of 1961, a wireless power transmission system was proven to achieve 100 % efficiency due to theoretical demonstrations presented in the paper "On the guided propagation of electromagnetic wave beams" by Goubau and Schwering. The organization that published this paper, Institute of Radio Engineers (IRE), was the predecessor of the Institute of Electrical and Electronics Engineers (IEEE), which is the largest association in the world of technical professionals [17].

A variety of experiments from far-field to near-field transmissions of power were attempted and developed throughout the years, culminating, today, in its everyday use by millions of people, proving, once more, its growth and potential.

2.2.2 Far-Field and Near-Field Power Transfer

When it comes to WPT, there are two different approaches, far-field and near-field transmissions, with all its variations attached, and both methods have distinct working ways and are targeted to different applications. The goal behind this chapter is to understand both systems and come to a suitable verdict on which presents the better solution for this work. Figure 2.9 shows the main methods used in WPT.

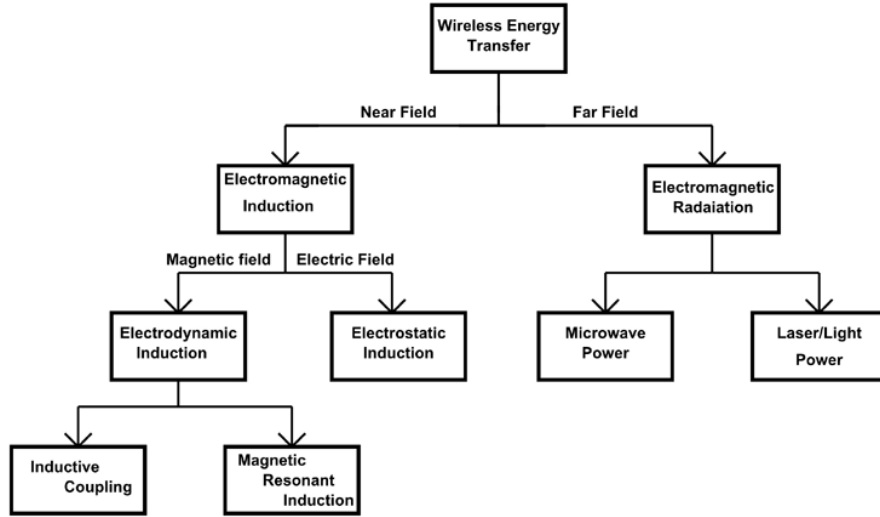


Figure 2.9: Types of WPT. Data gathered from [21].

When comparing far-field and near-field techniques, one of the main differences to enunciate is that for the former, the radiation absorption has little or no effect on the transmitter. On the other hand, for the latter, the radiation absorption influences the transmitter and its charge [22].

Low-power sensors are, commonly, the target systems of far-field power transfer and large-scale applications, due to the fact that, for low-power sensors, efficiency is not the main objective and microwave radiation can be used without exceeding safety standards, and for large-scale applications, where the ability to receive power wirelessly outweighs the cost [23]. Although this type of radiation allows power transfer over long distances, reaching the kilometer mark, the power loss and safety concerns make this technology both inefficient and dangerous when compared with the most used option, near-field power transfer.

Near-field power transfer systems are a growing tendency in everyday electronic appliances, as the research for this technology is growing daily and the market popularity is equivalently high, culminating in the attraction for a device with freedom of movement while maintaining its full capabilities. RF exposure safety standards are not as strict as microwave radiation ones and the efficiency for close contact wireless power transfer is much higher than its counterpart [23]. Still, radio frequency wireless charging operates in a low-power region, due to it still being the target of safety protocols that restrict power usage, leading to non-radiative options becoming the target for commercial use. This radiation-free technology is based on the coupling of the magnetic field between two coils, where the magnetic field of an electromagnetic wave attenuates much faster than the electric field, having the counterpart that the importance of having a short distance between the receiver and the appliance being charged is much more crucial [3]. In figure

2.10, a near-field WPT system can be seen.

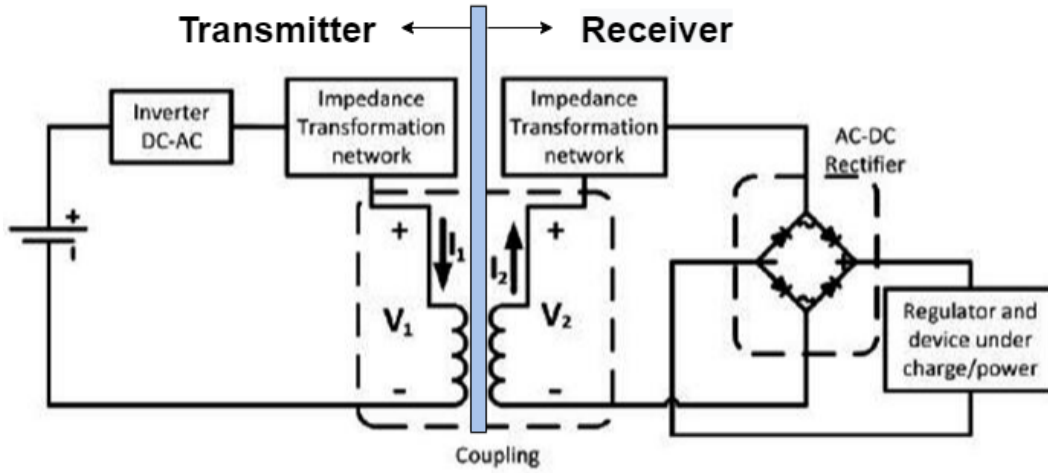


Figure 2.10: Near-field transfer system. Data gathered from [23].

The Direct Current (DC)-to-Alternating Current (AC) conversion takes place in the **inverter unit** of the transmitter. The inverter unit is composed of different sub-units that perform essential steps of the conversion. The first step is increasing the voltage using a DC-to-DC converter. Then a switching unit alternates the polarity of the output from positive to negative, creating a square wave. Finally, a rectifier is used in order to prevent damage to the equipment due to the abrupt discontinuous nature in the wave. The end result is a modified AC sine wave [24].

The **impedance transformation network** is a way to control power management according to the receiver capabilities and needs [16]. The impedance that may come from the transmitting coil goes through this network so the range of the loads that are presented in the circuit during an operation will have values within the ones for which the inverter has an optimized efficiency. The network may consist of passive components, but, in principle, could also be composed of electronically adjustable elements to obtain different performance characteristics [23]. The **AC-DC rectifier**, also called a converter in some areas of application, is responsible for converting the power back to DC and for the efficiency of the system on the receiver's end [16].

2.3 Inductive Coupling

Inductive Coupling (IC) is a type of near-field wireless energy transfer technology where two conductors are set in a way that, any change that might happen in the current of a wire, will induce a voltage on the other end of the coupled device using the principle of electromagnetic induction. This is set on the premises described in Ampere's circuit law, which describes the connection between the magnetic field of the system around the coil and the electric current passing throughout it, and Faraday's law of induction, that focus on the time-varying effect of a magnetic field on an induced electric field [22].

Inductive Power Transfer (IPT) is the process where a coil, made to be the **primary** one, of a transmitter of energy is set to generate a varying magnetic field across the other coil of the system, the

secondary one, that is set on the receiver's end. The receiver's coil has to be within the field generated by the transmitter's coil which is much smaller than a wavelength. As can be seen in figure 2.11, the magnetic field produced by the primary coil, based on a near-field IC system, induces a voltage in the secondary coil that is within the region of the magnetic lines [3].

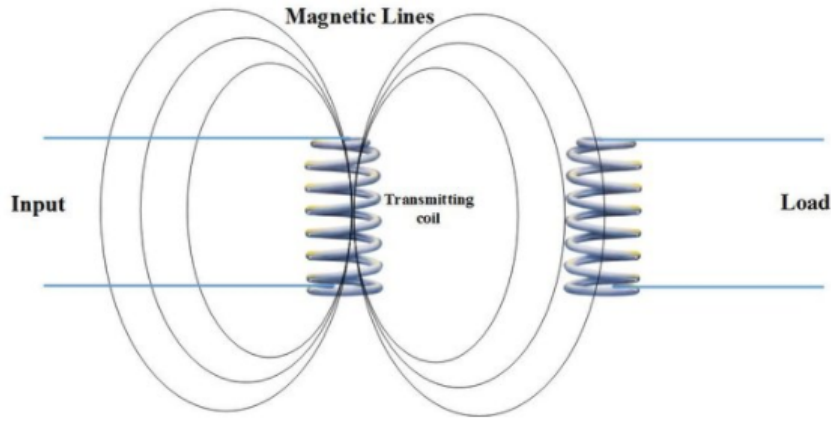


Figure 2.11: Wireless charging using an IC system. Data gathered from [25].

IPT systems work on the kilo Hertz region and both coils must have the same frequency, in order to allow for better throughput of the power transfer [26]. The efficiency of the WPT is dependent on the coupling coefficient, which is in a direct relationship with the distance between coils. Due to this, a distance that surpasses the millimeter scale will compromise the quality of the power transfer and bring down efficiency, but this value might change in accordance with the power levels needed [22]. There are successful attempts of charging a device that have extended the previously referenced range, like Radio Frequency Identification (RFID), that can operate at a distance of tens of centimeters, although the received power is at the micro watt range [26].

In terms of advantages, it has proven to be one of the safest, most reliable, easy to use, and more efficient methods on the market, therefore, it has seen many applications throughout the years.

This method is the oldest type of WPT, with many mobile appliances like battery chargers still using it to this day like the "Felica" IC cards, a product of Sony that operates with a frequency of 13.56 MHz [22]. Wireless charging pads are also primary users of IC, mainly the ones that utilize the Qi standard technology, developed by the WPC in 2011 [27].

2.3.1 Physics of Inductive Coupling

An IC link can be represented as a transmitter inductor and a receiving inductor, as was previously stated, that transfers energy through variable magnetic field lines [28].

By analyzing Biot-Savart's law it is noticeable that a relationship between a magnetic field and the magnitude, proximity, length, and direction of an electric current that passes through it. This relation gives out the magnetic flux density which is generated by the flow of charges and can be represented by the following expression:

$$B = \frac{\mu_0}{4\pi} \int_l \frac{Idl e_r}{r^2} \quad (2.3.1)$$

where μ_0 is the permeability of free space, Idl is the infinitesimal current source point in the wire, r is the full displacement vector from the current source to the field point, e_r is the unit vector of r [29].

Considering a distance r , the Electric field is inversely proportional to r^2 and the Electric Potential is inversely proportional to r . As seen in equation 2.3.1, and for the same distance r , the variation of the magnetic field can be explained using Biot Savart's law that is used to calculate the magnetic field at a certain point [30]. As this law states, the magnetic field is inversely proportional to the square of the distance between the current element and a certain point assuming the following:

$$dB \propto \frac{1}{r^2} \quad (2.3.2)$$

In a situation where two coils are separated by a distance d somewhere in the near-field region like in figure 2.12, the magnetic field generated by the transmitter in the receiver coil can be represented by:

$$B_2 = \frac{\mu_0 N_1 I_1 r_1^2}{2(d^2 + r_1^2)^{\frac{3}{2}}} \quad (2.3.3)$$

where N_1 is the number of circular wire loops of the transmitter, I_1 is current, r_1 is the radius of the transmitter coil, μ_0 is the magnetic permeability in the vacuum and d the distance between coils [28].

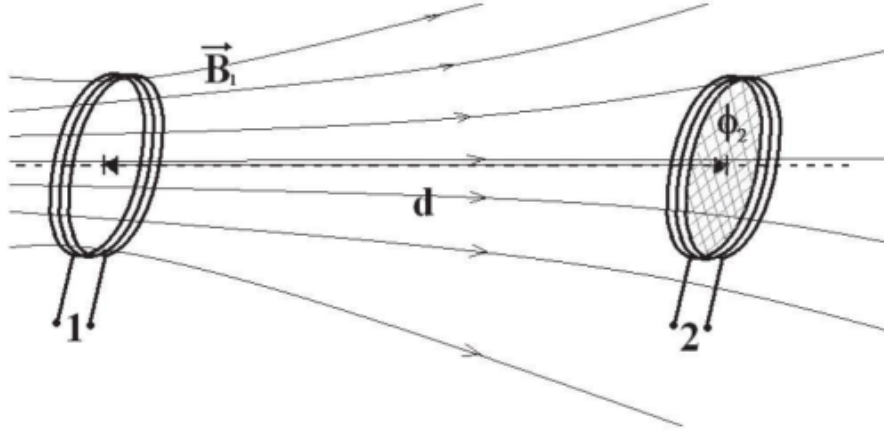


Figure 2.12: Magnetic flux representation between two coils. Data gathered from [28].

The magnetic flux that passes through the receiver is expressed as:

$$\phi_2 = \int \int_S B dS \quad (2.3.4)$$

where B is the magnetic flux density from (2.3.1) and S is the coil surface area [29]. It is now possible to represent the electromotive force (ε) induced in the receiver coil using (2.3.6), which has the following expression:

$$\varepsilon = -\frac{d\phi}{dt} \quad (2.3.5)$$

the electromotive force is responsible for driving the current in the receiving coil whose time variation in the magnetic flux is opposed by the magnetic field [31].

Mutual inductance M is a parameter that is directly related to the coupling coefficient and to the self-inductances of both the receiver and transmitter and it can be represented by the following expression:

$$M = k\sqrt{L_1 L_2} \quad (2.3.6)$$

where L_1 and L_2 represent the transmitter and receiver inductance, respectively, and k which is the coupling coefficient, the parameter that defines how much flux passes to the receiver coil. Its values go from 0 to 1, with being 1 the ideal transformer, where both inductors have the same magnetic flux [28]. The coupling coefficient k is given by:

$$k = \sqrt{1 - \frac{L_s}{L_1}} \quad (2.3.7)$$

Using equation 2.3.7, where L_1 is the inductance of the TX coil and L_s is the inductance of the Transmitter while the Receiver is in short-circuit [32].

The self-inductance of the coil is applied when the magnetic field of a circuit is opposing the changes in the current and is represented as:

$$L = \frac{N\phi}{I} \quad (2.3.8)$$

where N is the number of wire loops, ϕ is the magnetic flux and I is the current of the circuit in question [31].

Both Mutual Inductance (MI) and self-inductance can also be represented as parameters that are directly proportional to the induced electromotive force which is presented as:

$$\varepsilon = -M \frac{dI}{dt} \quad (2.3.9)$$

$$\varepsilon = -L \frac{dI}{dt} \quad (2.3.10)$$

where L is self-inductance, M is the mutual inductance of two coils and I is the current of the coil [31].

In order to represent the efficiency and power output of an IC circuit it will be used a two coil coupling system. One example can be seen in figure 2.13.

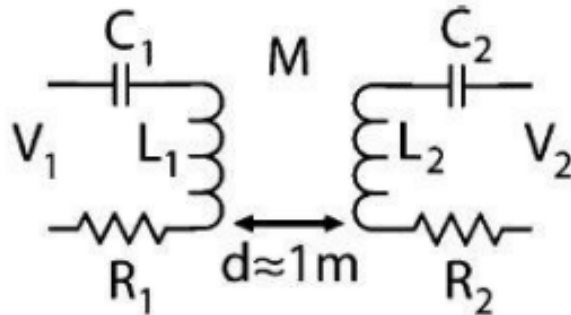


Figure 2.13: Example of two coil coupling system. Data gathered from [23].

The output power of the receiver is:

$$P_{out} = \frac{V_1^2 \omega^2 M^2 R_L}{(R_1(R_2 + R_L) + \omega^2 M^2)^2} \quad (2.3.11)$$

where V_1 is the input voltage, ω is the operating frequency, M is the mutual inductance, R_L is the load resistance, R_1 and R_2 are, respectively, the loss resistances of each inductor.

The Quality factor Q can be defined by the ratio between the inductive reactance ωL and the resistance R of a coil, which remains constant for different arrangements with the same volume and shape. The operating frequency is responsible for the scaling of the current in the inductor and that correlates with the apparent power of the device, thus increasing the quality factor. This is represented as:

$$Q = \frac{\omega L}{R} \quad (2.3.12)$$

with $\omega = 2\pi f$.

This factor has its values varying between 0 and infinity, but values above 1000 are considered to be extremely difficult to obtain [27]. A higher quality factor means that there is a narrower bandwidth, and this results in lower coupling efficiency. The typical value found in mass-production appliances is around 100 [27].

The transmission efficiency (η), which varies between 0 and 1, is given by:

$$\eta = \frac{\omega^2 M^2 R_L}{R_1(R_2 + R_L)^2 + \omega^2 M^2(R_2 + R_L)} \quad (2.3.13)$$

with this expression, it is possible to say that the overall transmission efficiency of the circuit is only dependable on the operating frequency, mutual inductance, circuit's parasitic resistances, and load resistances [23].

Using (2.3.12) and (2.3.7) it is possible to get the maximum transfer efficiency given by:

$$\eta = \frac{Q_1 Q_2 k}{(1 + \sqrt{1 + k^2 Q_1 Q_2})^2} \quad (2.3.14)$$

where Q_1 and Q_2 are the quality factors of the transmitter and receiver coils [29].

2.3.2 Coupling Coefficient on Inductive Coils

Many variables influence the efficiency of a power transfer, such as the Quality factor (Q), Coupling Coefficient (k), Circuit Inductance of both coils (L_1 and L_2), and resonant frequency (f_0). As seen in equation 2.3.15 the Optimal Load Resistance (R_{L_opt}) can be calculated using these variables [33].

$$R_{L_opt} = R_{p2} \sqrt{1 + \frac{\omega_0^2 M^2}{R_{p1} R_{p2}}} \quad (2.3.15)$$

where R_{p1} and R_{p2} represent the parasitic resistances of both coils, seen in equation 2.3.16, $\omega_0 = 2\pi f_0$ is the angular frequency and the Mutual inductance (M) is represented in equation 2.3.6.

$$R_p = \frac{\omega_0 L}{Q} \quad (2.3.16)$$

Considering both transmitter and receiver coil as identical we get the values of $L_1 = L_2 = 7.5 \mu H$ from the transmitter specifications gathered from [34], $Q=186$, and $f_0 = 169 \text{ kHz}$ from the transmitter Graphical User Interface (GUI), during testing. The coupling coefficient takes values between 0.01 and 0.5 to allow the gathering of different results for the optimal Load Resistance and Efficiency. In order to calculate η , seen in equation 2.3.18, there is the need to calculate the reflected impedance (Z_{ref}), seen in equation 2.3.17 [33].

$$Z_{ref} = \frac{\omega_0^2 M^2}{R_{p2} + R_{L_{opt}}} \quad (2.3.17)$$

$$\eta = \frac{Z_{ref}}{R_{p1} + Z_{ref}} \cdot \frac{R_{L_{opt}}}{R_{p2} + R_{L_{opt}}} \quad (2.3.18)$$

With this, the influence of the coupling coefficient in both the optimal load resistance and efficiency can now be calculated as seen in table 2.1. The Efficiency is considerably affected by the coupling coefficient, as well as the $R_{L_{opt}}(\Omega)$ meaning that for a stronger coupling coefficient, and increased inductance, there is also the need for a higher resistive load on the secondary coil in order to maximize the Efficiency [33].

k	$R_{L_{opt}}(\Omega)$	$(\eta)Efficiency$
0.50	3.98	97.9 %
0.20	1.59	94.8 %
0.10	0.80	89.8 %
0.05	0.40	80.7 %
0.02	0.16	58.8 %
0.01	0.09	35.7 %

Table 2.1: Efficiency and Optimal Load Resistance variation with the Coupling Coefficient.

The results presented in the table above have high efficiency for a bigger k , as seen. These results have been gathered in an optimal situation where both the Transmitter (TX) and Receiver (RX) coils have the same dimensions and characteristics (Quality factor and Coil Inductance).

2.4 Magnetic Resonance Coupling

Magnetic Resonance Coupling (MRC) is very similar to IC in terms of architecture. In figure 2.14 it is possible to see that a resonator is created using a capacitance on both coils. The two resonators are then coupled, like in the induction case, but now the energy is transferred from one resonator to the other through an evanescent mode wave [22]. An evanescent field or evanescent wave is a type of electric or magnetic field that oscillates and whose energy is spatially concentrated close to the source. Also, these waves are characterized by having an exponential attenuation, rather than sinusoidal, as well as a lack of phase shift [35].

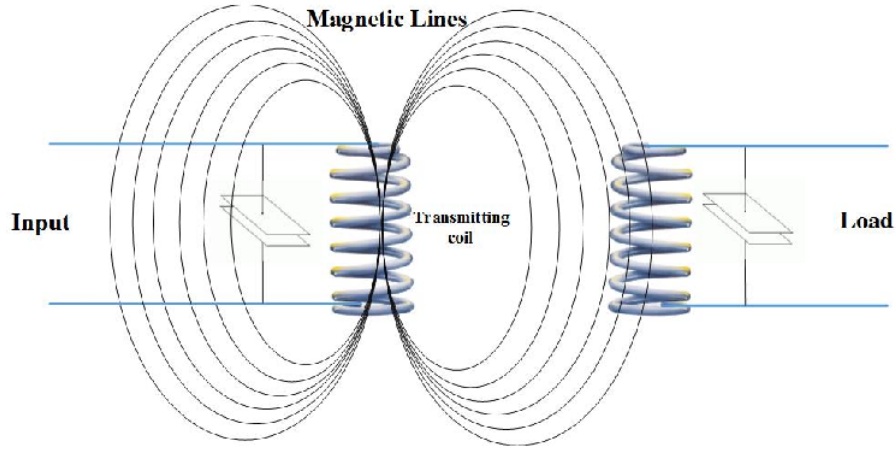


Figure 2.14: Wireless charging using an MRC system. Data gathered from [25].

The two resonant coils usually operate at a frequency typically in the megahertz region, which makes the quality factors high. This quality factor helps to maintain efficiency when the distance of the coupling is greater, making it possible to use this technology with a range of one meter. Transfer efficiencies of 92.6 % over the distance of 0.3 cm have been recorded and it is said that due to the property of resonance, this type of power transfer has the advantage of being immune to outside environments. Another advantage is that MRC can be applied from one transmitting resonator to various receiving ones, thus enabling concurrent charging [3].

This coupling method has seen applications in microwave microstrip bandpass filters in the past, but, recently, has been used as a WPT alternative. Research from Massachusetts Institute of Technology (MIT) on this topic, in 2006, has set MRC to be used in mobile devices, televisions, electric vehicles, and other appliances. Later in 2011, WiTricity Corporations, which is one of the major names in resonant coupling WPT, saw investments by Toyota Motor Corporation [22].

2.4.1 Coupling Coefficient on Resonant Coils

Mur-Miranda *et al.* [36] implemented a system that consisted of two magnetically coupled resonant coils. One resonator is connected to a power source acting as the transmitter, while the other is set up with a load resistance, acting as the receiver. The described model is solved analytically leading to an expression that encapsulates the performance intricacies of a wireless power transfer that uses resonant magnetic coupling.

The inductance of both coils is used as a function of their geometry on calculations, having the magnetic coupling coefficient for resonator coils (k_r) be defined as:

$$k_r = \frac{L_M}{\sqrt{L_1 L_2}} \quad (2.4.1)$$

where L_M is the mutual inductance of the system, L_1 and L_2 are the TX and RX coils inductance, respectively.

Mur-Miranda *et al.* [36] stated that, if the distance between coils (d) is much bigger than their radius (r_1 and r_2), then their geometry becomes irrelevant for the calculations. When this is the case, the

magnetic coupling becomes a non-viable method of charging due to high decreases in efficiency, and the expression for k_r becomes

$$k_r \approx \frac{1}{2(\frac{d}{\sqrt{r_1 r_2}})^3}, \quad d \gg r_1, d \gg r_2. \quad (2.4.2)$$

On the other hand, when the distance between coils is comparable to the effective radius of the coils, the magnetic coupling can be performed. For this case, the expression is the following

$$k_r \approx \frac{1}{\left[\frac{1}{1 + 2^{\frac{2}{3}} (\frac{d}{\sqrt{r_1 r_2}})^2} \right]^{\frac{3}{2}}}. \quad (2.4.3)$$

2.5 Qi Standard Wireless Charging Technology

Qi, the wireless power transfer interface specification, was published by the WPC and, since its release in 2010, has been regarded as the standard for wireless charging equipment and has been widely adopted in the industry all over the world [37]. One of the main focuses of this technology is to allow as much spatial freedom as possible between the power transmitter and receiver, which grants more user freedom and is one of the critical factors for the success of this charging technique [37].

Wireless charging is present in various applications like electric vehicles, consumer electronics, and the biomedical field. To guarantee interoperability between power transmitters and receivers, the WPC published the communication interface, the *Qi* interface specification, the power electromagnetic interface, and the control interface for this technology [27].

The specifications presented by WPC apply to devices that use up to 15 watts of power, although the power profile is set to increase to accommodate equipment such as computers and tablets which typically charge at 30 to 60 watts [27]. The *Qi* system utilizes magnetic induction to transfer power from a transmitter to a receiver. The operating frequency of devices equipped with this standard ranges from 87 to 205kHz.

2.5.1 Qi Communication Protocols

The amount of power that is transferred between the transmitter and receiver is determined by the receiver's requested amount for the device to be charged, and the power transmitter delivers it. The *Baseline Protocol* is a unidirectional communication protocol from the receiver to the transmitter that was introduced with the earliest versions of this technology (versions 1.0 and 1.1), which allows for power transfers below 5 W. An extended protocol was introduced with version 1.2 that allows for bidirectional communication between transmitter and receiver and it enables enhanced FOD features and allows for power transfers up to 15 W [27].

In figure 2.15 it is possible to see the communication protocol between the transmitter and the receiver.



Figure 2.15: Communication protocol phases. Data gathered from [27].

The **Ping Phase** is when the transmitter tries to find and establish a connection with the receiver. In order to do so, it performs measurements to find objects that can damage the equipment during the power transfer, which, if that is the case, the receiver will not be connected to avoid problems on both ends. The transmitter postpones the conclusion of this process if the detected metals are foreign objects, even after obtaining design information from the Receiver [27].

The **Configuration Phase** is when the receiver sends its identification and configuration to the transmitter in order to be detected as a *Friendly Object* and to initiate the power transfer. After this step, the transmitter and receiver decide whether to proceed with the Baseline or Extended Protocol based on the version of each piece of equipment [27].

The **Negotiation Phase** is not part of the Baseline Protocol and can only be found in versions 1.2 or higher. In this phase, the transmitter and the receiver can make use of features such as enhanced Foreign Object Detection (FOD), data transport streams, and authentication. Also, the power receiver gives information about its design [27].

The **Power Transfer Phase** begins with calibration between the receiver and transmitter, only on the Extended Protocol, and then proceeds to do the power transfer [27].

2.5.2 Qi Power Delivery

The wireless power transfer interface specification comprises guidelines and requirements for power receivers such as their design, standby power, circuitry, power transfer efficiency, power consumption, and operating power levels.

There are a set of power profiles, and each one determines the level of compatibility between a power transmitter and receiver. These profiles are the following:

1. *BPP PTx*: Baseline Power Profile Power Transmitter;
2. *EPP5 PTx*: Extended Power Profile Power Transmitter having a restricted power transfer capability;
3. *EPP PTx*: An Extended Power Profile Power Transmitter;
4. *BPP PRx*: A Baseline Power Profile Power Receiver;
5. *EPP PRx*: An Extended Power Profile Power Receiver.

The power transfer system in question works like the one described in section 2.3, with the exception of having a communications modulator and control unit working in parallel with this system in order to guarantee all the safety checks needed to accomplish the power transfer safely. Figure 2.16 depicts a block diagram of a baseline power profile receiver.

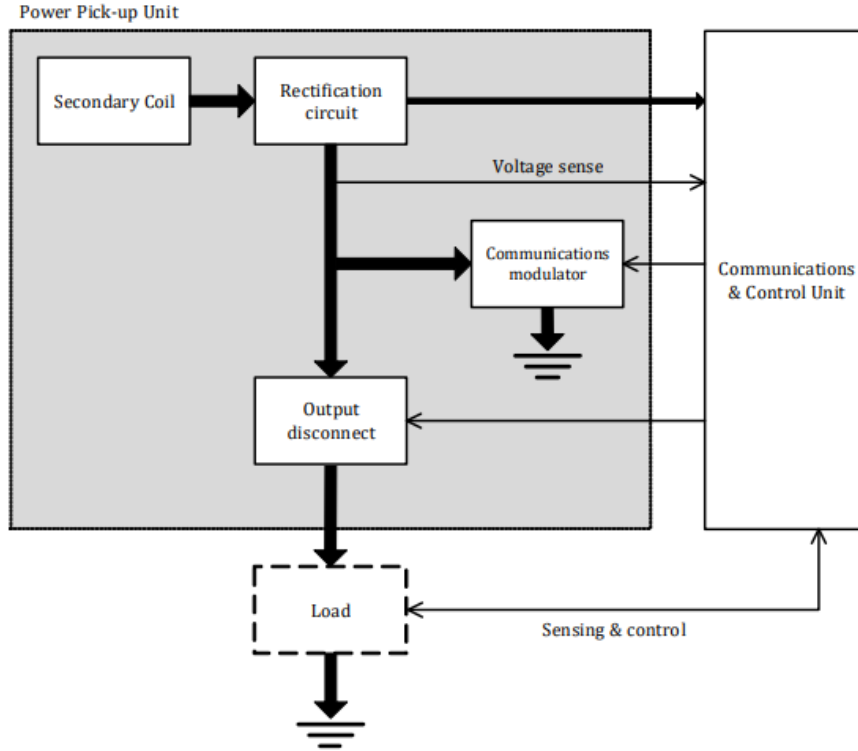


Figure 2.16: Diagram for a Baseline Power Profile Power Receiver. Data gathered from [27].

The Power Pick-up Unit of figure 2.16 includes the analog components of the receiver responsible for communication with the transmitter.

- A Secondary Coil accompanied by parallel capacitance that is responsible for enhancing the power transfer and enabling the resonant detection method;
- The rectification circuit executes wave modulation and rectification of the AC signal. This circuit is also responsible for providing power to the control unit;
- The communications modulator consists on the DC side of the receiver, the communications modulator typically consists of a resistor in series with a switch and, on the AC side of the receiver, the communications modulator typically consists of a capacitor in series with a switch;
- A rectified voltage sense;
- The Communications and Control Unit includes the digital logic and computing of this system. It is where algorithms and protocols are applied, as well as system monitoring.

The exception between the diagram referenced above and a diagram of an Extended Power Profile receiver is the communication demodulator, which acts in order to perform Frequency Shift Keying (FSK). This transmission scheme consists of the transmitter communicating with the receiver by means of frequency switching [27].

2.5.3 *Qi* Foreign Object Detection

During a power transfer, the Power Signal of the transmitter establishes a connection with the receiver. However, metallic objects that may interfere with the connection are, sometimes, placed within the power link between TX and RX, either before the start of the power transfer, or while it is ongoing. These objects are referred to as Foreign Objects [27]. The problem with these objects is that they can dissipate power from the magnetic field, and, as a result, cause an overheating of the components. The system should have safety mechanisms that allow it not to initiate, limit, or stop the power transfer when foreign objects are detected [27].

One of the methods for Foreign Object Detection (FOD) consists in having the receiver communicate with the transmitter, sending information about its design properties, identification, and power necessities.

Resonance change is a method of detection where the transmitter applies a weak power signal and then examines it to see if there are changes in the resonance frequency and quality factor. The receiver communicates a reference Resonance frequency and quality factor to serve as a guideline of what values to expect during power transfer. This way, if any different value is detected by the transmitter then it means there is a foreign object present. This method helps to discriminate between foreign, and friendly objects, and it is only available in Extended Power Profile devices [27].

2.6 Power Over Ethernet

PoE is a charging method, capable of powering electricity, using DC, to devices that are connected to some kind of network, for example, a Local Area Network (LAN), through the means of Ethernet cables [38]. This powering principle has made itself one of the major contributors to the development of the Internet of Things (IoT), which has the goal of allowing information exchange and communications for anything using solely the Internet [38].

When discussing a power connection that relies on a network, some issues should be addressed, such as connection, distribution, charging technologies, and management. These problems are felt due to the complexity, multi-functionality, and wide-scale deployment of existent applications [38].

In order to better understand how this technology works some principles must be discussed such as an on-site data center and the LAN itself. An on-site data center is the center of all the information that travels through the network, which includes every appliance, workstation, and network access point. The LAN is the network itself and serves as the connection line between every single one of these components [38].

Switches are a crucial component of a network. They work as an inverter units in a circuit and are responsible for converting AC to DC power that can be used to charge any connected device [38].

The existing IEEE 802.3bt PoE standard allows for up to 100 W of power at the source power output, which enables the use of PoE charging for an enormous range of devices and applications [39]. An IPT application, such as the one that is to be implemented in this study, could benefit from this type of system, as a complementary or even primary power source.

2.7 Health and Safety Considerations

The implementation of a WPT system can bring many advantages in terms of agility of use and compatibility across powered devices and receivers, but when it comes to this technology, there is a set of considerations that should be addressed namely, health and safety ones. In this section, the goal is to better understand what limits and reservations should be taken into account when developing and using a WPT system, in order to achieve the most optimized working option. EF exposure will be the main focus of this section, mainly on the range between 3 kHz and 300 GHz [40]. Concerns about ferrite magnets exposure will also be addressed.

Although there are still no official guidelines or regulations when it comes to WPT systems, there are two documents that are considered to be reliable when it comes to reference standards of usage [16]. The WHO has claimed that these two documents are "The IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz (IEEE C95.1-2005)", and the document from The International Commission on Non-Ionizing Radiation Protection (ICNIRP), "ICNIRP Guidelines For Limiting Exposure To Time Varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz)" [41].

2.7.1 Safety Factor

The limits of usage and the set of rules to be followed when working with EF are personified by the safety factors, that give the user a safety margin in which to operate electronic appliances. This safety margin presents itself to be conservative, so an exposure that exceeds the margin does not automatically mean that it has reached harmful levels [40].

In terms of Electromagnetic Fields (EF) exposure, the safety factor is, by definition, a multiplier or a divisor used to derive maximum permissible exposure values, which provides for the protection of individuals, uncertainties risen by the threshold effects due to drug treatment or pathological conditions, uncertainties in reaction thresholds, and uncertainties in induction models [40].

When it comes to the attribution of a safety factor to a specific situation, such as RF exposure below 100 kHz, the existence of a hazard threshold is mandatory, which is, by definition, the point above which some parameter related to exposure is associated with the existence of some hazardous effect must be identified. Once a hazardous event occurs and a hazard threshold is defined, accompanied by enough supporting information, a safety factor can be applied in order to derive an exposure limit based on the more accurate scientific research available [40].

The process for selecting a safety factor is mainly an arbitrary process, which is influenced by the amount of knowledge on the situation at cause and is selected with the sole purpose of preventing another hazardous event by working with a sufficiently wide margin. Because of this, the values may have a small range, like when dealing with low frequencies, or a wide range, like when dealing with frequencies above the 100 kHz threshold [40].

2.7.2 Health Concerns

Tissue heating, unhealthy levels of energy absorption through the skin, and temperature rise are some of the most concerning short-term effects that RF can cause on a person. Many studies have tried to find the correlation between exposure and adverse effects on volunteers, but, throughout these experiments, there was no proof of harm found, keeping in mind that imposed safety levels, that all electronic hardware must follow, were not exceeded [41].

In terms of long-term effects, cancer-related illnesses are one of the major targets when trying to pinpoint liabilities in the usage of RF systems. But the nature of cancer itself makes it hard to detect its presence until many years after its appearance, and since electronic appliances only became popular in recent years, it is still very difficult to find significant data that supports that exposure to RF is responsible for this disease [41].

2.7.3 Low and High Frequencies Exposure

For RF exposure below 100 kHz, for a lower tier exposure, the safety factor in terms of currents or fields is between 3 and 10 (10-20 dB), varying due to different situations and people, and for an upper tier, applicable to controlled environments, the safety factor is considerably smaller reaching levels near unity. Above 100 kHz, the exposure takes into account an averaging time, due to a heating effect, that varies with frequency. The frequency of 100 kHz marks a threshold, below which it is found that electrostimulation effects dominate, and thermal effects dominate above that frequency [40]. For frequencies that surpass the 100 kHz threshold, safety factors are equivalent to the specific absorption rate, which is expressed in W/kg, relative to the exposure values. The main concern when it comes to RF exposure is not to surpass the basic restrictions and maximum permissible exposure throughout the use of safety programs, which include RF awareness training, use of protective equipment, and periodic health evaluations of the users.

2.7.4 Ferrite Magnets

Ceramic magnets are made of ferrite, which is a mixture of ceramic materials and iron oxide. These magnets are utilized in many sectors of appliances such as security systems, loudspeakers, and medical instruments. Although they are commonly used, there are still hazardous concerns to be accounted for when handling magnets [42].

Due to their nature and force exerted when coupled, breaking or chipping is a fairly common problem. Magnetically sensitive items such as mechanical watches, heart pacemakers, and credit cards are all susceptible to powerful magnets. There is still no evidence that magnets can cause detrimental effects on people or animals [42].

Some safety measures that can be taken when handling powerful ferrite magnets include the use of safety glasses and gloves, use of separative materials in between magnets to prevent breaking or chipping, and keep a safe distance of at least 20 cm from magnetically sensitive items. These safety measures are dependent of the type and power of the magnets being used [42].

Chapter 3

Equipment: Analysis and Specifications

This chapter is comprised of two different equipment analyses. The first one focus on the power needs and specifications of the main handheld and personal equipment used by the Portuguese Army. The second part of this section aims to describe the functionality, specifications, and working modes of the transmitter and receiver, used in the practical component of this dissertation.

3.1 Target Equipment for Wireless Charging

One of the main parameters that influenced the testing phase of this work is the equipment used. Understanding the power requirements, working mode, and charging environment of the target equipment is fundamental. As it was said in section 1.2, the goal of this dissertation is to measure the efficiency of a wireless charging system and to come up with a viable charging solution for the Soldier Combat Systems program. To achieve this goal, it is mandatory to present the key components that will be charged by this system and its architecture. The equipment listed below is included in the program in question and follows all the equipment regulations and guidelines imposed by NATO [9].

3.1.1 DSI-104 - Data and Power Hub

The DSI-104 is a prototype of a Central Data and Power Hub which is to be implemented in the Soldier's Combat Systems program, and it is, currently, in development by EID - Defense Communication Systems [43]. This hub is the main component of this system since it will allow for data and power to reach and come from the man-portable devices. The specifications of this hub will need to be able to cover the power and data necessities of said equipment, in order for the overall system to work accordingly. Figure 3.1 shows this component.



Figure 3.1: DSI-104 Central Power and Data Hub. Data gathered from [43].

The available interfaces for the DSI-104 are the following:

- 1 Portable Radio;
- 1 Data Hub;
- 1 Personal Radio;
- 3 USB Ports;
- 1 Soldier's External Battery;
- 1 External Battery;
- 1 Data and Audio connection to the vehicle.

3.1.2 Charging Environment Description

This section will be dedicated to a description of the charging environment for the wireless power system. The concept design presented in figures 3.2 and 3.3 has the functionality of charging the hardware attached to the user's torso, like a radio, a tablet, or any man-portable device carried by the soldier, and it is based on the architectural design that is being developed by NATO member states, and the STASS program. This design is directly related to the present work since the wireless charging system will have the function of charging the central power hub, which serves as a bridge connection to the man-portable devices.

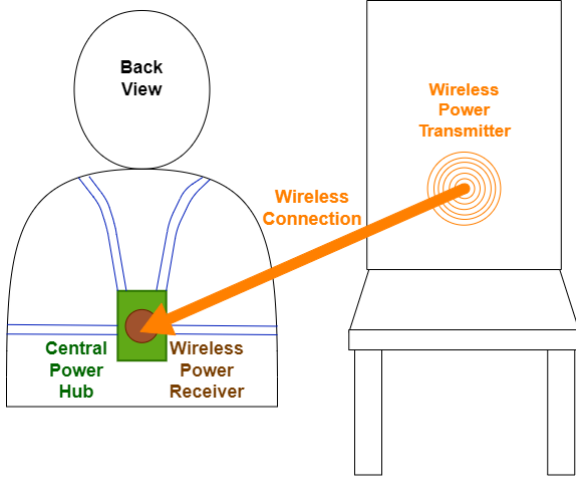


Figure 3.2: Charging System Concept (Back View).

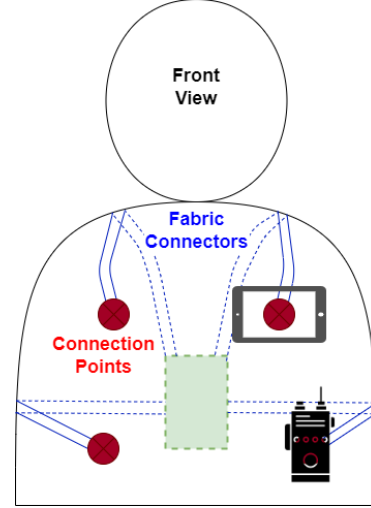


Figure 3.3: Charging System Concept (Front View).

The wireless power receiver and the wireless power transmitter, which can be seen in figure 3.2, are the focus of this study, and their functionality and optimization are the main priority. Both these components are described in sections 3.2.1 and 3.2.2, respectively. The central power hub, also seen in the back view concept, is a power and data integrator that will store the power that is coming from the wireless power receiver, and send it to the devices carried by the user.

Figure 3.3 represents the front view of the concept implementation. The fabric connectors and the connection points are the essential parts in terms of carrying the power to external devices connected to the vest. The fabric connectors can be implemented using the technology of e-textiles, which are woven from conductive yarns in order to create a durable material [15].

The connection points represent the other end of the power hub. They establish a direct connection with electronic devices.

Various concept ideas of this product have been in development by various third-party companies, like BAE Systems' Broadsword® Spine®, in association with armed forces across the world [15].

3.2 Testing Equipment - Hardware and Software

In this section, the main equipment and software used to achieve a functional solution for a wireless transfer system are identified and described. These devices were essential during the theoretical and practical components of this dissertation. The main aspects of the work performed with the hardware and software are presented in section 5.

3.2.1 STEVAL-ISB047V1T Wireless Power Transmitter

The STEVAL-ISB047V1 wireless battery charger TX evaluation kit consists of the STEVAL-ISB047V1T evaluation board and STEVAL-WBCDNGV1 USB-to-UART dongle. The transmitter operates at a fixed frequency of 127.7 kHz, is prepared to operate with any *Qi*-certified receivers that support Qi 1.2.4 ver-

sion, and can resistive and capacitive modulation [34]. The USB-UART dongle serves as an adapter for computer communication purposes. Both this equipment can be seen in figures 3.4 and 3.5.



Figure 3.4: Wireless Power Transmitter. Data gathered from [34].



Figure 3.5: USB-UART dongle. Data gathered from [34].

The board is equipped with a STWBC-MC digital controller, 15 W available power, fixed frequency operation, and MP-A15 3-coil array.

The STWBC-MC, described in section 3.2.8, monitors the transmitter. It supports automatic coil selection based on the best coupling with the receiver. The evaluation kit is capable of charging a variety of appliances where the necessity for high power is a requirement, like smartphones or any *Qi*-compliant devices, up to 15 W [34].

The transmitter has the following interfaces:

- J101 Power supply jack connector (5 to 20 V);
- J800 Power supply USB connector (5 to 20 V);
- J400 UART connector;
- Green LED and Red LED;
- J401 SWIM connector;
- Power Coil connections;
- Test points;
- Jumper for supply selection.

During the testing and assessment phase of this work, the interfaces used were the J101 Power supply jack connector, connecting the module to power, and the J400 UART connector, for accessing the GUI of the transmitter.

3.2.2 STEVAL-ISB68WA Wireless Power Receiver

The STEVAL-ISB68WA wireless power RX evaluation kit contains the wireless power receiver, STWLC68JRH, and a USB-to-I2C bridging dongle. Both devices can be seen in figures 3.6 and 3.7. The USB to I2C

bridging dongle allows to establish a connection between the receiver and GUI, referenced in section 3.2.8, running on a computer [44]. The receiver is composed of 3 essential elements:

- Printed circuit board, which houses the STWLC68JRH wireless power receiver and all the other components;
- Plastic spacer;
- Diameter receiving coil.

STWLC68JRH is made to allow the charging of the batteries for wearable applications, and it is configured to provide 5 V output voltage with a maximum power of 2.5 W. It works when used on a suitable wireless power transmitter since the only power input for the system is the coil [44].



Figure 3.6: Wireless Power Receiver. Data gathered from [44].

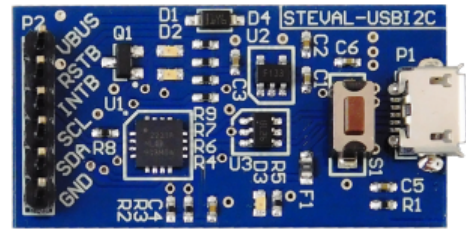


Figure 3.7: USB-I2C dongle. Data gathered from [44].

The Receiver has the following interfaces:

- Two AC input (RX coil);
- VRECT (rectifier output);
- Power return (ground);
- VOUT power output (5 V output voltage with a maximum power of 2.5 W);
- INT (digital output);
- SCL (digital input);
- SDA (digital I/O);
- Signal ground.

During the testing and assessment phase of this work, the interfaces used were the INT, SCL, SDA, signal ground, and VOUT power output to access the GUI of the transmitter.

3.2.3 ASHATA Transmitter Module for Wireless Charging

This 3 coils transmitter module, shown in figure 3.8, is widely compatible with *Qi* standard equipment. It has multi-level protection that counts with built-in short-circuit protection, and over-voltage protection

to ensure safe charging. It has a universal micro USB interface and a high-quality circuit board with CE/FCC/ROSH certification [45].

The transmitter has the following specifications:

- Input power: 5 V 2 A;
- Output: 1 A;
- Charging power: 5 W;
- Transmission distance: 2-8 mm.

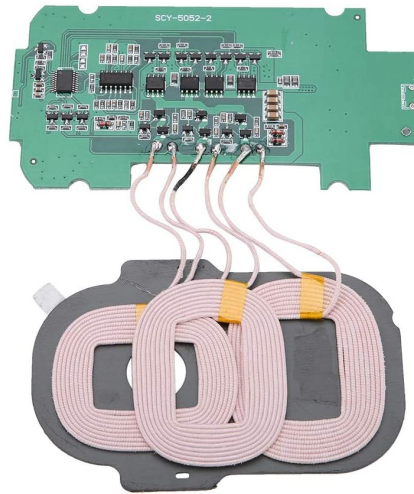


Figure 3.8: ASHATA *Qi* Wireless transmitter module. Data gathered from [45].

3.2.4 Zerone Wireless Power Receiver

This wireless power receiver, shown in figure 3.9, is widely compatible with *Qi* standard transmitters. It has multi-level protection that counts with built-in short-circuit protection, and over-voltage protection to ensure safe charging. It has a power of 5 W and CE/FCC/ROSH certification [46].

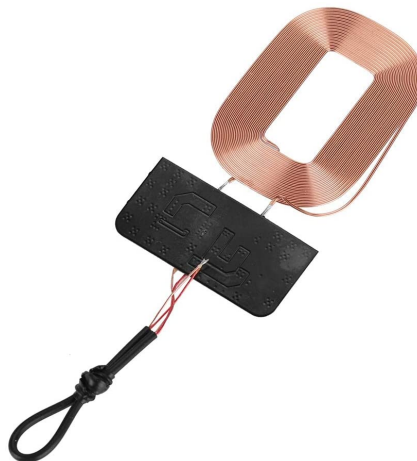


Figure 3.9: Wireless Power Receiver. Data gathered from [46].

3.2.5 Flat Oval Coils

The flat oval coils, seen in figures 3.10 and 3.11, are the original coils from the ASHATA Transmitter Module for Wireless Charging and the Zerone Wireless Power Receiver, referenced in sections 3.2.3 and 3.2.4, respectively. Also, the transmitter coil is used by the STEVAL-ISB047V1 Wireless Power Transmitter, referenced in section 3.2.1. The specifications can be seen in table 3.1.

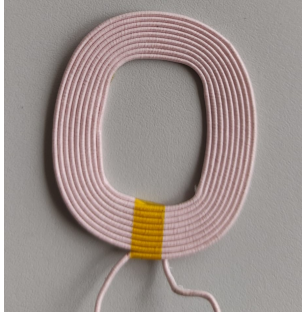


Figure 3.10: Transmitter flat oval coil.



Figure 3.11: Receiver flat oval coil.

The transmitter coil has 9 turns, an internal diameter of 21 mm for the minor axis and 28 mm for the major axis and an external diameter of 41mm for the minor axis and 49 mm for the major axis. On the same note, the Receiver coil has an internal diameter of 10 mm for the minor axis and 28 mm for the major axis and an external diameter of 41 mm for the minor axis and 49 mm for the major axis.

	L (μ H)	Q	Turns	Internal Diameter (mm)	External Diameter (mm)
Flat Oval Coil (TX)	4.04	55.89	9	21x28	41x49
Flat Oval Coil (RX)	7.85	17.73	-	10x22.5	29.5x41

Table 3.1: Flat oval coils specifications.

3.2.6 Conical Coils

The conical coils, seen in figures 3.12 and 3.13, were welded on the ASHATA Transmitter Module for Wireless Charging and the Zerone Wireless Power Receiver, referenced in 3.2.3 and 3.2.4, respectively, replacing their original coils. In order to use these coils with the wireless modules, the inductance values had to be similar to those of the original coils. The specifications can be seen in table 3.2.

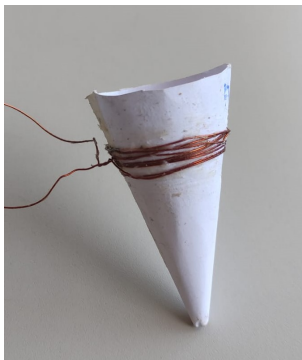


Figure 3.12: Transmitter Conical Coil.

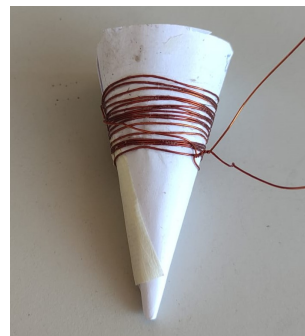


Figure 3.13: Receiver Conical Coil.

The transmitter coil has 8 turns and diameters of 28 mm and 41 mm, respectively, for the smaller and bigger portion of the cone. On the same note, the receiver coil has 16 turns and diameters of 20 mm and 31 mm.

	L (μ H)	Q	Turns	Internal Diameter (mm)	External Diameter (mm)
Conical Coil (TX)	4.36	14.59	8	28	41
Conical Coil (RX)	6.92	17.98	-	20	31

Table 3.2: Conical Coils specifications.

3.2.7 Rectangular Coils with Circular Corners

Both support structures were developed using a 3D printer. The smaller structure, seen in figure 3.14, was made in order to replicate the dimensions of the DSI-104 - Data and Power Hub, referenced in 3.1.1, and it fits inside the bigger structure, seen in figure 3.15.

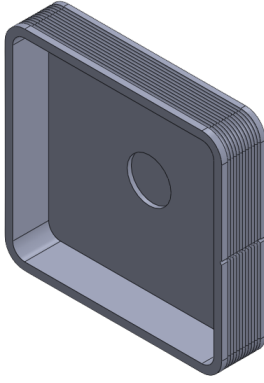


Figure 3.14: Receiver rectangular Coil.

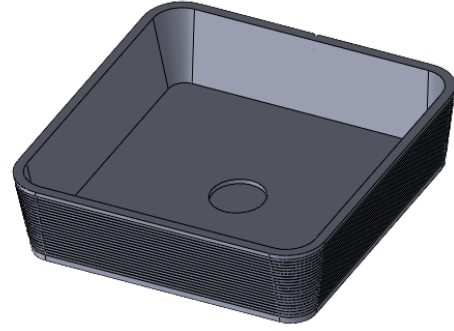


Figure 3.15: Transmitter rectangular Coil.

The bigger structure, visible in figures 3.15 and 3.16, has a slight upwards curvature of 10° , making it of a trapezoidal nature, and it involves the smaller structure that fits inside it when the wireless power setup is mounted, as seen in figure 3.16. The coil is made to fit the outside bumps of both models.

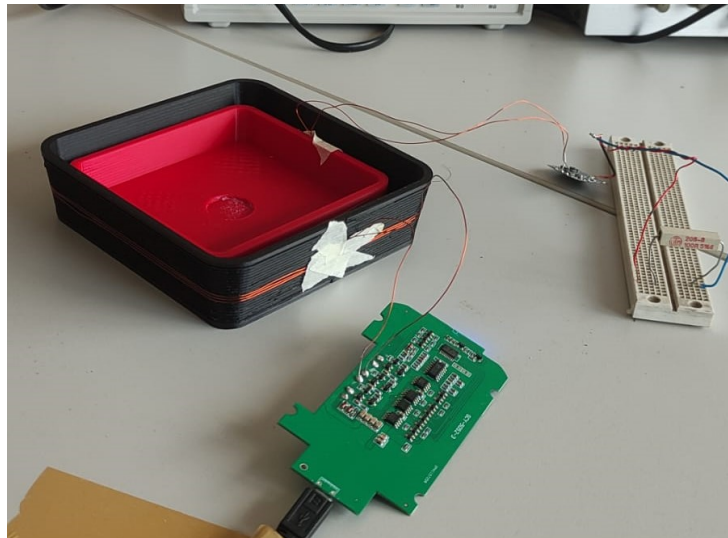


Figure 3.16: Wireless power setup mounted with both 3D structures.

Similar to the other coils, these were welded on the ASHATA Transmitter Module for Wireless Charging and the Zerone Wireless Power Receiver, referenced in 3.2.3 and 3.2.4, respectively, replacing their original coils for the purpose of experimental work. In order to use these coils with the wireless modules, the inductance values had to be similar to the ones of the original coils. The specifications can be seen in table 3.3.

	L (μ H)	Q	Turns	Dimensions (mm)
Rectangular Coil (TX)	4.24	10.34	3	134x130x35
Rectangular Coil (RX)	7.67	13.21	5	109x105x22

Table 3.3: Rectangular Coils specifications.

3.2.8 Graphical User Interface (GUI)

In order to monitor the TX board parameters, the STSW-STWBCGUI graphical interface is used. It allows the user to access runtime information such as regulation errors, protocol status and power delivered. Parameters can also be adjusted with these tool [34]s. The main window of the GUI indicates the transmitter state, which comprises the receiver and *Qi* detection status, as well as power information. In order to test if the transmitter could detect the receiver, readings were taken with and without the presence of the receiver. It is shown, in figures 3.17 and 3.18, the main window of the GUI when the receiver is not detected and when it is, respectively.



Figure 3.17: Main window without RX presence detected.

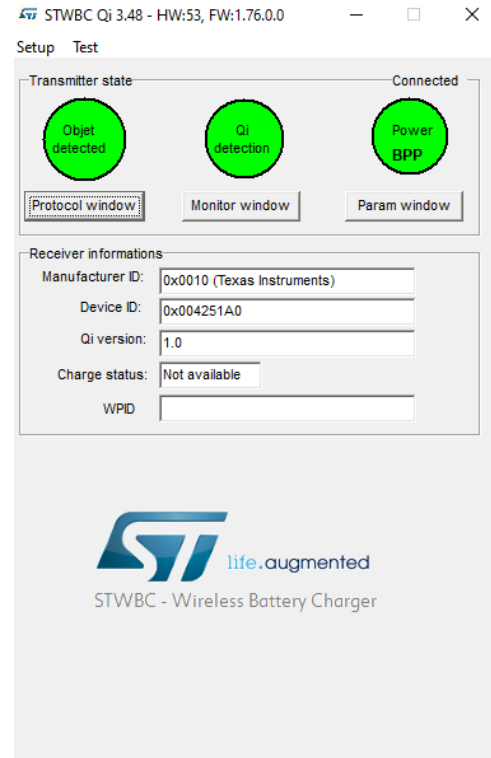


Figure 3.18: Main window with RX presence detected.

It is also possible to register the intensity of the coupling between the transmitter and the receiver using the monitor window. When the receiver is not coupled, the RX presence parameter has values close

to 0, as seen in figure 3.19. On the other hand, when it is coupled, the value of this parameter goes up, as seen in figure 3.20.

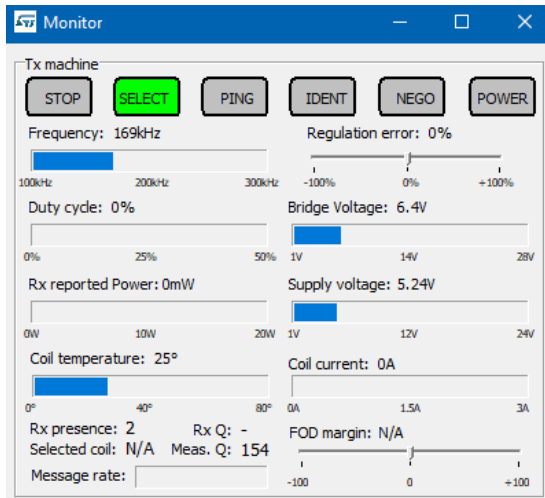


Figure 3.19: Monitor window readings without RX presence.

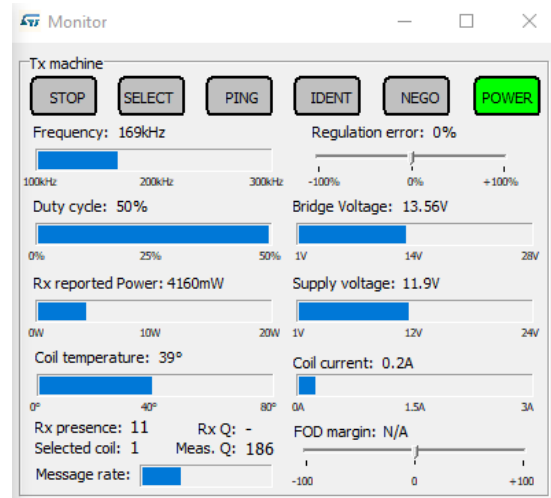


Figure 3.20: Monitor window readings with RX presence.

The STSW-ISB68GUI enables the evaluation, control, and modification of the STEVAL-ISB68WA Wireless Power Receiver. The GUI enables real-time monitoring of internal specifications that are streamed over a USB-to-I2C connection. After establishing a successful connection, the GUI allows the user to alter various parameters concerning the registers as shown in figure 3.21.

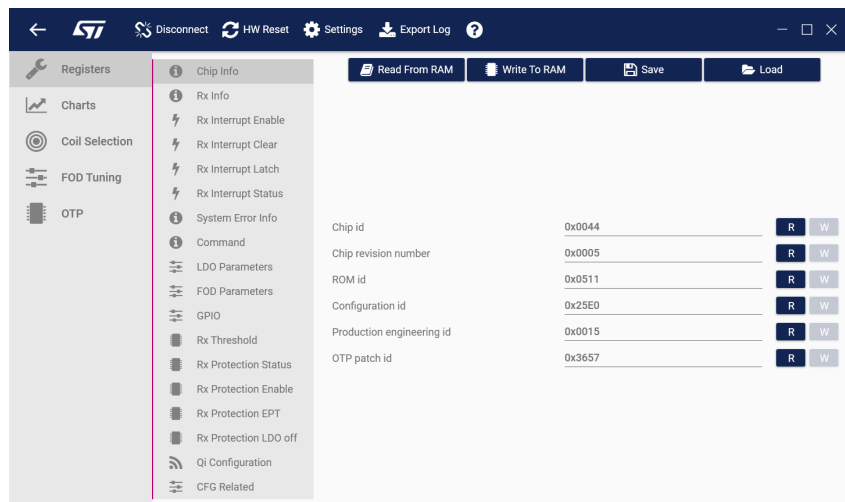


Figure 3.21: Register section of the STSW-ISB68GUI.

In figure 3.22 it is possible to see the voltage readings taken while testing the receiver in self-powering mode.

Besides controlling the behavior of different aspects such as voltage, current, and temperature, the STSW-ISB68GUI has other functionalities such as register tuning, coil selection, FOD Tuning, and Open Telecom Platform (OTP) programming.

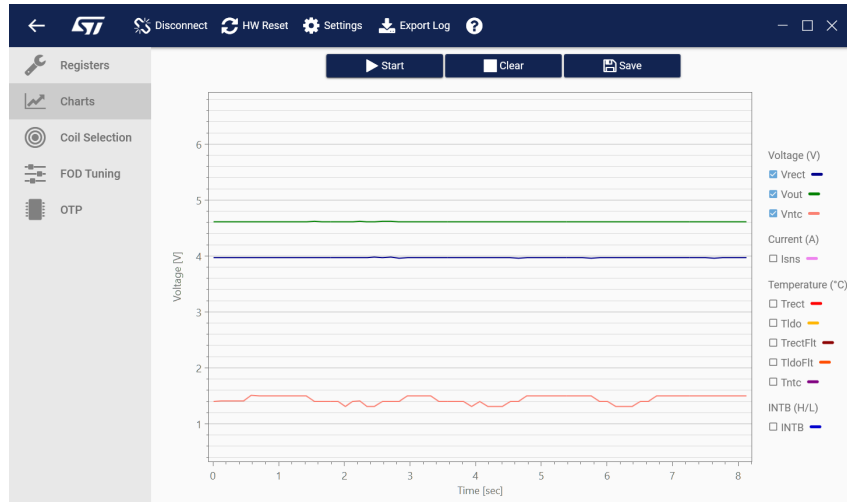


Figure 3.22: Chart section of the STSW-ISB68GUI.

The representation of the architecture of both the TX and RX is shown in figure 3.23 and it comprises the following:

- The connection between the transmitter and the receiver, via IPT;
- The communication with the computer in order to access the GUI, via the USB-UART dongle for the transmitter, and via the USB-to-I2C bridging dongle for the receiver;
- The setup and monitoring unit that is represented by a computer where all the necessary system configurations will take place, using the system's dedicated software;
- The charging system used for the transmitter, which can be done through the J101 Power supply jack connector or the J800 Power supply USB connector;
- The electronic appliances battery being charged by means of the receiver.

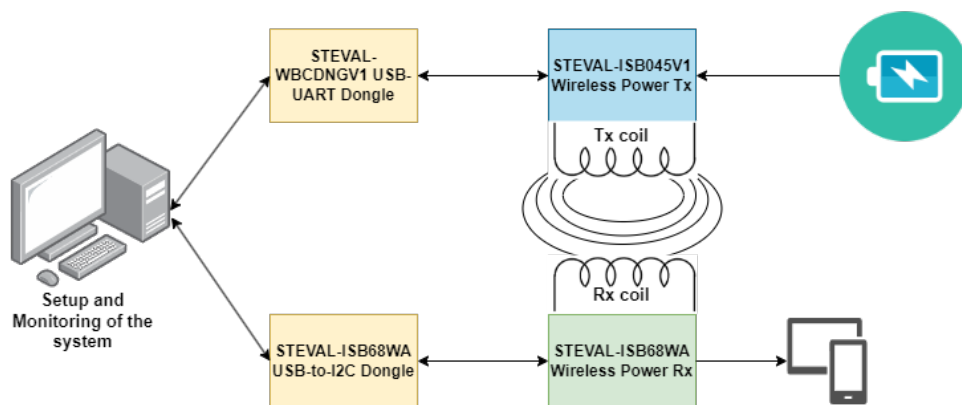


Figure 3.23: Overall WPT System's Architecture.

Chapter 4

Theoretical Foundation

The theoretical works, presented in this chapter, have the objective of supporting both the case study of this dissertation, and the practical works, presented in chapter 5. This chapter comprises two major parts: (i) related works and (ii) theoretical deductions.

The related works, present compelling studies on the alteration of the geometry of the coils. These changes produce different magnetic field distributions, as well as variations in crucial parameters of the power transfer. The geometry approaches of this dissertation are based on these studies. The theoretical deductions had the prime objective of studying the influence, on a power transfer, of a certain set of parameters, in order to find the best results. Also, it confirmed and strengthened the results achieved in the practical works.

4.1 Related Work

This section includes studies that have useful information on how to better understand the details and behavior of existing approaches to WPT systems. With these results, it was possible to form a comparative tool that was helpful in terms of finding the best course of action for the present dissertation.

Many studies have tried to appropriate the shape and dimensions of the coils used in WPT systems to accommodate the needs of the equipment being charged, facilitate the power transfer in terms of user experience and reduce loss of energy [6]. Aspects such as inductance, coupling coefficient, quality factor, and parasitic resistance between transmitter and receiver are important parameters to consider when working with wireless power transmission, in order to guarantee a high-performing system. These variables can significantly impact the power transfer efficiency by simply changing the size or the geometry of the coils [7]. In this section, the variances in shape and size of a coil, and their influence on the overall performance of a wireless power system will be approached in order to better understand the dynamics behind them.

4.1.1 Influence on the Radiation Pattern of the Magnetic Field

Mohamed *et al.* [7] show that, by comparing cylindrical and conical coils, the change in geometry of the coils has a great effect on the radiation pattern of the magnetic field produced by the power transfer. The idea behind the design of the conical coil was based on wave reflection.

In order to calculate the inductance of the horn shaped coil, the authors divided it into several parts that were dependent on the number of turns and, for each part, calculated the inductance using the following equation:

$$L = N^2 4\pi \times 10^{-7} r \ln\left(\frac{2r}{d}\right) \quad (4.1.1)$$

where d and r are the diameter and radius of a conical coil, respectively, and N is the number of turns. The total inductance of the coil is the sum of each part's inductance.

In this experiment, various coils were tested with regard to the radius, the number of turns, and the angle. The chosen approach for the testing coil was the one with an angle of 40° , 60 turns, and a radius of 2.7 cm and 6 cm with the larger portion facing the receiver.

The magnetic flux pattern of a cylindrical coil presents itself to be symmetric and with no more than a range of about 30° , for the reach of the electromagnetic field, as seen in figure 4.1. This type of coil can be used in applications that need power transferred in two directions.

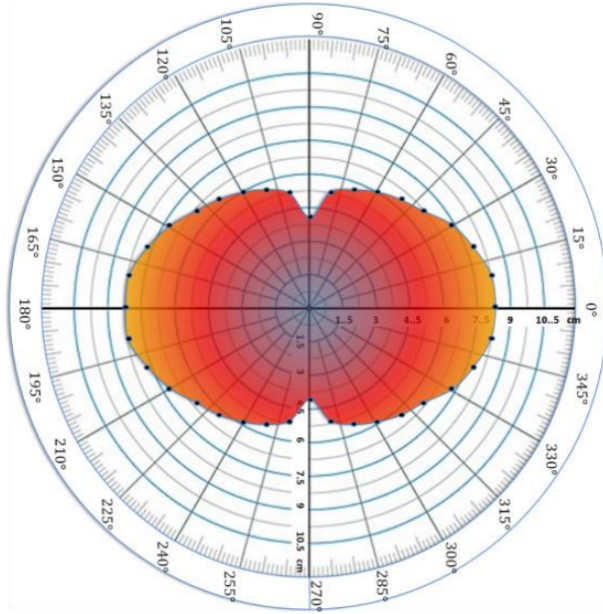


Figure 4.1: Magnetic field of a cylindrical coil. Data gathered from [7].

When looking at the results from the conical coil, seen in figure 4.2, the pattern of the magnetic field is considerably larger from the top radius, which suggests that the density and shape of the magnetic field are stronger and bigger on this portion of a conical coil. The electromagnetic field pattern is bounded to a range of 120° , which is much larger than the one seen in the cylindrical coil [7].

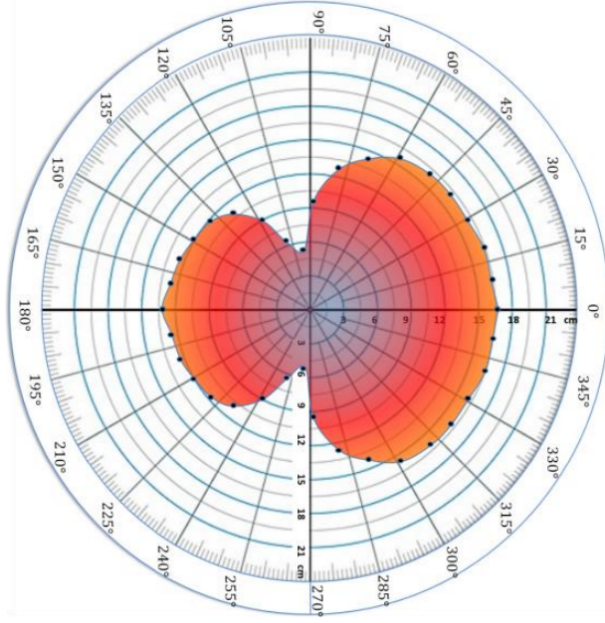


Figure 4.2: Magnetic field of a conical coil with an angle of 40° . Data gathered from [7].

When testing with a coil with an angle of 20° , the system performance was considerably altered. The electromagnetic field's range increased to a maximum of 140° , as seen in figure 4.3, which is wider and more directive.

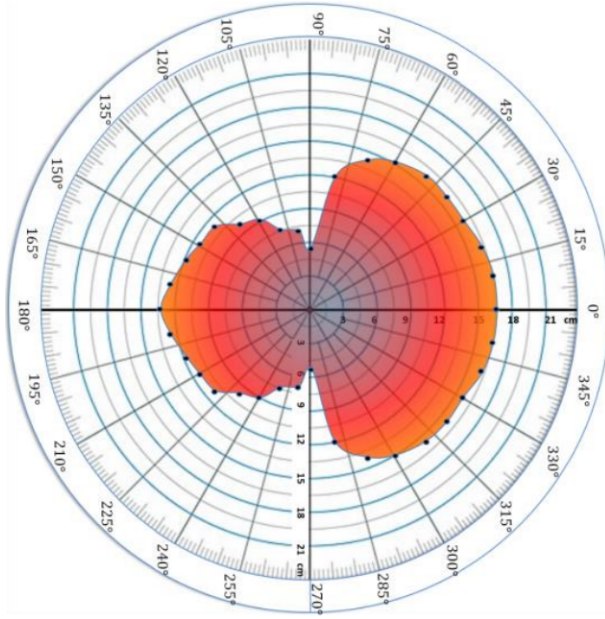


Figure 4.3: Magnetic field of a conical coil with an angle of 20° . Data gathered from [7].

Mohamed *et al.* [7] also denote, by testing the voltage received by a cylindrical and a conical coil, that in the cylindrical coil the maximum voltage is received at a distance of 5 cm, with a 50 % efficiency, and the maximum distance at which the coil can receive voltage is of 30 cm with an efficiency of around 3 %. On the other hand, the values from the voltage efficiency of the conical coil case at the same distance of 5 cm and 30 cm are 75 % and 5 %, respectively.

With this, it is not only possible to conclude that the conical coil design allows for an improved electromagnetic field range and width, but also a better overall efficiency of the system, making it ideal for applications that need a wider and more directive path for the magnetic field and that require focused power in one direction [7].

4.1.2 Improvement of The Magnetic Field Distribution

Liyuan *et al.* [47] propose a planar spiral square coil approach in order to achieve uniform distribution of the magnetic field. In this work, it was calculated the strength of the transmitting coil's magnetic field on both the coil axis and above its surface, and the density of the current was analyzed. This process was done in order to reach an optimized model of the square coil.

The reach of the magnetic flux on a circular coil is low, which demands that the position of the primary and secondary coil be crucial to maintain a connection, making a small variation in distance between coils highly penalizing in terms of efficiency. On the other hand, circular shaped coils produce a stronger magnetic field in comparison with square coils [48].

The general expression for the magnetic induction produced by a square coil at a point above the central axis, seen in equation 4.1.3, can be described by the vector superposition of the magnetic fields generated by the current of each straight line, seen in equation 4.1.2, that make the sides of the square.

$$B = \frac{\mu_0 I}{4\pi d} (\cos \theta_1 - \cos \theta_2) \quad (4.1.2)$$

where d represents the distance from the point to the wire and θ_1 and θ_2 represents the angle between the ends of the wire and the point. Equation 4.1.3 solves the magnetic field distribution of the square coil.

$$B_1 = \frac{2\mu_0 I l^2}{\pi [l^2 + (a + z)^2] \sqrt{2l^2 + (a + z)^2}} \quad (4.1.3)$$

Liyuan *et al.* [47] present a series of results using a square spiral coil with dimensions of 20cm x 20cm and 11 turns, with an excitation voltage of 100V and a frequency of 2MHz as shown in figure 4.4. The uniformity of the magnetic field proves to be stable with just a small depression at the center of the coil. Figure 4.5 shows the density of the magnetic flux, which is fairly uniform. In the lower right corner, the excitation point produces a peak and the superposition effect of the field on each corner also is responsible for a slight increase in flux density.

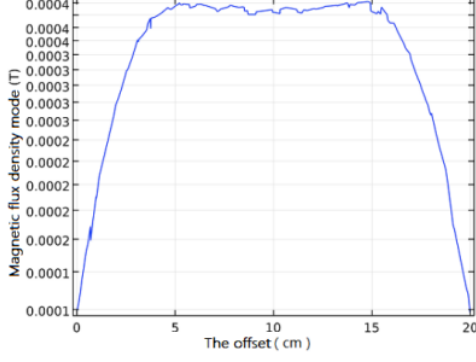


Figure 4.4: Uniformity of the magnetic field distribution on a square coil. Data gathered from [47].

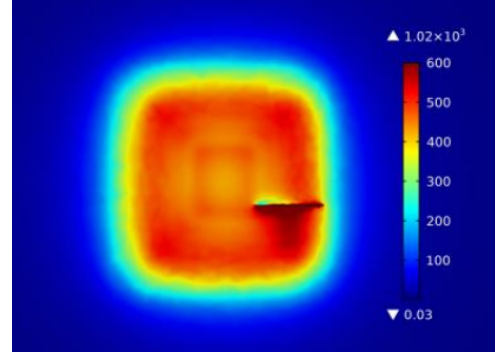


Figure 4.5: Density of the magnetic field distribution on a square coil. Data gathered from [47].

This study proves that the surface of the flat square spiral coil has uniform axial magnetic field distribution, which makes it possible to increase the area of magnetic field reach.

4.1.3 Effect of Rounded Corners on the Behavior of the Magnetic Field

Erman *et al.* [49] state that, there are difficulties in the production of sharp corners coils when making a square coil. This translates in a square-like shaped coil with rounded corners called a *squircle*. This study explored this particular shape in order to better understand the influence of rounded corners on the magnetic field intensity and density. *squircle* geometry gets closer to either circular geometry or square geometry depending on the angle and points where the rounding starts and ends.

The analysis of a *squircle* shaped coil is done by calculating the magnetic flux density on the arc at the corner of the coil. The geometrical parameters are shown in figure 4.6 and 4.7. In these calculations, the length and dimensions of the wire, the sides, and the arc are known, as well as the points at which the arc begins [49].

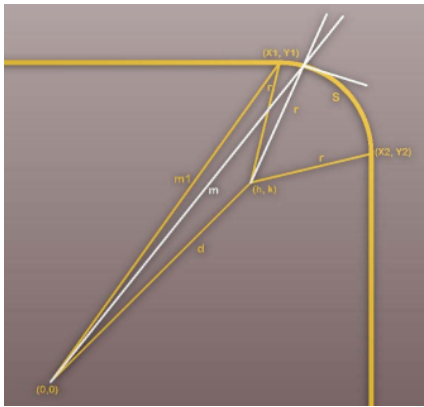


Figure 4.6: Geometrical parameters of the *squircle* shape. Data gathered from [49].

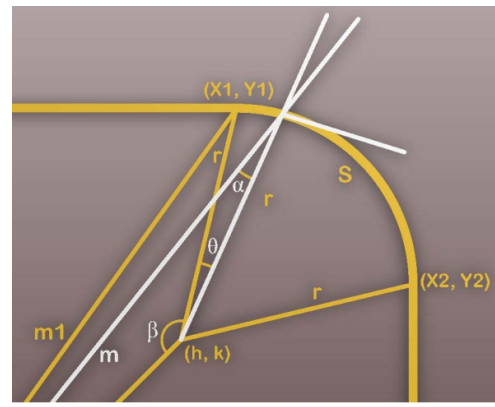


Figure 4.7: Closer look to the Geometrical parameters of the *squircle*. Data gathered from [49].

Erman *et al.* [49] present calculations, where m_1 is the distance between the center of the coil and the start point of the arc (X_1, Y_1) , shown in equation 4.1.4.

$$m_1 = \sqrt{x_1^2 + y_1^2} \quad (4.1.4)$$

It is possible to define m_1 as a function of the radius (r) of the arc, d as the distance between the center of the *squirle* geometry, and the angle between d and the line that passes on points (h, k) , the center of the arc, and (X, Y) , the start and end points of the arc. This relation can be found in equation 4.1.5, and the relation between parameters β and θ in equation 4.1.6

$$\cos(\beta) = \frac{r^2 + d^2 - m_1^2}{2rd} \quad (4.1.5)$$

$$\cos(\beta + \theta) = \frac{r^2 + d^2 - m^2}{2rd} \quad (4.1.6)$$

The cosine term can be expanded as sine and cosine functions of angles β and θ , seen in equations 4.1.7, 4.1.8, and 4.1.9.

$$\sin(\beta) = \sqrt{1 - \cos^2(\beta)} \quad (4.1.7)$$

$$\sin(\beta) = \sqrt{1 - \left[\frac{r^2 + d^2 - m_1^2}{2rd} \right]^2} \quad (4.1.8)$$

$$\cos(\beta + \theta) = \cos(\beta) \cos(\theta) - \sin(\beta) \sin(\theta) \quad (4.1.9)$$

It is now possible to derive 4.1.10 by placing 4.1.6, 4.1.5 and 4.1.8 into 4.1.9.

$$\frac{r^2 + d^2 - m^2}{2rd} = \frac{r^2 + d^2 - m_1^2}{2rd} \cos(\theta) - \sqrt{1 - \left[\frac{r^2 + d^2 - m_1^2}{2rd} \right]^2} \sin(\theta) \quad (4.1.10)$$

By isolating m , it is possible to get 4.1.11.

$$m = \sqrt{-(r^2 + d^2 - m_1^2) \cos(f) + 2rd \sqrt{1 - \left[\frac{r^2 + d^2 - m_1^2}{2rd} \right]^2} \sin(f) + r^2 + d^2} \quad (4.1.11)$$

The cosine of angle α is seen in equation 4.1.12.

$$\cos(\alpha) = \frac{m^2 + r^2 - d^2}{2mr} \quad (4.1.12)$$

By applying the central angle of the arc, θ_1 , on the Biot-Savart equation, seen in equation 2.3.1, it is possible to get equation 4.1.13

$$B = \frac{\mu_0 I}{8\pi} \int_0^{\theta_1} \frac{m^2 + r^2 - d^2}{m^3} d\theta \quad (4.1.13)$$

The calculations of magnetic flux density were calculated using Simpson's rule on equation 4.1.13. Then, calculations for the side lengths of 7.5 cm, 16 cm, and 28 cm were performed. The arc start and end points were varied in order to evaluate different rounding effects on the flux density, for each *squirle* coil. For each different arc, the error rate was calculated between the derived formula and magnetic field densities calculated with known formulas of straight lines and a circular coil [49].

Erman *et al.* [49] achieved a maximum error of 4.6 % between the calculations, which proves the validity of the formula. When the error rate was checked for each case, it was noted that the closest the

shape was to a square or a circle, the smaller it was. Also, the best flux density results were achieved when the coil presented a bigger arc, or, in other words, a more rounded shape.

4.2 Influence of the Coupling Coefficient on the Power Transfer

In order to have a realistic set of values of the coupling coefficient (k) of an IC wireless power transfer, measures of the inductance and quality factor across a set of coils were taken [32]. In the following theoretical calculations, it was used five sets of coils, which are the following:

- STEVAL-ISB047V1T Wireless Power Transmitter and the the Zerone Wireless Power Receiver flat oval coils, TX_{flat} and RX_{flat} (referenced in 3.2.5);
- Two conical coils with similar values of inductance of the flat coils mentioned above, TX_{con} and RX_{con} (referenced in section 3.2.6);
- Two conical coils that had the best theoretical efficiency results, the $TX_{con_{opt}}$, with 27 turns and diameters of 28 mm and 45 mm, and $RX_{con_{opt}}$, with 28 turns and diameters of 20 mm and 40 mm;
- Two rectangular coils with similar values of inductance of the flat coils, TX_{rect} and RX_{rect} (referenced in section 3.2.7);
- Two rectangular coils that had the best theoretical efficiency results, the $TX_{rect_{opt}}$, with 16 turns and $RX_{rect_{opt}}$, with 11 turns, having equal dimensions to TX_{rect} and RX_{rect} (referenced in section 3.2.7).

The optimal conical, and rectangular coils with the best results were only used for theoretical calculations. Their inductance values did not match the ones of the flat oval coils, which meant that, although they were the most optimized coils for the geometry in question, they were not properly adapted to function with the power modules used in the practical work. As a result, when trying to establish a power transfer between TX and RX, with these coils welded to the power modules, no connection was made. The measured values of the inductance of each coil (L_i), inductance measured across TX coil with RX coil shorted (L_s), quality factor (Q), and coil dimensions are presented in table A.1.

Using equation 2.3.7, it was possible to get the coupling coefficient (k) of this system.

By using equations 2.3.15, 2.3.16, 2.3.6, 2.3.17 and 2.3.18, it was also possible to get the parasitic resistances of both coils, mutual inductance, optimal load resistance, reflected impedance, and efficiency of the power transfer, which are detailed, for the three sets of coils, on table A.2, where R_{p1} and R_{p2} are the parasitic resistances of TX and RX coils, respectively.

By looking at table A.2, the highest efficiency is achieved when using a conical coil, in spite of not being possible to obtain the optimal results with the conical coils used for the practical experiments.

By looking at the flat oval coils calculations, it is possible to achieve the highest system efficiency with a load resistance of 9.253Ω for the TX_{flat} and RX_{flat} pair of coils. This theoretical value proves the accuracy of the practical test, where the values of the system efficiency were tested for the TX and

RX in question. The optimal value of $9,253 \Omega$ for the load resistance is inside the interval of values that were considered to be optimal on the practical test (between 6.42Ω and 10.61Ω), done in section 5.1.1.

The value for the theoretical optimal load resistance for the conical coils pair, TX_{con} and RX_{con} , and the rectangular coils pair, TX_{rect} and RX_{rect} , also proves the concurrence between the theoretical and the practical results presented in sections 5.1.2 and 5.1.3, respectively. Both theoretical values for the $R_{L_{opt}}(\Omega)$, 3.758Ω and 3.522Ω , respectively, for the conical and rectangular coils resistance variation test, fit inside the intervals of the practical test, which, once again, brings to the conclusion that both the theoretical and practical results are viable.

The efficiency values achieved in this section are derived from the theoretical calculations using the parameters from equation 2.3.18, thus having different results than those from section 5.1, that uses equation 5.1.1 for the efficiency calculations, which only had the power of the receiver and transmitter to account for.

4.3 Influence of the Distance Variation on the Coupling Coefficient of Resonant Coils

Although inductive coils are capable of maintaining the power transfer when slightly separated from each other, distance is not used as a variable when calculating their coupling coefficient. Resonator coils are capable of working at distances of around one meter, as depicted in section 2.4, thus the coupling coefficient of resonator coils uses distance as a variable.

This section follows a modeled expression that focuses on the behavior of the coupling coefficient on resonant coils (k_r), seen in equation 2.4.3, with a distance between TX and RX coils as the variable parameter for a MRC power transfer system. This modeled expression allows for a theoretical study that leads to a better understanding of how the distance between distinct coupled coils affects the overall performance of the power transfer.

On the following calculations, the efficiency of the five sets of coils used and referenced in section, 4.2, will be tested using distance variation as the main variable parameter.

Using equation 2.4.3, and the values taken from tables A.1, and A.2, it was possible to get the efficiency results for each distance. The maximum tested distance was 6 cm in order to follow the same variation done on the practical calculation presented in section 5. Since the distance between resonator coils does not overly surpass the radius of the tested coils, it was used expression 2.4.3 for parameter k_r calculations.

Table A.3, shows the results for the flat oval coils, TX_{flat} and RX_{flat} , described in section 3.2.5.

As expected, the overall output of the system decreases in function with distance, as well as the coupling coefficient. The maximum efficiency achieved, at 0 cm, is 93.8 %. The behavior of the efficiency curve, in figure 4.8, does not resemble the one obtained in the practical distance variation experiment, in section 5.2.1. This is due to the fact that in this experiment it was used MRC coils, instead of IC ones. As it was described in section 2.4, power transfer efficiency on resonant coils is much less susceptible to distance variation in comparison with inductive coils, which explains the less abrupt behavior of the efficiency curve in figure 4.8.

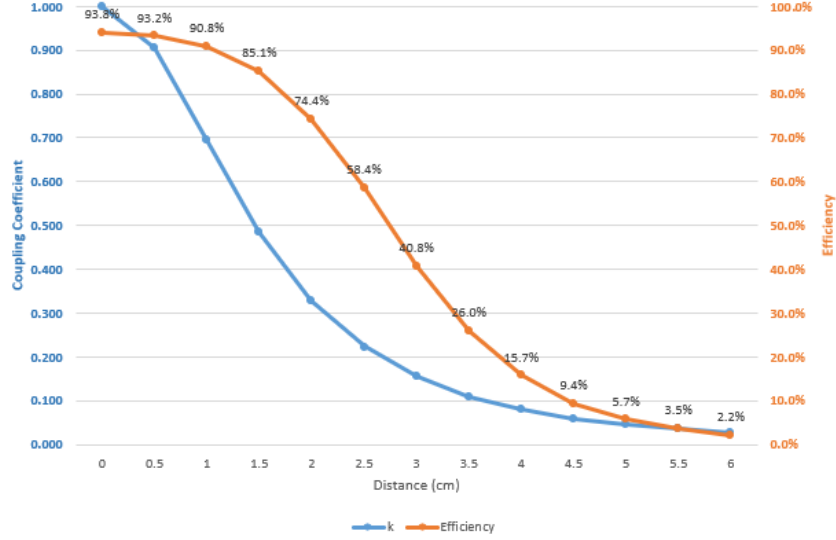


Figure 4.8: Behavior of Efficiency and k_r with Flat Oval Coils, referenced in section 3.2.5.

The results for the conical coils that were used in the course of the practical experiments in section 5, TX_{con} and RX_{con} , are presented in table A.4.

The results for the optimal conical coils, TX_{con_opt} and RX_{con_opt} , are presented on table A.5.

There is a clear difference between the results of the conical coils that were used on the practical tests, TX_{con} and RX_{con} , and the theoretically optimal conical coils, TX_{con_opt} and RX_{con_opt} . The latter presents a better maximum signal amplitude and a slower decrease in efficiency with distance, as is also visible in figures 4.9 and 4.10.

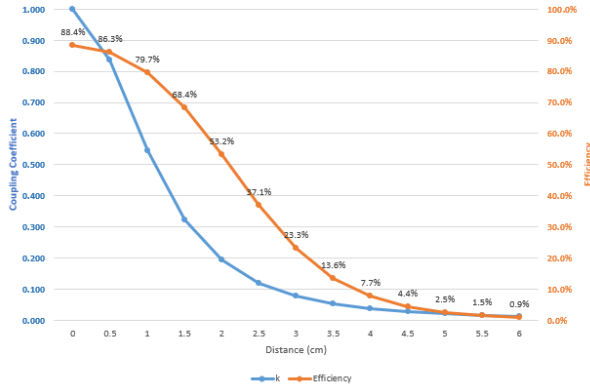


Figure 4.9: Behavior of Efficiency and k_r with Conical Coils, referenced in section 3.2.6.

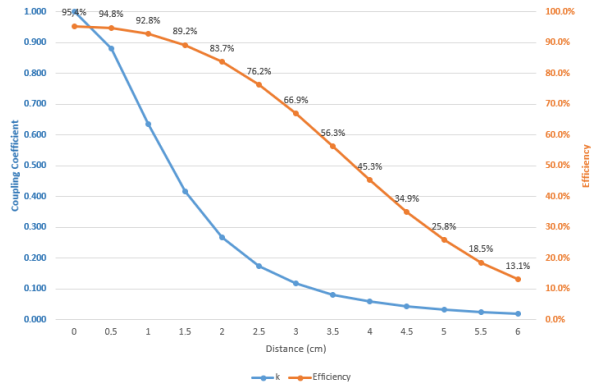


Figure 4.10: Behavior of Efficiency and k_r with Optimal Conical Coils.

The optimal conical coils present a slower decrease in efficiency, as seen in figure 4.10, when compared to the experimental coils, presented in figure 4.9.

The bigger discrepancy in terms of maximum system efficiency is found when looking at the results from both sets of rectangular coils. The ones used on the practical tests, TX_{rect} and RX_{rect} , have the lowest maximum efficiency, at 77.9 %, while the theoretically optimal rectangular coils, TX_{rect_opt} and RX_{rect_opt} , achieve a maximum of 92.3 %, as seen of tables A.6 and A.7.

The decrease in efficiency with distance variation follows the same behavior in both results, with both

sets of rectangular coils presenting slower decreases than all prior tests.

The unique behavior of the efficiency curve of the rectangular coils experiment is seen in figures 4.11 and 4.12. Both results derive greatly from the previous ones and have a much lower decrease in efficiency. TX_{rect_opt} and RX_{rect_opt} maintain an almost linear curve up to 2 cm, making this set of coils the most stable with distance variation.

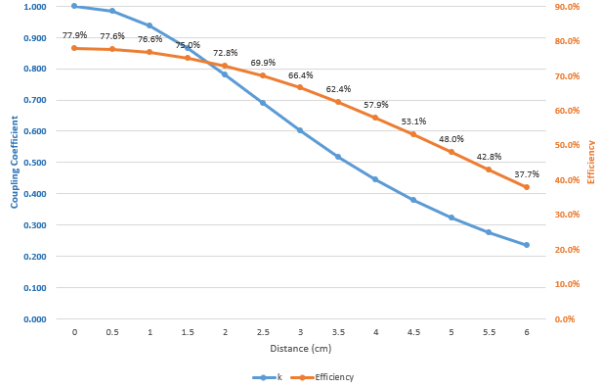


Figure 4.11: Behavior of Efficiency and k_r with rectangular Coils, referenced in section 3.2.7.

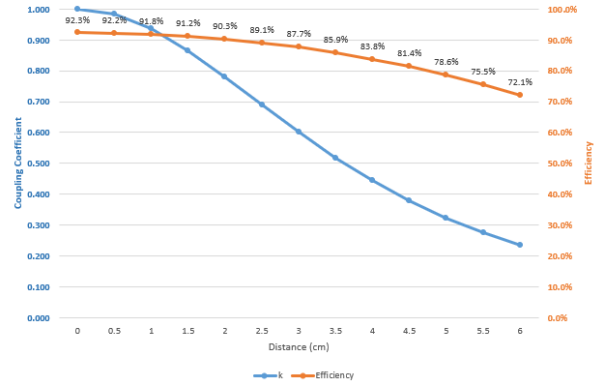


Figure 4.12: Behavior of Efficiency and k_r with Optimal rectangular Coils.

In figure 4.13, all efficiency curves are depicted together, in order to better understand the differences between each and every set of coils. The difference between the sets of rectangular coils and the other sets is clearly visible and proves that TX_{rect_opt} and RX_{rect_opt} have the better results of all five sets.

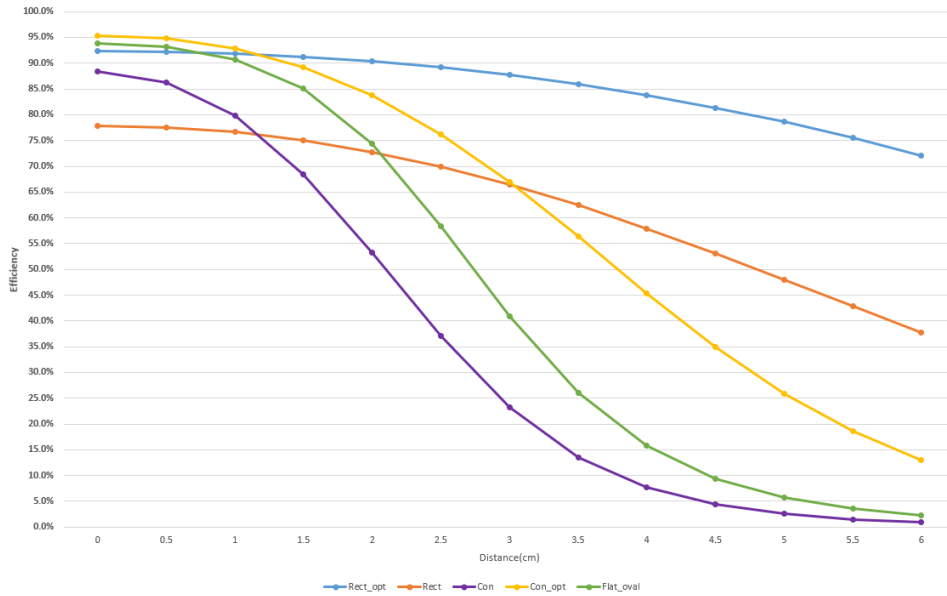


Figure 4.13: Efficiency Comparison between all coils.

The set of optimal conical coils, TX_{con_opt} and RX_{con_opt} , presents the highest maximum achievable efficiency, with 95.4 %, and it maintains the highest percentage, up until 1 cm of distance variation. Due to its slow slope curve, the set of optimal rectangular coils, TX_{rect_opt} and RX_{rect_opt} , have the highest efficiency when compared with the other sets for all distances above 1.5 cm.

Using these calculations, it was possible to test all coil dimensions and geometries with the same

testing conditions. This comes as an important milestone in gathering not only the best but also the more accurate results for the case study at hand.

4.4 Theoretical Results

One of the major outcomes of the theoretical works of this dissertation sits upon the achieved results on the importance and dynamics of the coupling coefficient (k), as well as how the geometry of the coils influences a wireless power transfer based on IC. By focusing on related works that focused on these matters, it was possible to find viable solutions to be tested and implemented.

On the theoretical deductions presented in section 4.2, five sets of coils (TX and RX), had their inductance, and quality factor measured, using equation 2.3.7. With these, it was possible to conduct this study based on real values that were also used in the course of the practical work.

With the values of k for each set of coils, it was possible to get the maximum expected efficiency of each set, using equation 2.3.18, thus providing insightful results on how the geometry and size of a coil influence the efficiency of the power transfer.

It was possible to prove that the coupling coefficient is one of the biggest factors contributing to the efficiency of the power transfer. The results also showed that the conical shaped coils present the most viable solution in terms of maximum efficiency and that the rectangular shaped coils present the worst maximum efficiency, much due to their large radius. In spite of this, these results only present the maximum efficiency of these coils, not showing how the magnetic field behaves when distance between coils is a factor.

The following deductions, in section 4.3, focused on how the distance variation influences the efficiency of the referenced sets of coils. This study allowed for a better understanding of the magnetic field varies with each different geometric approach. Instead of just having the maximum efficiency, or, in other words, the efficiency when the distance between coils is at its minimum, this study allowed to see these values for various distances.

Using a modeled expression of the coupling coefficient, seen in equation 2.4.3, which is used in resonator coils, and the values of inductance, and quality factor of each coil, it was possible to get the efficiency results for distances up to 6 cm, matching the distance range used on the tests.

The unique behavior of each efficiency curve led to the understanding that the geometry of the coils influences the magnetic flux over distance. The set of flat oval coils decreases faster in efficiency when compared to the optimal conical coils, although they present similar maximum efficiencies, which proves the unidirectional stronger magnetic field of the conical coils [7]. The optimal rectangular coils present the slowest decrease in efficiency, maintaining an efficiency above 90 % up until 2 cm. The rectangular coils present a much larger radius than the other coils, and a slight curve, done to replicate the unidirectional stronger magnetic flux verified on the conical coils.

With these unique results, it is possible to say that a larger radius of the coils, as well as their conical nature, leads to a bigger and stronger magnetic field distribution with distance, which presents itself as ideal for unidirectional charging scenarios in which the coils are not always at close distances.

Chapter 5

System: Assessment and Practical Works

This chapter includes a series of experimental works, which had the main objective of assessing and improving the functionalities, working conditions, restrictions, and overall efficiency of a wireless power system, comprised of a wireless power transmitter, a receiver, and their respective circuits. It used two different transmitter modules, the STEVAL-ISB047V1 Wireless Power Transmitter, and the ASHATA Transmitter Module for Wireless Charging, referenced in sections 3.2.1, and 3.2.3, respectively. The receiver module chosen for the following experiments was the Zerone Wireless Power Receiver, referenced in section 3.2.4, since it was the best suited in terms of compatibility with the transmitter modules.

As it was said above, the following work outlines the intricacies of a wireless power system and pinpoints the main restrictions, as well as improvable areas of this technology. This was possible by conducting experiments focusing on the behavior of different sets of coils, deferring from each other in geometry, dimensions, and materials, and finding the best-suited parameters that lead to an efficient, and stable power transfer.

The experimental and theoretical works of this dissertation, which focused on achieving the most appropriate set of parameters for a wireless power system, were performed to reach a final product that can be used in a future implementation in military vehicles for charging man-wearable equipment.

5.1 Influence of the Load Resistance on the Efficiency of the Power Transfer

In order to better understand the range and efficiency limitations of a WPT, various tests were performed with the purpose of finding the optimal load resistance for each setup. Load resistance is commonly used to maximize the power transfer efficiency which was the main focus of this experiment. There is an optimal value for the load resistance (R_L), and when both coils are strongly coupled, the transfer efficiency is close to the maximum, but it is dependent on a wide range of loading conditions

such as the load resistance [33].

The main purpose in finding the optimal load resistance ($R_{L_{opt}}$) is to provide the best setup of parameters for a WPT, and for each set of coils used, which will ultimately lead to the achievement of the best results on future theoretical and experimental studies of said coils.

The testing setup that was used for this study, seen in the form of a diagram in figure 5.1, incorporates the GUI of the transmitter, detailed in section 3.2.8, a voltmeter, an ammeter, and an oscilloscope. On the receiver's end, a load resistance was incorporated. All the measurements and equipment descriptions are presented and discussed below in this section.

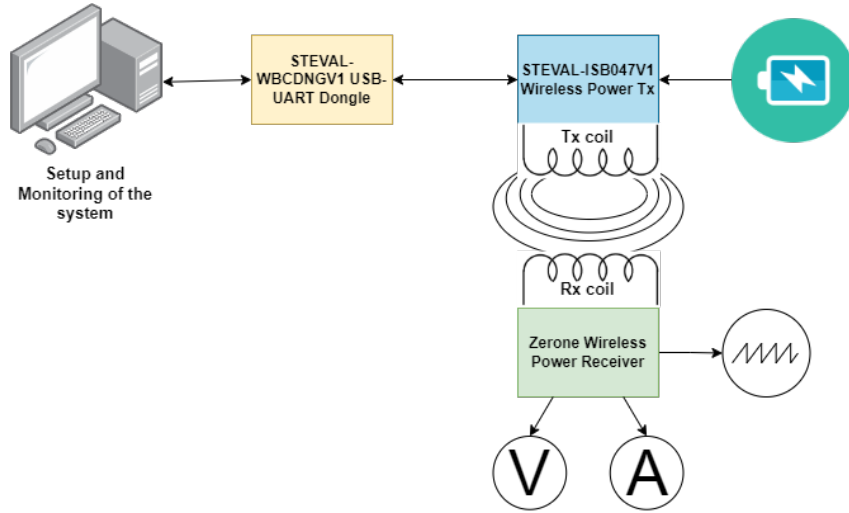


Figure 5.1: Diagram of the Testing setup.

By using Ohm's law, which shows that $I = \frac{V}{R}$ and $P = V \times I$, it was possible to calculate I_{Rx} , P_{Tx} and P_{Rx} . After gathering the power of the transmitter and receiver, the efficiency of this power transfer was obtained by measuring the ratio between useful output and given input, represented in the following equation:

$$\eta = \frac{P_{Rx}(W)}{P_{Tx}(W)} \quad (5.1.1)$$

In the following experience, a rheostat was used to carefully monitor the variation of the system's Efficiency without damaging the receiver and to gather information about the optimal load resistance ($R_{L_{opt}}$) value. The rheostat was set in a serial circuit with the receiver in order to serve as the load resistance, or, in other words, the cumulative resistance of the circuit. The values of the tension of the receiver V_{Rx} and the current of the receiver I_{Rx} were taken using an ammeter and a voltmeter. The current of the transmitter I_{Tx} was measured using the power supply of the module, a Dual-Tracking DC Power Supply, seen in figure 5.2.



Figure 5.2: Power Supply for the transmitter module.

5.1.1 Load Resistance Variation - Flat Oval Coils

On the first set of tests, it was used the original flat oval coils of the STEVAL-ISB047V1 Wireless Power Transmitter and the Zerone Wireless Power Receiver, referenced in sections 3.2.1 and 3.2.4, respectively.

The values of V_{Rx} were stable at 4.88V. The value used in the calculations for the tension of the transmitter V_{Tx} , also measured by the DC power supply, was stable at 12V. Using Ohm's law it was possible to get I_{Rx} , P_{Tx} and P_{Rx} , and by using equation 5.1.1 the Efficiency of the system was obtained.

In table A.8 the values of this experiment are displayed.

As it is possible to see, there is a stable set of values that got around 60 % efficiency between the rheostat values of 6.42 Ω and 10.61 Ω . In figure 5.3, the peak in Efficiency is clear, which means there is in fact an optimal value for the load resistance that maximizes Efficiency.

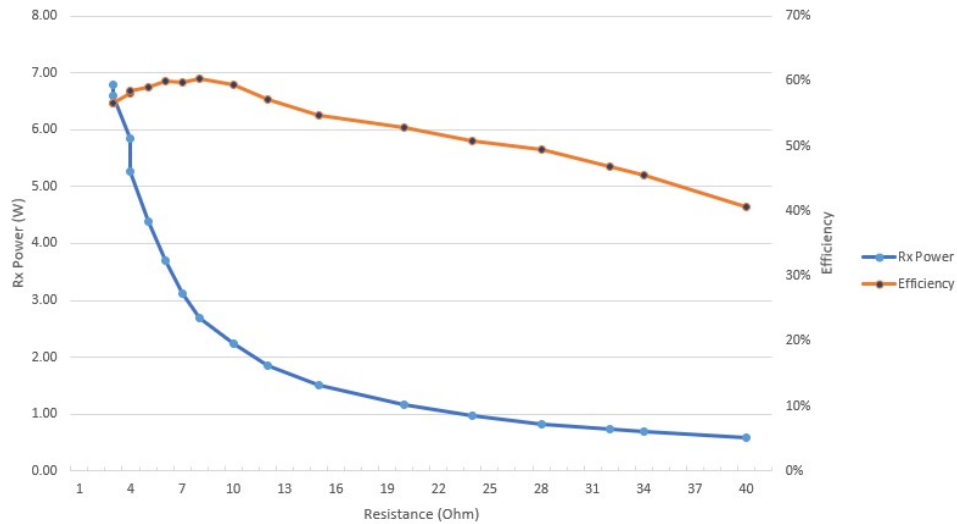


Figure 5.3: WPT Efficiency and Receiver's Power Variation with Different Rheostat values using flat oval coils.

Looking at figure 5.4, the variation between the power of the transmitter and the power of the receiver is much more significant at high power levels. This can be explained due to equipment limitations on

the receiver's end. The power capabilities of the Zerone Wireless Power Receiver are limited to around 5 W [46].

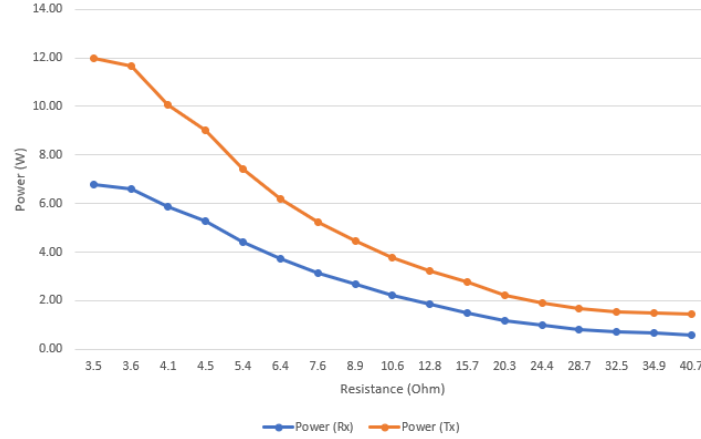


Figure 5.4: Comparison between TX and RX Power with load resistance variation using flat oval coils.

Also, this variation intensifies around the interval of the theoretical peak value for the efficiency, 6.42 Ω and 10.61 Ω . This occurs due to the fact that the receiver requires more power from the transmitter.

5.1.2 Load Resistance Variation - Conical Coils

On this set of tests, two conical coils were used. The original flat oval coils were removed from the transmitter and receiver modules, and the conical coils were welded into place. In order for this to work, the conical coils needed to have their inductance values similar to those from the original coils, due to the fact that the wireless modules were optimized to work with such values. The modules used were ASHATA Transmitter Module for Wireless Charging and the Zerone Wireless Power Receiver, referenced in 3.2.3 and 3.2.4, respectively. Both coils are referenced in section 3.2.6.

In this experiment, a different transmitter module unit was used in order to avoid damaging the STEVAL-ISB047V1 Wireless Power Transmitter due to the need to weld the conical coils. With this in mind, the power readings and other factors varied in comparison with the previous experiment, much due to the difference in power between both modules. A rheostat was used to monitor the variation of the system's efficiency and to gather information about the optimal load resistance ($R_{L_{opt}}$) value. The rheostat was set in a serial circuit with the receiver in order to work as the load resistance. The values of the tension of the receiver V_{Rx} and the current of the receiver I_{Rx} were taken using an ammeter and a voltmeter. Neither the current nor tension of the transmitter could be measured efficiently since the power supply of the ASHATA Transmitter Module is a serial port from a computer. Due to this, the power of the transmitter was set at 5 W. By utilizing Ohm's law it was possible to get P_{Rx} , and by using equation 5.1.1 the efficiency of the system was obtained.

In table A.9 the values from this experiment are displayed.

The optimal R_L is found between the values of 2.82 Ω and 4.80 Ω , achieving a maximum of 89.3 % on this experiment, as seen in the table above and in figure 5.5. The conical coils presented themselves as much more susceptible to load resistance variation than the oval coils. As it is seen in figure 5.4, the

power of both the TX and RX coils varies accordingly with the change of R_L , which does not happen in this experiment, since the power coming from the transmitter was set at 5 W.

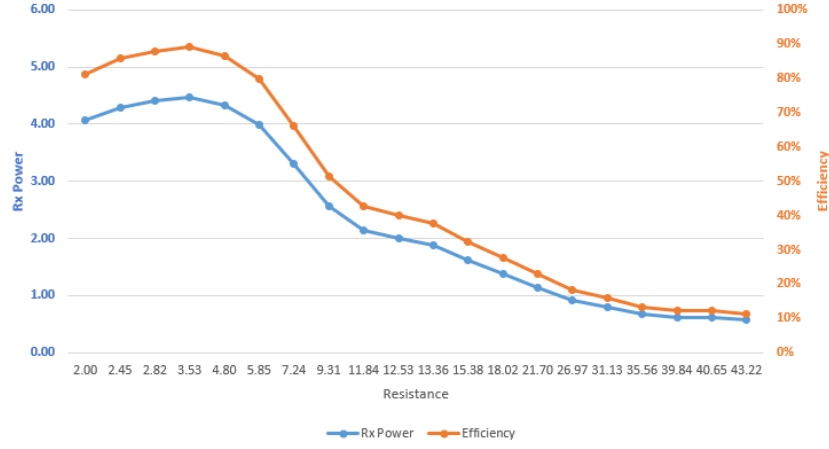


Figure 5.5: WPT Efficiency and Receiver's Power Variation with Different Rheostat values using conical coils.

As it was seen in the previous experiment, in figure 5.3, Tx power varied accordingly with different resistance loads, altering the efficiency and overall results of the experiment. The fact that it was not possible to read the transmitted power proves that the results, in terms of system efficiency, are not relevant. In spite of this, finding the values for the optimal load resistance proves extremely useful in terms of achieving the best performance configuration for conical coils.

5.1.3 Load Resistance Variation - Rectangular Coils

Finding the optimal value for the load resistance ($R_{L_{opt}}$) on the rectangular-shaped coils, referenced in section 3.2.7, followed the same procedure in section 5.1.2. The original flat oval coils were removed from the TX and RX wireless power modules, and the rectangular coils were welded in place. The modules used were the ASHATA Transmitter Module for Wireless Charging and the Zerone Wireless Power Receiver, referenced in 3.2.3 and 3.2.4, respectively. In similarity with the previous section, a rheostat was set in a serial circuit with the receiver module and used as its load resistance. The values of the tension and current of the receiver were obtained with an ammeter and a voltmeter. The power of the transmitter was set at 5 W. By using equation 2.3.13 the efficiency of the system was obtained. The values taken during this experiment can be seen in table A.10.

The peak in efficiency, reaching up to 86.63 %, is found between the load resistance values of 2.38 Ω and 4.62 Ω as seen in table A.10, and as represented by the peak on the efficiency curve in figure 5.6. In similarity to the conical coils, the rectangular coils presented themselves as much more susceptible to load resistance variation than the oval coils. This can be explained by the fact that the power modules were not optimized to work with these coils, thus such variance.

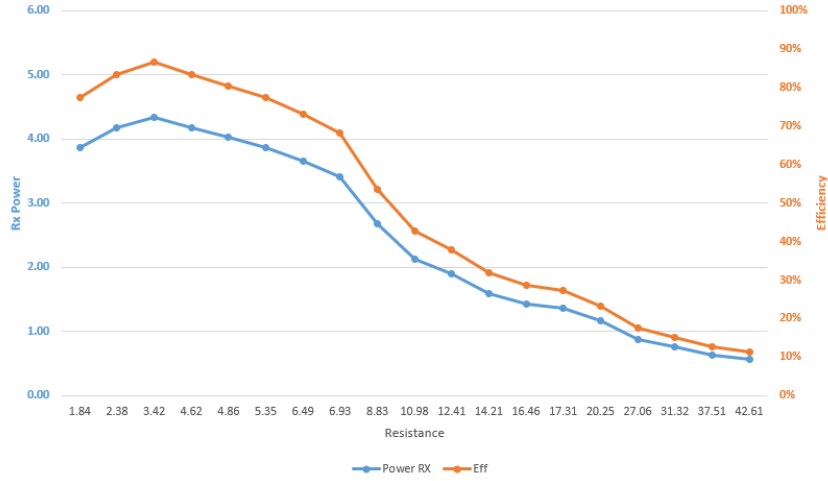


Figure 5.6: WPT Efficiency and Receiver's Power Variation with Different Rheostat values using rectangular coils.

This set of values for the optimal load resistance is also verified in section 4.2, where the theoretical approach found the optimal value for the R_L to be 3.52Ω , which is within the range verified in this section.

5.1.4 Load Resistance Variation - Results

The objective of this experiment was to find the best-suited load resistance for each type of coil. This was an important study, since one of the goals of this dissertation is achieving the best possible wireless power system solution, and getting the most compatible load resistance for each coil promotes the best condition for a more stable, and higher power transfer. Also, it was possible to compare these results with the ones obtained through theoretical deductions, in section 4.2, and come to the conclusion that the results fit in the same intervals. This serves to, not only prove the veracity of the practical experiments but also strengthen the overall results.

Finding R_L for the flat oval, conical, and rectangular coils were performed by the process of testing various resistance values, using a rheostat connected to the RX circuit, and registering the power levels of both the TX, and RX coils. This allowed the conclusion that both power levels are dependent on the load resistance that is used. This is due to the fact that it is the receiver who controls the amount of power that the transmitter sends, so, by using a more compatible load resistance, the receiver could ask for more power and considerably raise both the emitted and received power levels, as it is described in section 2.5.

5.2 Behavior of the Signal Amplitude with the Distance Variation from the Coils

Understanding how much the distance influences the signal strength between Transmitter and Receiver coil is crucial when it comes to designing a wireless power system. By measuring the signal amplitude of

various montages and sets of coils, the readings of signal amplitude for different distances are measurable. With this, it is possible to have an in-depth understanding of how the shape of the coil influences the magnetic field density and behavior with distance. The used wireless modules are optimized for working with flat oval coils. Throughout this section, different coils, which are not optimized to work with these modules, were tested, thus making them achieve a lower maximum amplitude than that registered with flat oval coils. Because of this behavior, it is important to denote that the focus of this section is not to compare maximum signal amplitude, but to compare how the amplitude decreases, percent-wise, as a function of distance variation.

On the first set of tests, the used power modules were the STEVAL-ISB047V1 Wireless Power Transmitter and the Zerone Wireless Power Receiver, referenced in sections 3.2.1 and 3.2.4, respectively. These control tests were done to understand the viability of the distance variation experiment and were only performed using one set of coils, the oval coils referenced in section 3.2.5.

In the following experiments, the ASHATA Transmitter Module for Wireless Charging and the Zerone Wireless Power Receiver, referenced in sections 3.2.3 and 3.2.4, respectively, were used. In these tests, three sets of coils were welded to the transmitter and to the receiver boards, they were submitted to distance variation experiments, and the results were compared. The transmitter and the receiver were always communicating at the same distance from each other during testing, as seen in figure 5.7.

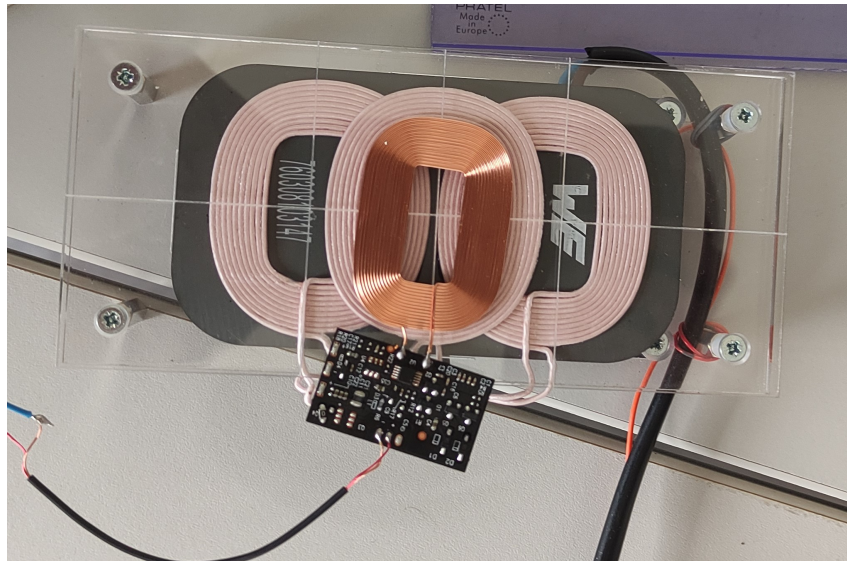


Figure 5.7: Testing setup with TX and RX established connection.

Different sets of transmitter and receiver coils were used during the course of this experiment, as listed below:

- The original flat coils from the TX and RX unit (described in section 3.2.5);
- Conical coils (described in section 3.2.6);
- Rectangular coils with circular corners (described in section 3.2.7).

By using different coils, it was possible to get information on how the dimensions, form, and number

of turns impact the efficiency of the power transfer. These testing coils were subjected to the same tests and to the same testing environment in order to gather practical and accurate results.

The concept of the experiments was to move the testing coil, depicted in figure 5.8 away from the stationary power modules.



Figure 5.8: Coil taken from Zerone Wireless Power Receiver.

By moving this testing coil, the measurement of the signal amplitude with vertical and horizontal distance variation, as seen in figures 5.9 and 5.10, was made possible without breaking the connection. The testing coil was connected to an oscilloscope in order to take signal amplitude readings.

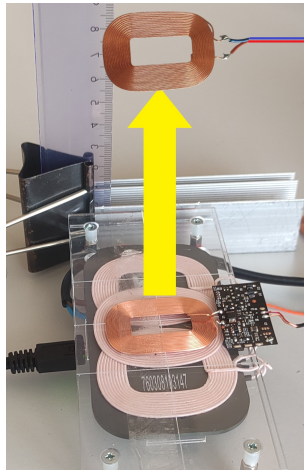


Figure 5.9: Vertical distance variation.

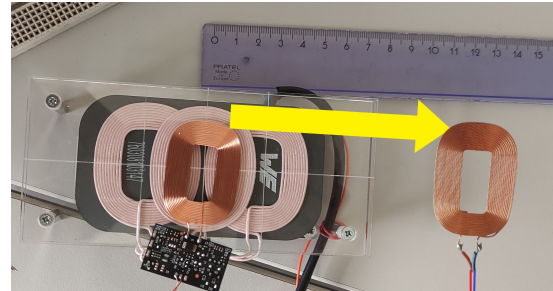


Figure 5.10: Horizontal distance variation.

5.2.1 Distance Variation - Control Test

By moving the testing coil, depicted in figure 5.8, over the testing setup depicted in figure 5.7, it was possible to measure the amplitude of the wireless power signal of the stationary coupled TX and RX coils.

The results of the vertical distance variation experiment using this coil are presented in table A.11 and figure 5.11.

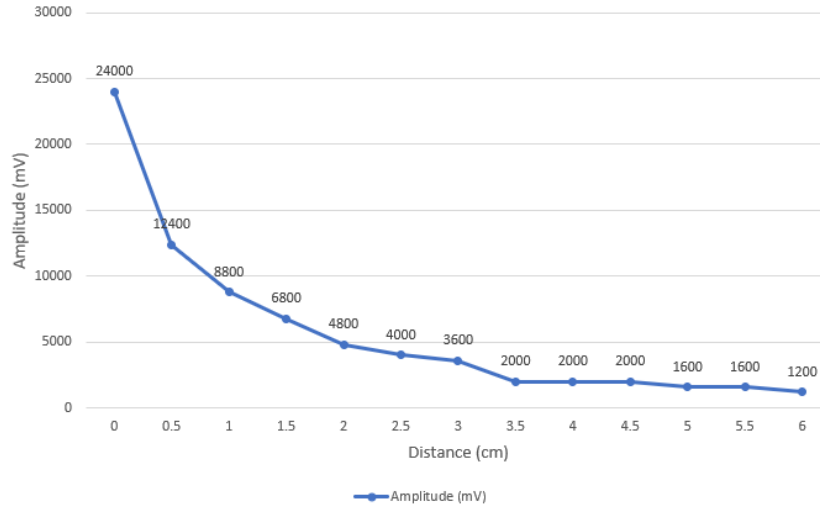


Figure 5.11: Behavior of signal amplitude (mV) with vertical distance.

The value of peak-to-peak amplitude has a maximum value of 24000 mV. This high value is due to the fact that the testing coil is equal to the receiver coil used in this experiment.

When it comes to Biot Savart's law that is used to calculate the magnetic field at a certain point, depicted in equation 2.3.1, it is possible to see, in figure 5.12, a variation of the behavior of the signal amplitude curve, that aligns with function $\frac{1}{x}$ [30].

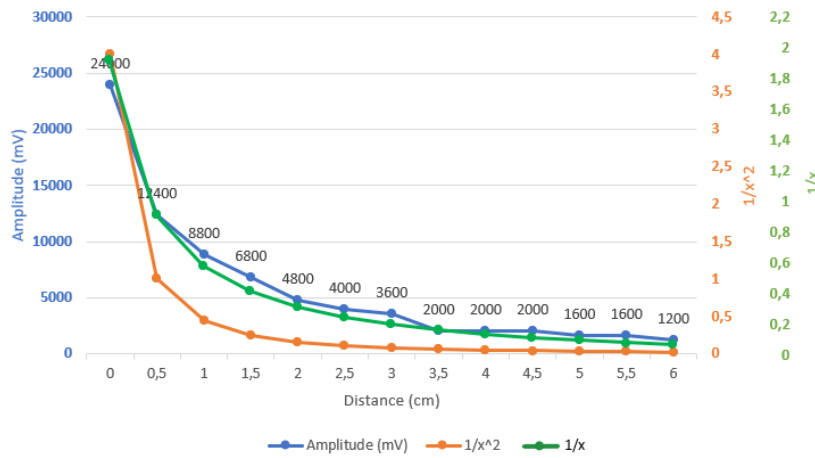


Figure 5.12: Comparison between Signal amplitude (mV) variation and functions $\frac{1}{x}$ and $\frac{1}{x^2}$.

The coil used in this experiment has, in fact, a close behavior to the expected distance variation on a magnetic field. The curve does not align perfectly with function $\frac{1}{x^2}$, which is due to the difference in shape and material between the transmitting and receiving coils used in the connection, as well as the one used to measure the magnetic field. The fact that the transmitter had three coils also influenced the magnetic field as it is also possible to see this effect in section 5.3.

The horizontal distance variation is seen in figure 5.13. In order to stabilize the testing coil, there was the need to create a platform to move it, and that altered the values of the maximum peak-to-peak amplitude when compared with the vertical test results. The values of this experiment are presented in table A.12.

As seen in figure 5.13, the variation suffers from a less abrupt curve of the peak-to-peak amplitude due to its closer proximity to the testing setup.

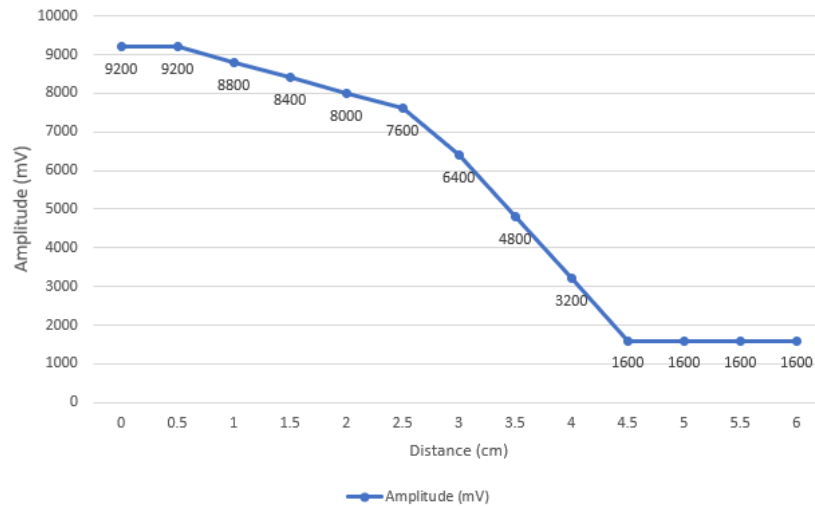


Figure 5.13: Behavior of signal amplitude (mV) with horizontal distance.

5.2.2 Distance Variation - Flat Oval Coils

The testing setup used in this section resembles the one in figure 5.8, except for the use of the ASHATA Transmitter Module for Wireless Charging, referenced in section 3.2.3 was used as the transmission module. The same procedure as in section 5.2.1 was used, where the testing coil, depicted in figure 5.8, is moved vertically and horizontally away from the established communication between the Transmitter and Receiver, while measurements of peak-to-peak amplitude are taken on an oscilloscope. The values obtained for the vertical distance variation experiment using oval coils are seen in table A.11 and their graphic representation is seen in figure 5.11.

By moving the testing coil 0.5 cm, there is a decrease of 61.47 % in amplitude, and only 20.18 % of maximum efficiency at a distance of 1cm, as seen when comparing the values from table A.13.

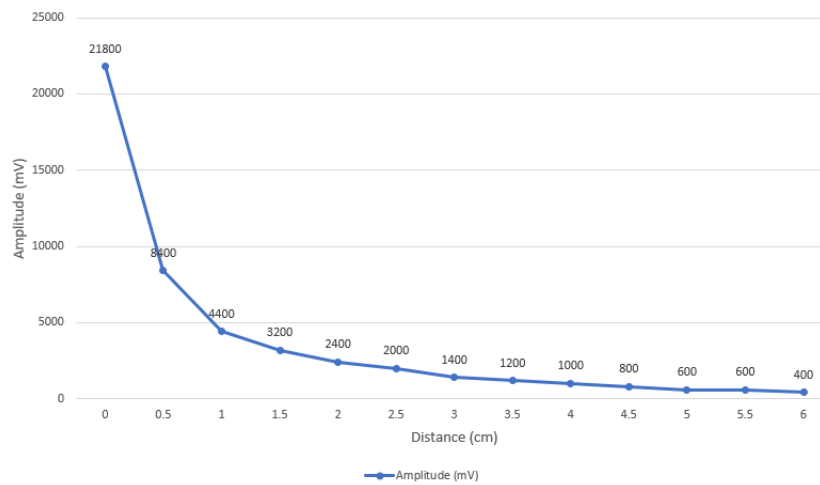


Figure 5.14: Behavior of signal amplitude (mV) with vertical distance using an oval coil.

As expected, by using only one coil, instead of three, the curve presents itself to be much more abrupt, than that in figure 5.12, and almost perfectly aligns with the function $\frac{1}{x^2}$. This alignment can be seen in figure 5.15.

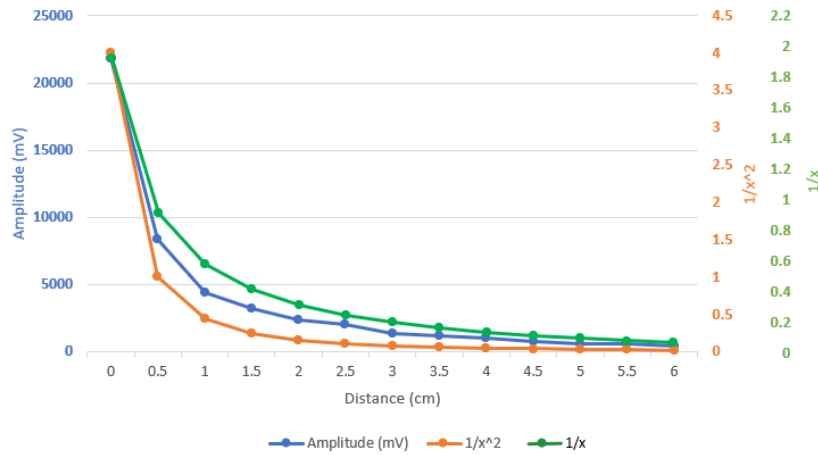


Figure 5.15: Comparison between Signal amplitude(mV) variation and functions $\frac{1}{x}$ and $\frac{1}{x^2}$ for oval coil.

In table A.14, the values taken from the horizontal distance variation influence the amplitude of the signal.

In resemblance with the vertical distance variation, the horizontal one, depicted in figure 5.16, behaves differently from that in the previous section. The curve descends much more abruptly due to the fact that only one coil was used.

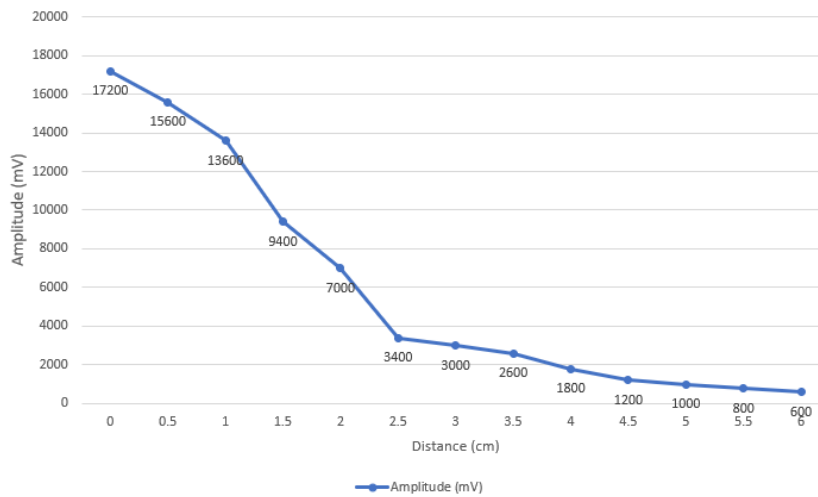


Figure 5.16: Behavior of signal amplitude (mV) with horizontal distance using an oval coil.

The achieved maximum amplitude, when using flat coils with a spiral nature as those used in this section, has proven to be very high. This high signal amplitude is due to the large contact surface between the coils. On the other hand, the rapid fall of the amplitude with the distance variation is also a consequence of using this flat geometry. The distribution of the magnetic field greatly suffers when using such coils, with an amplitude decrease of over 60% in just 0.5 cm of vertical distance variation. These results show that a flat coil geometry implementation on a wireless system only works if a stable and

highly close connection is guaranteed.

5.2.3 Distance Variation - Conical Coils

In this experiment, and following the procedure of section 5.2.2, the ASHATA Transmitter Module for Wireless Charging, referenced in sections 3.2.3, and the Zerone Wireless Power Receiver, referenced in sections 3.2.3, was used as the transmitter and receiver modules, respectively. By looking at table A.15, it is notable that the maximum amplitude that was achieved in this experiment is much lower than the one achieved with flat oval coils. This is much due to the fact that the used modules in the course of this work were made and optimized for their original flat and oval coils, which, this way, outperform other coil shapes and formats.

The behavior of signal amplitude is visible in figure 5.17. This variation is, at first glance, less abrupt than the one verified with the oval coils.

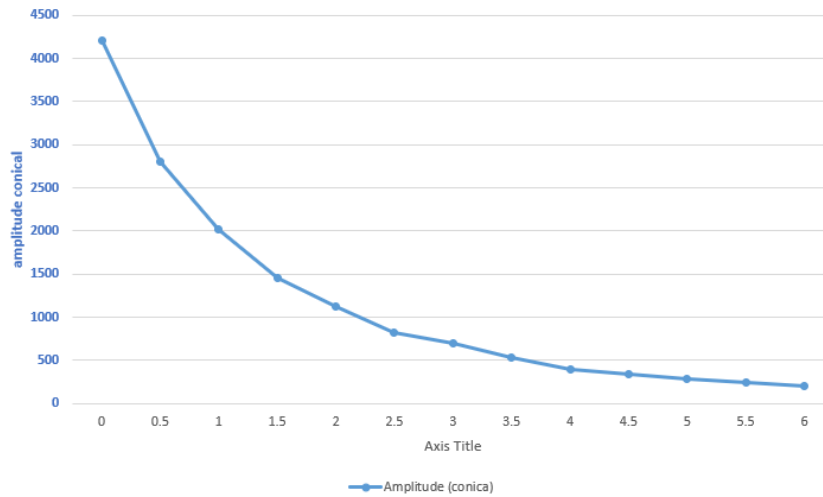


Figure 5.17: Behavior of signal amplitude (mV) with vertical distance using a conical coil.

It is clear, by looking at figure 5.18, that the behavior of this amplitude curve does not fit with function $\frac{1}{x^2}$ as well as the curve on the previous test. This proves that the change in geometry of the coil does, in fact, have an influence on the density and shape of the magnetic field.

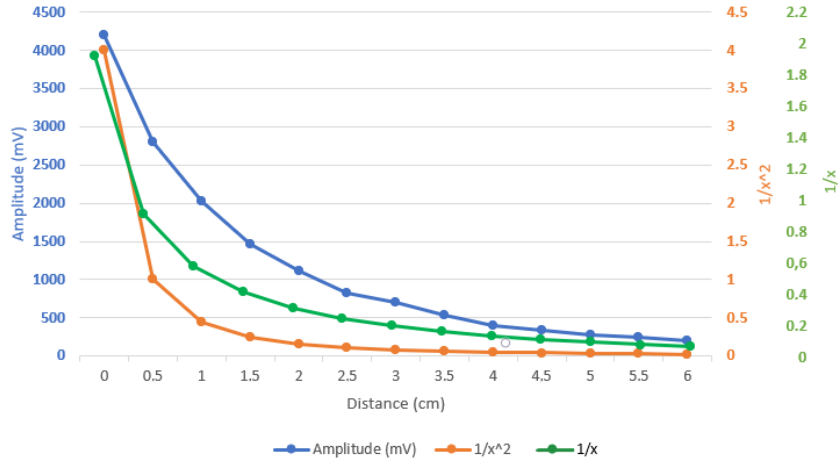


Figure 5.18: Comparison between Signal amplitude(mV) variation and functions $\frac{1}{x}$ and $\frac{1}{x^2}$ for conical coil.

Now looking at the horizontal distance variation, it is also notable that the maximum signal amplitude is lower than the one verified on the horizontal distance variation with the oval coil, in table A.12.

In spite of having a lower maximum amplitude, a product of using a less optimized coil for the wireless modules, the curves on both experiments are very similar, as seen when comparing figures 5.16 and 5.19, which is a consequence of both coils having similar diameters.

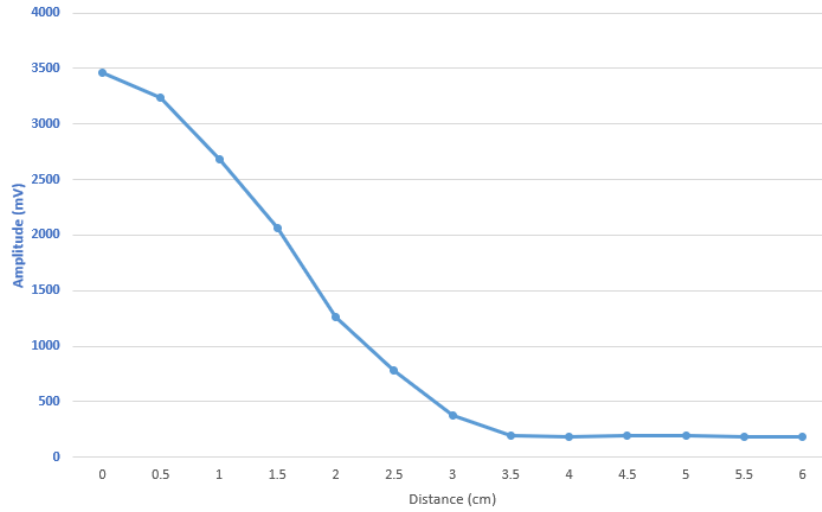


Figure 5.19: Behavior of signal amplitude (mV) with horizontal distance using a conical coil.

5.2.4 Distance Variation - Rectangular Coils

The rectangular coil, used on the TX module, has a slight upwards curvature of 10° , which makes it resemble the geometry of the conical coil, as described in section 3.2.7. In fact, this curvature was done in order to reproduce the effects of the work done by Mohamed *et al.* [7], which presented better results with a conical shaped coil in comparison to a cylindrical coil, having a uni-directional radiation pattern with a bigger and denser magnetic flux on the first one, all due to the curvature of the coil.

This experiment followed the guidelines of the previous ones, in sections 5.2.2 and 5.2.3. The only

exception was the placement of the testing coil during testing, where on the vertical distance variation, the testing coil was placed inside of the 3D printed structures and then moved up accordingly while taking measurements, as seen in figure 5.20, and on the horizontal variation it was placed at the center of one of the sides of the rectangular shaped structure, to promote stability of movement from the said coil, and then it was moved throughout that side, as seen in figure 5.21.

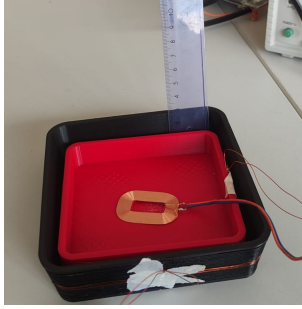


Figure 5.20: Vertical distance variation setup with rectangular coils.

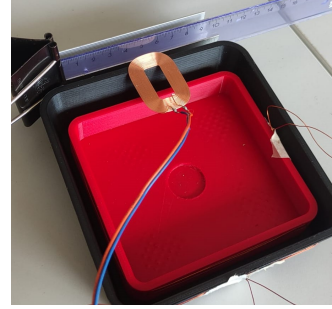


Figure 5.21: Horizontal distance variation setup with rectangular coils.

The measurements of the vertical distance variation test are presented in table A.17.

These results have the lowest values of maximum signal amplitude, considering all prior experiments. The larger diameter, which surpasses 10 cm on both coils, is much to blame when it comes to the low signal amplitude. Also, the chosen geometry is very different from the one of the original coil, thus being less optimized to the wireless charging modules in use, which also impacts overall signal amplitude.

On the other hand, the curve of signal amplitude variation, seen in figure 5.22, has the least abrupt descent of all experiments, not resembling in the slightest to function $\frac{1}{x^2}$, visible in figure 5.23, and having a desirable, and almost linear behavior on the first three distance measurements.

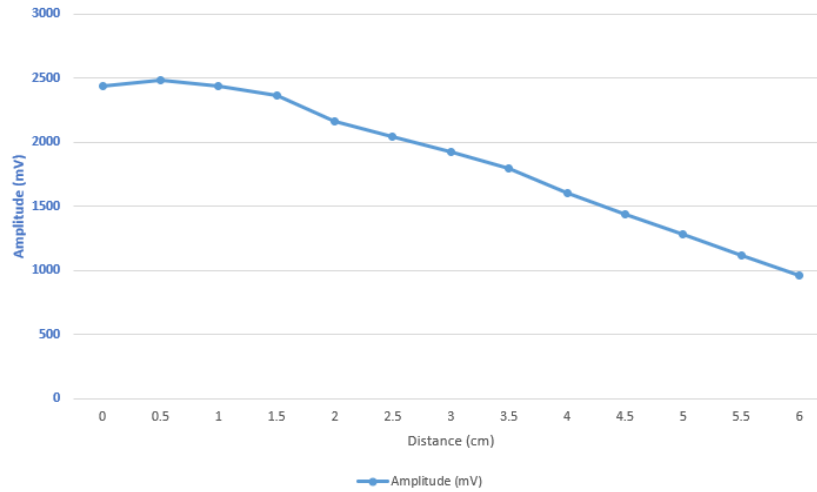


Figure 5.22: Behavior of signal amplitude (mV) with vertical distance using a rectangular coil.

This behavior is most likely due to the larger diameter of both the TX and RX coils, which is a major factor that substantially enlarges the reach of the magnetic field. On the other hand, diameter has also proven to be a factor that influences the maximum signal amplitude as seen in this particular set of results and on the theoretical works of section 4.3.

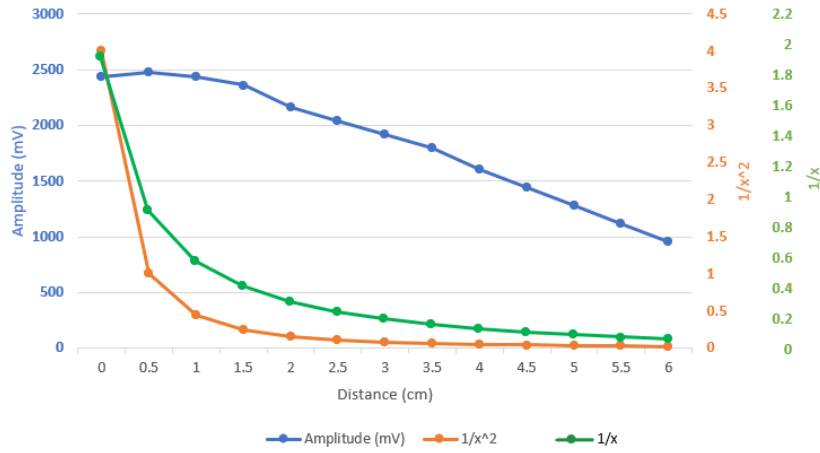


Figure 5.23: Comparison between Signal amplitude(mV) variation and functions $\frac{1}{x}$ and $\frac{1}{x^2}$ for rectangular coil.

On the horizontal distance variation, the lower maximum amplitude is also verified, as seen in table A.18.

The amplitude curve, seen in figure 5.24, shows a different evolution than the one seen in the other experiments. The amplitude rises up until it approaches 3.5 cm, where it is close to a maximum of 2320 mV. This behavior can be explained by the setup in which this experiment took place. The testing coil was placed at the center of one of the sides of the 3D structure and moved throughout that same side. Due to the large diameter of the structure, the testing coil stayed within the structure up until it reached around 5 cm, which explains why the amplitude levels did not decrease. The fact that the testing coil was slowly approaching the intersection between two sides of the coils is the reason why there was an increase in amplitude. Liyuan *et al.* [47] verified this phenomenon, where the peak at the corner of the square shaped coil was attributed to the superposition effect of the magnetic field.

On another note, the rapid drop in amplitude when the corner is reached, as seen in figure 5.24 at around 4.5 cm, can be explained by the edge effect of the coil, which causes a significant drop in the magnetic field [47].

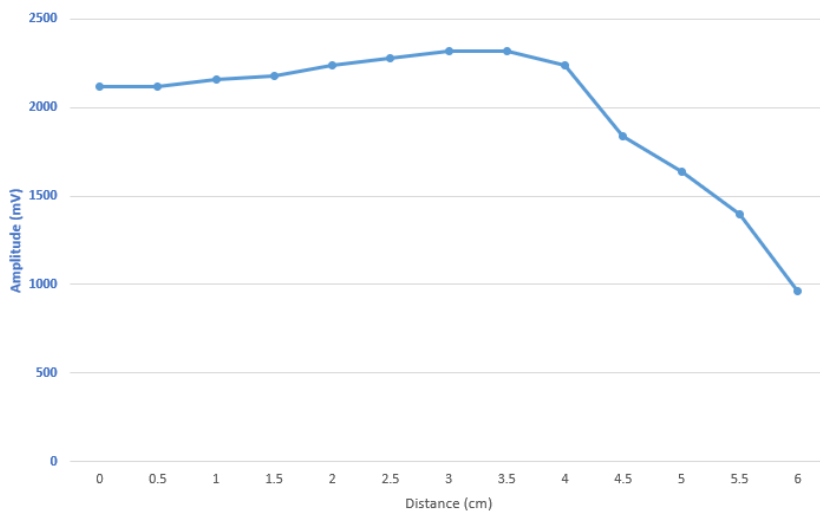


Figure 5.24: Behavior of signal amplitude (mV) with horizontal distance using a rectangular coil.

5.2.5 Distance Variation - Results

As seen in section 4.1, through theoretical and practical work, when it comes to wireless power systems, differently shaped coils produce differently shaped magnetic fields with distinct levels of intensity. The distance variation experiments had the purpose of showing the difference between the behavior and shape of the magnetic field of three sets of coils with distinct geometries. In order to accomplish this study, measurements of signal amplitude on each set of coils were performed and then compared, primarily focusing on the pattern of the amplitude curve.

Figure 5.25 shows all three distance variation test results, from the flat oval, conical, and rectangular sets of coils. These results depict the differences in signal amplitude behavior according to distance, solely focusing on the shape of the curve.

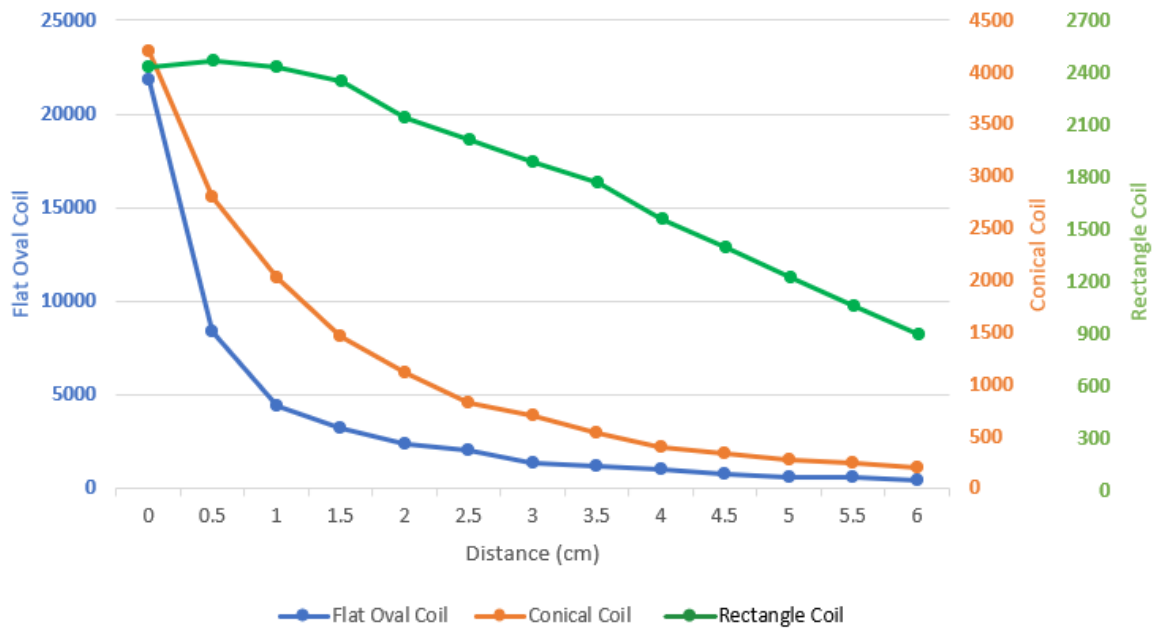


Figure 5.25: Signal Amplitude Behavior with Vertical Distance Variation for the Three Sets of Coils.

These results come in agreement with the study conducted by Mohamed *et al.* [7], presented in section 4.1.1, which proves that coils with conical geometry produce a considerably denser and bigger magnetic field in comparison with cylindrical geometry. In similarity with the cylindrical coil, referred to in the study section 4.1.1, a flat oval coil presents a symmetrical magnetic field shape on both sides. On the other hand, a coil that presents an upwards curvature such as the conical and rectangular coils will have a redirected magnetic field, bigger and denser on the larger side.

As a result of this experiment, and in concordance with the theoretical works performed in section 4.3, the diameter of the coil also influences the emitted radiation pattern, enlarging it as it is visible through the measurements of the rectangular coil.

Figure 5.26 shows the same results for the horizontal distance variation, which reinforce the previous statement about the influence of the diameter of the coil. In this case, there is no major difference between the results from the conical, and the flat oval coils, since their diameter is very similar. On the

other hand, the rectangular coils show much different behavior than their counterparts, having a rising amplitude up until the 3.5 cm mark, and only decreasing afterwards.

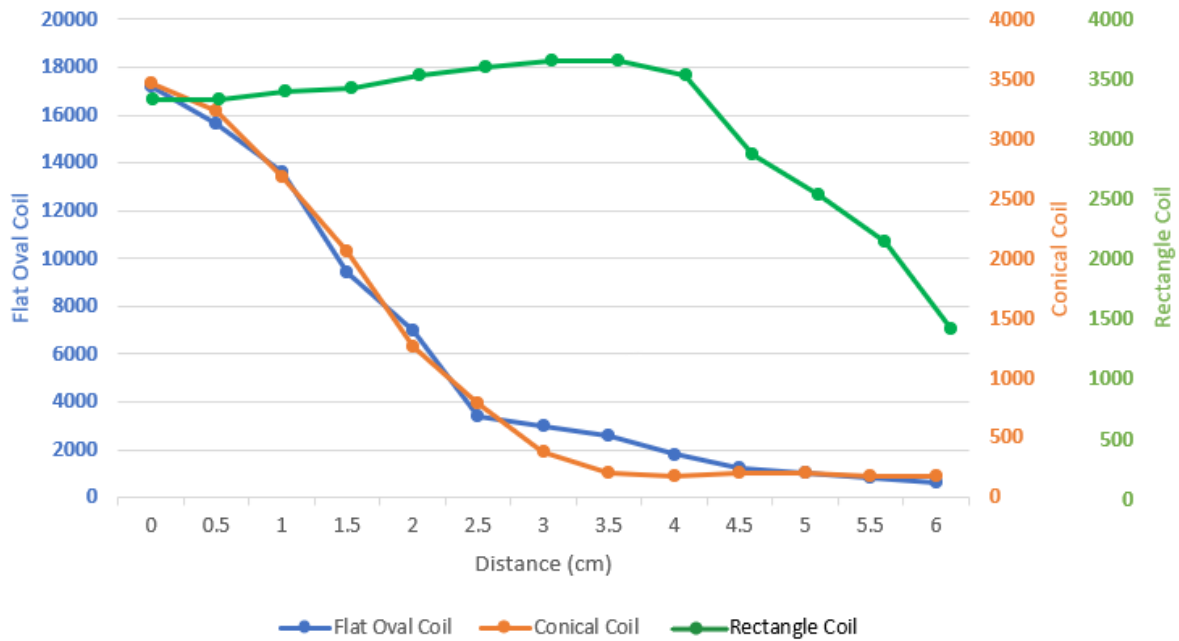


Figure 5.26: Signal Amplitude Behavior with Horizontal Distance Variation for the Three Sets of Coils.

In figure 5.27, it is possible to see a variation of the efficiency of the power transfer when it comes to signal amplitude. This figure comprises both vertical and horizontal distance variations from the oval coil testing results, seen in section 5.2.2. The value of peak-to-peak amplitude when the receiver is coupled to the transmitter at 0 cm was considered 100 % efficiency. The values of distance and amplitude were presented on tables A.13 and A.14, were then compared with the maximum amplitude to see how the efficiency behaved.

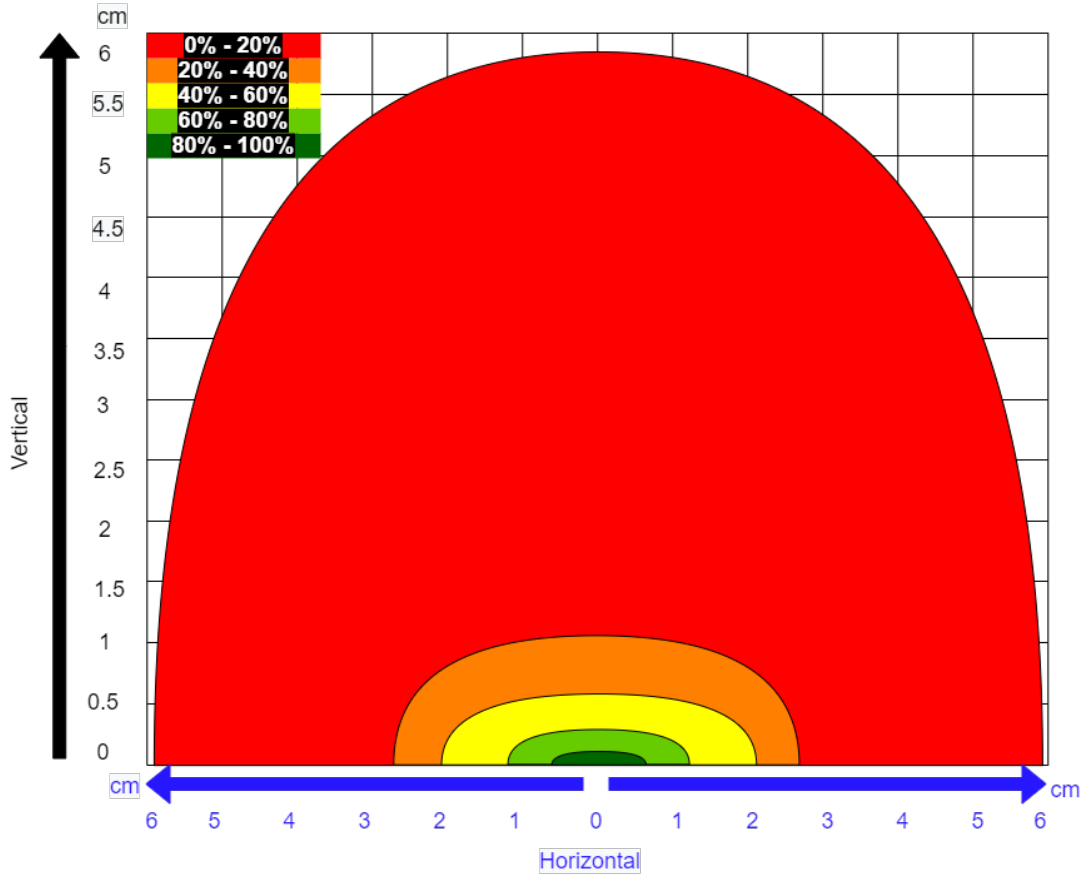


Figure 5.27: Variation in amplitude (mV) with vertical and horizontal distance for a Flat Oval Coil.

The results from the oval coil experiments show a larger signal amplitude variation with vertical distance in comparison with horizontal distance. At a vertical distance of 0.5 cm, the signal amplitude is already at 60 to 40 % of the maximum registered efficiency. On the other hand, in the horizontal test, the signal amplitude only drops below 20 % at around 1 cm. These results show the high volatility and instability of this wireless power system. In order to prevent a decrease in efficiency, the transmitting and receiving coils must either be physically coupled or at a very short distance from each other at all times during the power transfer.

Looking at figure 5.28, it is presented the same variation of efficiency as in figure 5.27, but for the conical coils. The values for the vertical and horizontal distance variation test used on this figure are listed in tables A.15 and A.16.

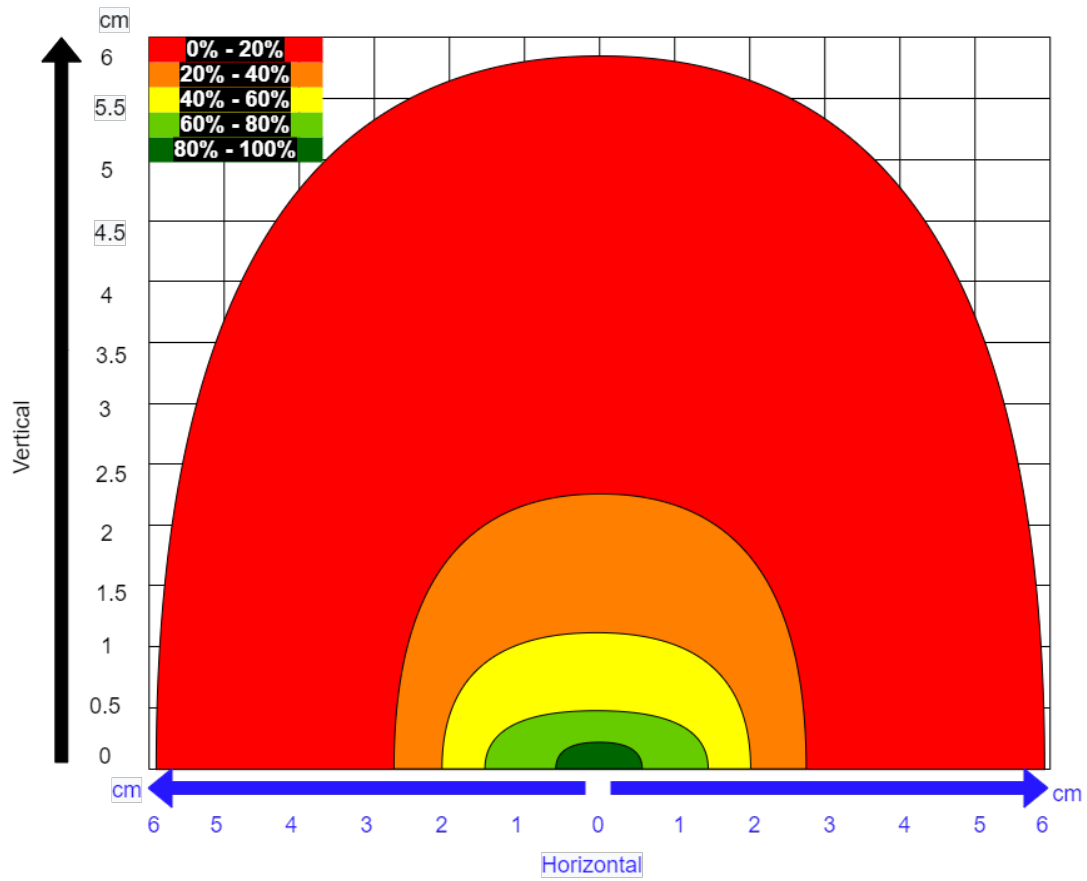


Figure 5.28: Variation in amplitude (mV) with vertical and horizontal distance for a Conical Coil.

In this case, the behavior of the signal amplitude is very similar, in terms of horizontal distance variation, to the one of the flat oval coils, but there is a clear difference when it comes to vertical distance. At 0.5 cm of vertical distance variation, the efficiency is still within 60 to 40 % of maximum signal amplitude, and it only falls below 20 % at around 2.5 cm. These results show a clear improvement in terms of magnetic field reach from the conical coil when compared with the flat oval coils.

The graphic presented in figure 5.29 presents the signal amplitude behavior from the vertical and horizontal distance variation experiments with rectangular coils. The values of distance and amplitude are presented in tables A.17 and A.18.

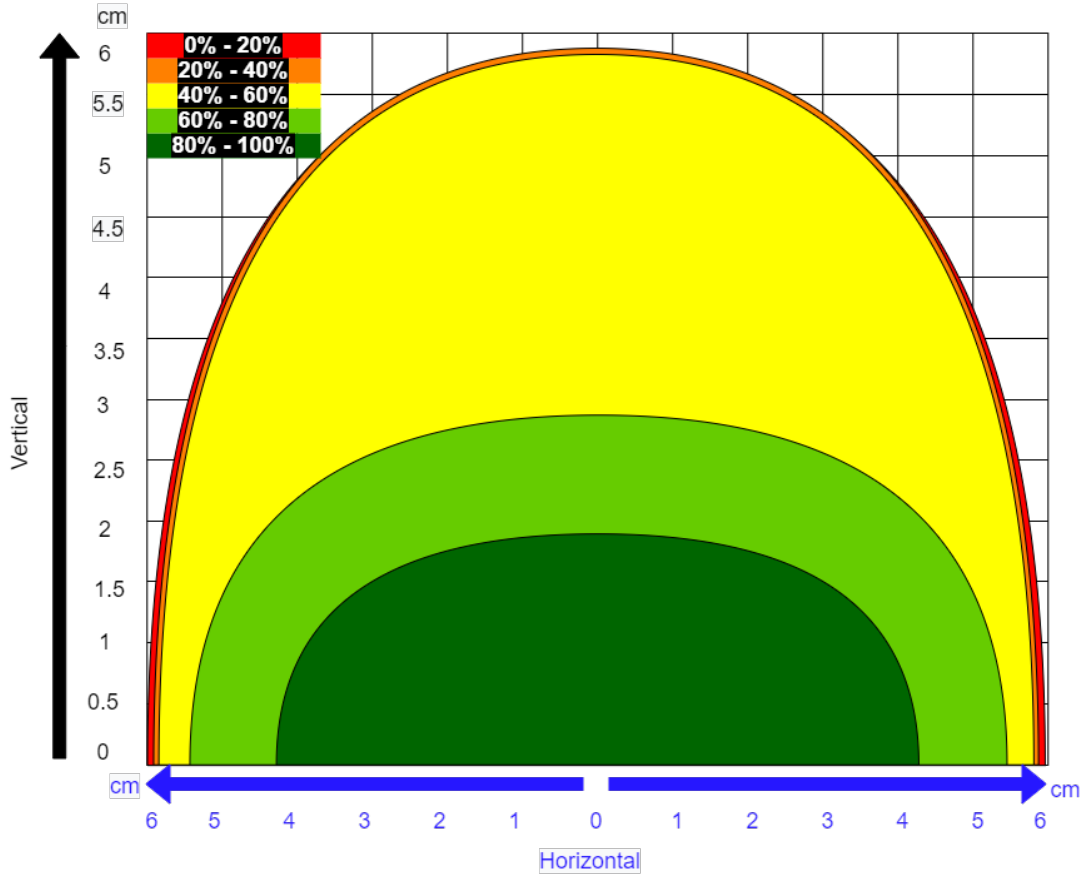


Figure 5.29: Variation in amplitude (mV) with vertical and horizontal distance for a rectangular Coil.

Efficiency is maintained above 80 % at around 2 cm on the vertical scale and 4 cm horizontally, not dropping below 40 % until 6 cm is reached. This distinct set of results comes as proof of how the rectangular coils differ from the other two sets of coils in terms of magnetic field reach.

5.3 Testing the "Sleeping" Coils' Influence on the Wireless Power Transfer

Both the transmitters used in the experiments had three coils, which allowed for the detection and charging of a receiving coil in each and any of these coils. As described in section 2.5.1, the *Qi* Communication Protocols have different phases in order to allow the detection, configuration, and calibration of a wireless power system, as well as prevention mechanisms that detect foreign objects that might damage the equipment. The Ping Phase marks the phase when a transmitter coil is searching for the receiver. When a receiver is detected by one of the coils, this one enters the next phase until it reaches a power transfer contract and, ultimately, enters the Power Transfer Phase. Only one of the three coils can establish a connection with a receiver, while the others stay in the Ping Phase. The objective of this test is to understand the influence on the wireless power transfer of the coils that remain in the Ping Phase. For this, two tests were conducted using the ASHATA Transmitter Module and the Zerone Wireless Power receiver, referenced in sections 3.2.3 and 3.2.4, respectively. For the first test, a wireless power transfer

was established between the transmitter, with three coils, and the receiver, using the middle coil of the transmitter as the transmitting coil. In similarity with the experiments in section 5.2.2, an oval coil was used to take measurements of the variation in signal amplitude with vertical distance variation. For the second test, the same experiment was conducted using the transmitter with only one coil as the other ones were removed. As seen in figures 5.30 and 5.31, the amplitude of the signal is 1.46 times greater at its peak when using only one coil. This can be explained by the fact that, when using 3 coils, the ones that are not in an established connection with the receiver are constantly emitting a ping signal in order to detect other objects.

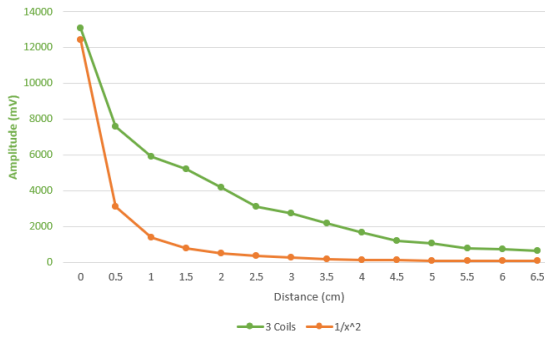


Figure 5.30: Behavior of signal amplitude (mV) with vertical distance using 3 coils Transmitter.

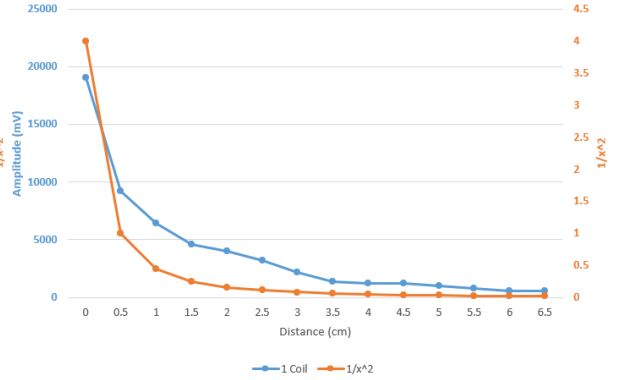


Figure 5.31: Behavior of signal amplitude (mV) with vertical distance using 1 coil Transmitter.

By comparing the amplitude curve of both figures with the curve from function $\frac{1}{r^2}$, it is possible to see that the presence of the other coils is altering the normal behavior of the power transfer. With these results, it is possible to say that a system comprised of just one coil in the transmitting end is capable of transmitting power with higher maximum signal amplitude. On the other hand, using a three-coil transmitter allows for a slower decrease in efficiency with distance.

5.4 Influence of magnets on the Efficiency of the Power Transfer

The proximity between coils in a wireless power transfer is essential to guarantee efficiency. Magnetic wireless power banks have been developed and implemented as a viable solution across the global market for wireless chargers because they present a unique way of securing both coils in a stable position without damaging or hindering the user experience [50]. A guide on safety concerns when using ferrite magnets is depicted in section 2.7.4, including safety hazards and precautions that should be taken when using such equipment. As it was said in section 2.5, a wireless charging system is very complex when it comes to FOD as a mechanism to protect the integrity of the equipment. Because of this, and in order to verify if magnets disrupt in any way the connection between the coils, their influence was tested in a wireless charging system. For this, it was used the same testing principle and equipment of section 5.2, where the variation of signal amplitude was measured using a coil that varied with distance from the wireless connection. This system is comprised of the STEVAL-ISB047V1 Wireless Power Transmitter and the Zerone Wireless Power Receiver, referenced in sections 3.2.1 and 3.2.4, respectively. For the distance-

varying testing coil, a circular coil, seen in figure 5.32, was made with a diameter of 20mm, 6 turns and with four magnets at its center.



Figure 5.32: Coil with magnets at its center.

On the second set of tests, the magnets were removed and both experiments were compared. Both results gathered by varying this coil vertically and away from the wireless charging system are seen in figure 5.33. It is possible to see that there is no significant difference between these two scenarios.

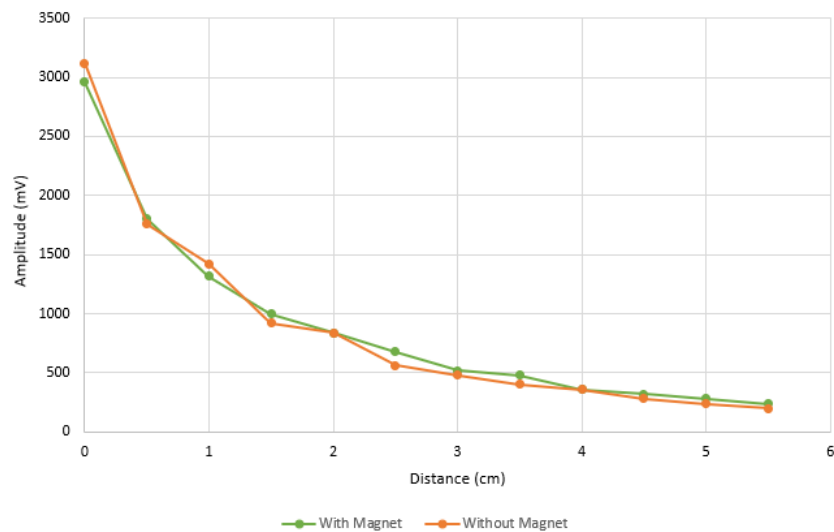


Figure 5.33: Behavior of signal amplitude (mV) with vertical distance with, and without, magnets.

By looking at the horizontal variation results, seen in figure 5.34, the conclusions are the same from the first set of results, as the variations are minimal and can be overlooked as experimental errors.

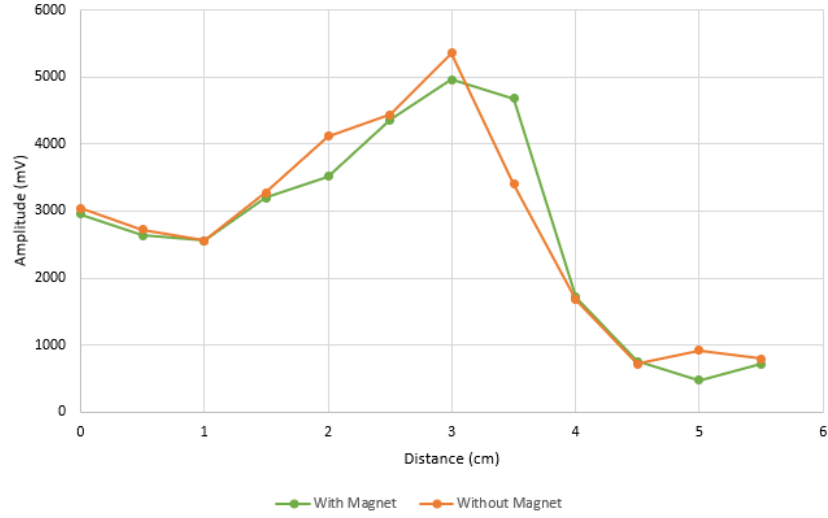


Figure 5.34: Behavior of signal amplitude (mV) with horizontal distance with, and without, magnets.

During the course of the testing phase, no disruption was made by using magnets as a support for the circular coil. An unreasonable result would be to have the wireless system shut down the connection due to the presence of the magnets. which was not verified.

In short, it is possible to conclude that the use of magnets does not derange the integrity of the wireless power transfer and does not decrease its efficiency. In terms of the work in hand, the use of magnets is a viable option for securing both coil structures in place, which can ultimately improve the stability of the connection between the transmitter and the receiver. In spite of this, safety concerns must be met to avoid malfunctioning devices, such as keeping magnetically sensitive items, like heart pacemakers and mechanical watches, at a distance of at least 20 cm from the magnets, as is depicted in section 2.7.4.

5.5 Overall Practical Results

The practical component was, from the beginning, the most crucial aspect of this work, and, through the various conducted experiments in this chapter, it was possible to achieve concise, useful, and strong results.

The first set of experiments presented in this chapter had the objective of assessing the necessities of the wireless power system, centering the research on the three different coil geometries of coils used. By finding the optimal load resistance of each coil it was possible to strengthen the theoretical results on the same matter, while testing the limits of the system, not only with the original coil but with those developed for this dissertation. Also, as it is said in section 5.1.4, finding the optimal load resistance has led to better optimization of the overall system.

The second set of experiments, in section 5.2, had the purpose of complementing the theoretical research done on each coil topology, by testing the variation of signal amplitude with distance as the main variable. These tests led to a better understanding of how each coil's magnetic field behaves, as it is described in section 5.2.5, and the results of this section led to the conclusion that differently shaped coils produce differently shaped magnetic fields with distinct levels of intensity. The experimental work

showed that a conical shaped coil has a bigger, and unidirectional magnetic field, which is ideal for the charging environment presented in this thesis. A large radius, such as the one of the rectangular shaped coil, also contributed to a bigger, and more distributed, magnetic field. These results helped to find the best coil shape solution for future implementation and came in concordance with the other studies, presented in section 4.1, which also helped to guide this present experimental work.

The third experiment, in section 5.3, was directed to system assessment, focusing on the behavior of the power system to internal variations. ASHATA Transmitter Module for Wireless Charging is equipped with three transmission coils, and the objective of the third experiment was to see if having multiple transmitter coils would in fact improve the power transfer when compared to having just one coil. Once again, using distance variation with a testing coil, it was possible to measure signal amplitude with three, and one transmitter coils, and compare the results, which proved to be two-sided. While multiple transmitter coils lead to a stronger detection of the receiver, and a slower decrease in efficiency with distance, having just one transmitter coil will produce a much stronger maximum amplitude, as seen when comparing figures 5.30 and 5.31.

The fourth experiment, in section 5.4, was also directed to system assessment, but with focus on external variations, namely the use of magnets. Using magnets on a wireless power transfer is a common way of securing both coils in a stable position. The objective of this test was to see if the use of magnets had any influence, positive or negative, on the power transfer. The results showed that the behavior of signal amplitude suffered no alteration with the use of magnets, with the variations being minimal and possibly product of small experimental errors.

Chapter 6

Proposal for the Wireless Charging System

The final stage of this study sits upon the proposal of a concept design for a wireless charging system. This system must contain a series of checked parameters that must be fulfilled in order to guarantee power necessities, compatibility, safety measures, and overall capability of the product.

During the experimental phase of this project, in sections 4 and 5, several variants were tested, and modified, in order to find the optimal solution for the charging environment in question. In this section, several requirements for the proposed system will be described, as well as the chosen approach, with emphasis on the type of system, geometry, dimensions, and other essential parameters.

6.1 Requirements

In order to create a wireless charging system capable of being used in military vehicles and fulfill the high power needs of various devices, there is a need to understand the basic requirements before product design. These requirements are the following:

1. An obligation for this WPT system is that it must not put at risk the well-being or safety of the users, since the appliances that are being charged are body-worn;
2. The power TX and RX, must be compatible with the power source and the charged devices, respectively;
3. The charging setup must be able to fulfill the electronic equipment power needs and the rigorous timings;
4. The system must have a charging setup that does not restrict the movements of the equipment bearer;
5. This system must be capable of withstanding external forces, that are characteristic of military operations. In order to guarantee this, its materials must have a high protection index.

6.2 System Architecture

A charging system such as this, and any system for that matter, should have all its major components working in a way that ensures efficiency, practicality, and control. A well-thought system architecture is one of the most important stepping stones to achieving these functionalities.

Similarly to the one that was used during the practical works, the proposed architecture for the WPT in question has the TX and RX modules at its *center*. Since wireless charging is the main purpose of this setup, the connection between both coils must be the priority.

As seen in figure 6.1, the wireless power transmitter presents three different connections.

- The **connection with the receiver**, which grants the transfer of power from one coil to the other, as well as data packets, which permit the control of the amount of power that is transferred, and FOD detection [27];
- The **connection with the power source**, which will be the vehicle's battery. The type of connection established between the TX coil and the battery can be accomplished by using the STANAG 4695 compliant input port, described in section 2.1.4, or by means of a PoE system, using an Ethernet cable, described in section 2.6. Choosing the most practical charging method is dependent on the power necessities of the man-portable devices;
- The **connection with the monitoring system** is essentially a GUI for the transmitter to be monitored and accessed during charging. This will help to assess the state of the connection between the power supply and the power receiver, as well as monitor the packet transfer between both coils.

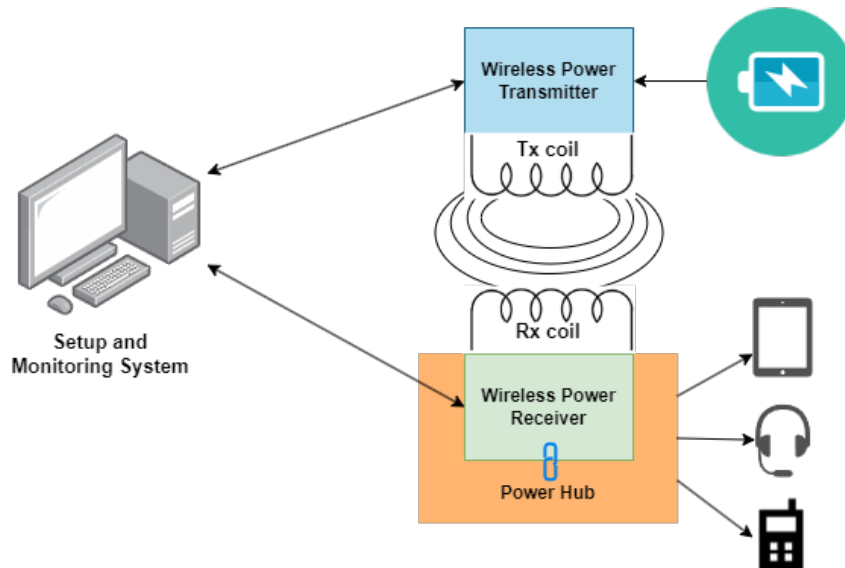


Figure 6.1: Concept for the Wireless Power System Architecture.

In terms of the receiver unit, as seen in figure 6.1, there are three different connections.

- The **connection with the transmitter**, which involves the transfer of power and packets between both coils, and will be the wireless link between the power from the battery supply, and the power hub, where the receiver will be located;
- The **connection with the power hub** represents the connection between the power receiver and the battery of the power hub, described in section 3.1.1. This connection will allow the battery to be charged by the power that comes from the wireless transfer established between the coils, as well as send its power needs through the receiver to the transmitter by means of data packets;
- The **connection with the monitoring system** allows for the control and monitoring of both the receiver and power hub charging state.

When it comes to the power hub, the **connection with the man-portable devices** is how the power will reach this equipment, using connection points and fabric connectors.

The communication protocol of the WPT must ensure that the power transfer is stable, safe, and, at the same time, does not compromise its efficiency. In figure 6.2 it is possible to see a diagram of a possible implementation of the communication protocol. This diagram is based on the *Qi* Standard communication protocol, and it comprises safety measures while promoting a stable connection between the TX and RX wireless modules [27].

The choice to present an approach similar to the *Qi* Standard is due to the fact that this communication protocol is widely used and is regarded as the main standard for wireless equipment that utilizes magnetic induction. Also, it presents all the characteristics needed for an efficient and safety-driven power transfer [27].

Qi communication protocol has four different phases during a power transfer, as documented in section 2.5.1. These four phases, ping, configuration, negotiation, and power transfer, make up the *Power Transfer Contract*, which ultimately culminates in the power transfer from the wireless power transmitter to the receiver.

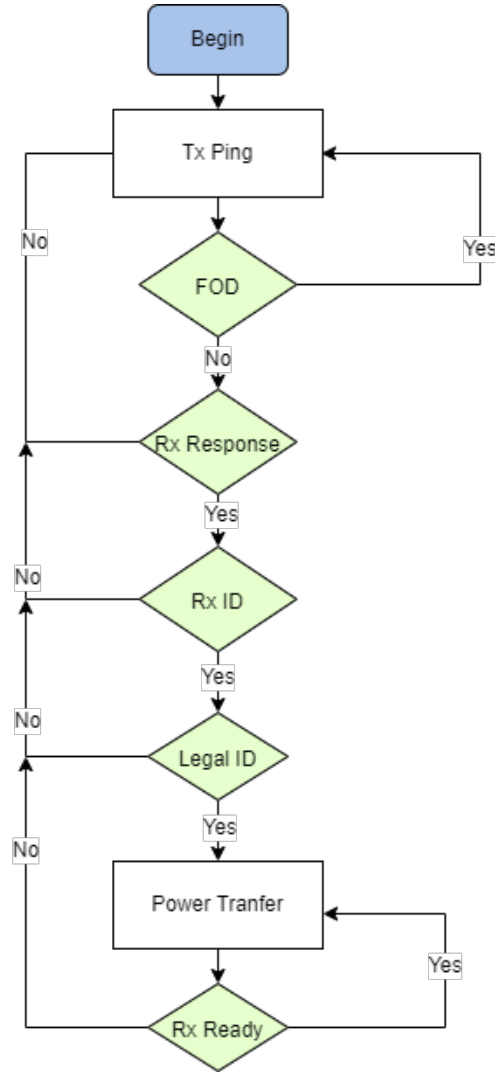


Figure 6.2: Concept for the Communication Protocol.

6.3 Chosen Approach and Implementation

The research work performed in this dissertation has led to many conclusions on how a wireless system must behave, and be executed. Many approaches were implemented in the hopes of finding the best-suited one for the scenario in question. This section has the purpose of pinpointing the best results and forming a concise and practical approach to the development of a WPT system. An IPT system, based on near-field WPT, was chosen as the charging method to guarantee power, safety, and time requirements. As it is referred in sections 2.2.2 and 2.3, this type of system focus on short-distance wireless power transfers with a high power output, which allows the charging time to be reduced to a minimum. IC uses a non-radiative method of wireless charging, so there are no concerns with the well-being of users, as long as the time of usage and the product specifications fulfill the imposed safety regulations, which are described in section 2.7.

One of the great obstacles that an IC system imposes on this research, was the fact that this method of wireless charging requires the power transmitter and receiver to be almost in contact with each other,

in order to maintain a stable and efficient connection. This comes as a problem due to the nature of the charging environment. The power hub, that will be charged by this system, will be part of the soldier's garments, so there is a need to create a system that does not restrict the movements of the soldier, and be able to charge the carried equipment efficiently. This problem was tackled during research by exploring different coil geometries, in order to create a larger magnetic field range, uniformity, and all without losing intensity. To improve the range of the wireless transfer, a conical-shaped coil proved to be the best overall option, due to its unidirectional, and stronger magnetic field. A rectangular shape proved to be more capable in terms of magnetic field distribution across the coil's range. With this, came the development of the prototype structure, seen in section 3.2.7.

Also, the use of magnets to promote a steady lock between both coil structures was tested, finding no repercussions on the efficiency of the power transfer, as seen in section 5.4. Despite this, the use of magnets comes with safety concerns, depicted in section 2.7.4, which were followed when developing the prototype structures. The use of ferrite magnets in a future implementation is of great interest since it promotes stability between both structures of a power transfer without damaging the charging equipment.

The concept of this design is based on practicality, and functionality with the power hub, along with the receiver, fitting inside the structure of the transmitter as seen in figure 6.3.

In terms of durability and protection, the equipment found in a wireless charging system is very susceptible to damage from air particles and external forces, and since this technology does not require a physical connection between components, it is possible to incorporate the device inside a protective structure. By using reinforced and resilient materials, it is possible to guarantee the system's structural integrity, so the risks of degradation can be mostly avoided.

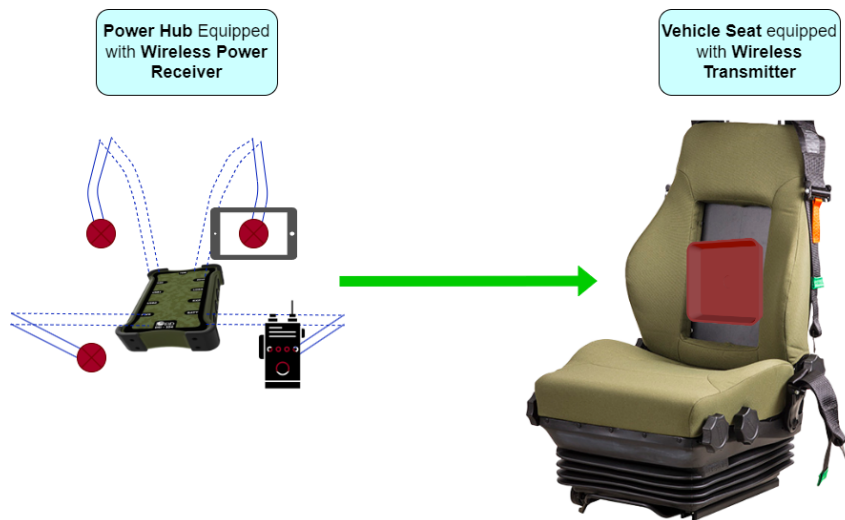


Figure 6.3: Concept System Implementation.

Chapter 7

Conclusions

The search for standardization, interoperability and interchangeability in soldier systems has seen many efforts over the years, with the focal point being to adapt to new technologies, and improve the overall usability of military equipment. The main objective behind this master's thesis, which stands as a contribution to this initiative, was to research the possibility of implementing a WPT system capable of efficiently charging man-portable devices on military vehicles. For this matter, it was conducted a set of studies, including theoretical deductions, and practical experiments, with the goal of finding the most viable set of parameters for this system, such as architecture, signal levels, and overall design, whilst taking into account the very specific working environment.

To correctly assess the problem, a deep study on the state of the art of power systems in the military was conducted in chapter 2, presenting standard equipment and current programs on the matter. In addition, to build a cornerstone for this project, it was assembled a theoretical basis for wireless power transfer, which included regulations, physics overview, standard protocols, and safety considerations. A complete guide of equipment that was used, and that was developed, during this dissertation is also compiled in chapter 3.

In Chapter 4, a series of related works on coil geometry and its influence on power transfer was presented. This was followed by theoretical deductions with the aim of understanding the weight of the coupling coefficient on the power transfer, as well as how distance variation alters this parameter.

The main contribution of this collection of studies and deductions was the development of a theoretical foundation that helped to guide the advances of the practical work, as well as reinforce its results.

The practical experiments, that are presented in chapter 5, on the influence of distance variation on the emitted magnetic field, came as the biggest contributor to this dissertation. By comparing the results of signal amplitude variation with distance, as the main variable parameter, on three distinct shaped sets of coils, each with a different radius and format, it was possible to develop an optimized coil design for the charging environment in question.

Moreover, the results from the experiments on the behavior of the power transfer when exposed to different configurations, such as the variation of the load resistance of the RX module, and the impact of internal or external factors, such as the presence of magnets, made it possible to assemble a concise and

practical view on the best course of action in terms of overall system design.

In chapter 6, a culmination of the results of this work is presented in the form of a proposal for the wireless charging system. This proposal comprises all the requirements that must be met, considering the characteristics of the charging environment and its needs, the system's architecture, communications protocol, and implementation.

As a consequence of the research and results that were conducted during the course of this dissertation, it was possible to assemble a concise and practical study on wireless charging systems. The optimized coil design, which was developed and presented as the proposed implementation, showed promising results in terms of the distribution and reach of the radiation pattern of the magnetic field produced by the power transfer, which can be used as the basis for future research and implementations.

7.1 Achievements

The present dissertation led to the design, and implementation of a wireless charging system. The analysis and understanding of the limitations and possibilities of wireless charging were made possible by testing different configurations of this system.

The chosen coil design, which has the objective of efficiently powering the DSI-104 - Data and Power Hub, was developed by taking into account its charging environment, dimensions, and capabilities. A series of studies were considered, which were used as references for the final coil design.

By conducting a series of theoretical deductions and experimental works, which were used to assess a variety of coil designs and of parameters such as the coupling coefficient and the load resistance of the receiver coil, it was possible to assemble the best-suited dimensions and geometry of the coil, as well as find the optimized values for the tested parameters, which then served as a guideline for the final product proposal that is presented in this dissertation.

The results on signal amplitude with distance as the main variable parameter proved that the chosen coil dimensions and geometry had the best results in terms of maintaining signal strength and distribution, maintaining above 80 % of maximum signal amplitude at around 2 cm of vertical distance variation, while the other coils had a maximum of 40 and 20 % of maximum signal amplitude, respectively for the conical and flat oval coil, at around the same distance.

The study on wireless power system architectures and communication protocols also contributed to elaborating a proposal for a future implementation of this system.

7.2 Future Work

During the course of this dissertation, the primary goal of studying, developing, and testing a wireless charging system was accomplished even though some alterations had to be done, mostly due to equipment limitations. Some of the possible future iterations of this work are presented below:

- Evaluation of the different coil geometries using a more precise method of measuring the pattern of the emitted magnetic field by the power transfer;

- Development and study of a wireless charging module that is compatible with the proposed coil design and its specifications;
- Development of a communication protocol and a setup and monitoring system, for a wireless charging system, taking into account the security needs of military operations;
- Development and field testing of a functional prototype of the wireless charging system;
- Study the benefits and limitations of using wireless charging in the military.

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Appendix A

Tables

	$L(\mu\text{H})$	Q	$L_s(\mu\text{H})$
TX_{flat}	4.04	55.89	2.47
RX_{flat}	7.86	17.73	2.47
TX_{con}	4.36	14.59	2.98
RX_{con}	6.92	17.98	2.98
TX_{con_opt}	20.21	44.66	10.72
RX_{con_opt}	17.07	39.81	10.72
TX_{rect}	4.24	10.34	3.48
RX_{rect}	7.68	13.21	3.48
TX_{rect_opt}	68.56	40.69	43.71
RX_{rect_opt}	27.53	57.34	43.71

Table A.1: Measurements of L , Q and L_s .

	$R_{p1}(\Omega)$	$R_{p2}(\Omega)$	M(μH)	k	$R_{L_opt}(\Omega)$	Z_{ref}	η
TX_{flat} and RX_{flat}	0.08	0.47	3.52E-06	0.62	9.25	1.43	90.3 %
TX_{con} and RX_{con}	0.32	0.41	3.10E-06	0.56	3.76	2.60	80.4 %
TX_{con_opt} and RX_{con_opt}	0.48	0.46	1.27E-05	0.69	13.16	13.40	93.3 %
TX_{rect} and RX_{rect}	0.59	1.02	2.41E-06	0.42	3.52	1.59	56.5 %
TX_{rect_opt} and RX_{rect_opt}	4.86	2.93	2.62E-05	0.60	21.75	34.65	77.3 %

Table A.2: Measuring Efficiency using the experimental Coupling Coefficients.

distance(cm)	M(μ H)	k	$R_{L_{opt}}(\Omega)$	Z_{ref}	η
0	5.63E-06	1.00	14.82	2.341	93.8 %
0.5	5.09E-06	0.91	13.41	1.918	93.2 %
1	3.91E-06	0.70	10.30	1.130	90.8 %
1.5	2.74E-06	0.49	7.21	0.552	85.1 %
2	1.85E-06	0.33	4.89	0.253	74.4 %
2.5	1.26E-06	0.22	3.34	0.117	58.4 %
3	8.70E-07	0.15	2.34	0.056	40.8 %
3.5	6.17E-07	0.11	1.69	0.028	26.0 %
4	4.49E-07	0.08	1.27	0.015	15.7 %
4.5	3.35E-07	0.06	1.00	0.008	9.4 %
5	2.55E-07	0.05	0.82	0.005	5.7 %
5.5	1.98E-07	0.04	0.70	0.003	3.5 %
6	1.57E-07	0.03	0.63	0.002	2.2 %

Table A.3: Variation of peak to peak amplitude with horizontal distance using flat oval coils.

distance(cm)	M(μ H)	k	$R_{L_{opt}}(\Omega)$	Z_{ref}	η
0	5.50E-06	1.00	6.64	4.835	88.4 %
0.5	4.61E-06	0.84	5.57	4.005	86.3 %
1	2.99E-06	0.55	3.63	2.501	79.7 %
1.5	1.78E-06	0.32	2.18	1.374	68.4 %
2	1.06E-06	0.19	1.34	0.723	53.2 %
2.5	6.57E-07	0.12	0.89	0.374	37.1 %
3	4.27E-07	0.08	0.66	0.192	23.3 %
3.5	2.89E-07	0.05	0.54	0.100	13.6 %
4	2.04E-07	0.04	0.48	0.053	7.7 %
4.5	1.48E-07	0.03	0.45	0.029	4.4 %
5	1.11E-07	0.02	0.43	0.017	2.5 %
5.5	8.50E-08	0.02	0.42	0.010	1.5 %
6	6.64E-08	0.01	0.42	0.006	0.9 %

Table A.4: Variation of peak to peak amplitude with horizontal distance using a conical coils.

distance(cm)	M(μ H)	k	$R_{L_{opt}}(\Omega)$	Z_{ref}	η
0	1.86E-05	1.00	19.20	19.78	95.4 %
0.5	1.64E-05	0.88	16.92	17.37	94.8 %
1	1.18E-05	0.64	12.21	12.40	92.8 %
1.5	7.73E-06	0.42	8.00	7.97	89.2 %
2	4.96E-06	0.27	5.15	4.95	83.7 %
2.5	3.24E-06	0.17	3.38	3.08	76.2 %
3	2.18E-06	0.12	2.30	1.94	66.9 %
3.5	1.51E-06	0.08	1.63	1.24	56.3 %
4	1.08E-06	0.06	1.21	0.80	45.3 %
4.5	7.99E-07	0.04	0.94	0.52	34.9 %
5	6.04E-07	0.03	0.77	0.34	25.8 %
5.5	4.658E-07	0.03	0.66	0.22	18.5 %
6	3.66E-07	0.02	0.59	0.14	13.1 %

Table A.5: Variation of peak to peak amplitude with horizontal distance using a conical coil.

distance(cm)	M(μ H)	k	$R_{L_opt}(\Omega)$	Z_{ref}	η
0	5.71E-06	1.00	8.03	4.24	77.9 %
0.5	5.61E-06	0.98	7.90	4.17	77.6 %
1	5.34E-06	0.94	7.53	3.95	76.6 %
1.5	4.94E-06	0.87	6.97	3.62	75.0 %
2	4.45E-06	0.78	6.30	3.23	72.8 %
2.5	3.94E-06	0.69	5.59	2.81	69.9 %
3	3.43E-06	0.60	4.89	2.40	66.4 %
3.5	2.95E-06	0.52	4.25	2.02	62.4 %
4	2.53E-06	0.44	3.68	1.68	57.9 %
4.5	2.16E-06	0.38	3.19	1.38	53.1 %
5	1.84E-06	0.32	2.77	1.13	48.0 %
5.5	1.57E-06	0.28	2.42	0.92	42.8 %
6	1.35E-06	0.24	2.14	0.74	37.7 %

Table A.6: Variation of peak to peak amplitude with horizontal distance using a conical coil.

distance(cm)	M(μ H)	k	$R_{L_opt}(\Omega)$	Z_{ref}	η
0	4.35E-05	1.00	35.92	58.43	92.3 %
0.5	4.27E-05	0.98	35.33	57.44	92.2 %
1	4.07E-05	0.94	33.64	54.62	91.8 %
1.5	3.76E-05	0.87	31.12	50.40	91.2 %
2	3.39E-05	0.78	28.09	45.32	90.3 %
2.5	3.00E-05	0.69	24.87	39.90	89.1 %
3	2.61E-05	0.60	21.70	34.58	87.7 %
3.5	2.25E-05	0.52	18.77	29.61	85.9 %
4	1.93E-05	0.44	16.15	25.14	83.8 %
4.5	1.65E-05	0.38	13.87	21.23	81.4 %
5	1.40E-05	0.32	11.93	17.86	78.6 %
5.5	1.20E-05	0.28	10.30	14.98	75.5 %
6	1.03E-05	0.24	8.94	12.54	72.1 %

Table A.7: Variation of peak to peak amplitude with horizontal distance using a conical coil.

$R_L (\Omega)$	$I_{Tx} (mA)$	$I_{Rx} (mA)$	$V_{Rx} (V)$	$P_{Rx} (W)$	$P_{Tx} (W)$	Efficiency (η)
3.51	1000	1390	4.88	6.78	12.00	56.5 %
3.61	970	1350	4.88	6.59	11.64	56.6 %
4.07	840	1200	4.88	5.86	10.08	58.1 %
4.52	750	1080	4.88	5.27	9.00	58.6 %
5.42	620	900	4.88	4.39	7.44	59.0 %
6.42	515	760	4.88	3.71	6.18	60.0 %
7.63	435	640	4.88	3.12	5.22	59.8 %
8.87	370	550	4.88	2.68	4.44	60.5 %
10.61	315	460	4.88	2.24	3.78	59.4 %
12.84	270	380	4.88	1.85	3.24	57.2 %
15.74	230	310	4.88	1.51	2.76	54.8 %
20.33	185	240	4.88	1.17	2.22	52.8 %
24.40	160	200	4.88	0.98	1.92	50.8 %
28.71	140	170	4.88	0.83	1.68	49.4 %
32.53	130	150	4.88	0.73	1.56	46.9 %
34.86	125	140	4.88	0.68	1.50	45.6 %
40.67	120	120	4.88	0.59	1.44	40.7 %

Table A.8: Efficiency and Receiver's power variation with different Rheostat using flat oval coils.

$R_L (\Omega)$	$I_{Rx} (mA)$	$V_{Rx} (V)$	$P_{Rx} (W)$	$P_{Tx} (W)$	$Efficiency (\eta)$
2.00	1425	2.85	4.06	5.00	81.2 %
2.45	1325	3.24	4.29	5.00	85.9 %
2.82	1250	3.52	4.40	5.00	88.0 %
3.53	1125	3.97	4.47	5.00	89.3 %
4.80	950	4.56	4.33	5.00	86.6 %
5.85	825	4.83	3.98	5.00	79.7 %
7.24	675	4.89	3.30	5.00	66.0 %
9.31	525	4.89	2.57	5.00	51.3 %
11.84	425	5.03	2.14	5.00	42.8 %
12.53	400	5.01	2.00	5.00	40.1 %
13.36	375	5.01	1.88	5.00	37.6 %
15.38	325	5	1.63	5.00	32.5 %
18.02	277.5	5	1.39	5.00	27.8 %
21.70	230	4.99	1.15	5.00	23.0 %
26.97	185	4.99	0.92	5.00	18.5 %
31.13	160	4.98	0.80	5.00	15.9 %
35.56	137.5	4.89	0.67	5.00	13.4 %
39.84	125	4.98	0.62	5.00	12.5 %
40.65	122.5	4.98	0.61	5.00	12.2 %
43.22	115	4.97	0.57	5.00	11.4 %

Table A.9: Efficiency and Receiver's power variation with different Rheostat using Conical Coils.

$R_L (\Omega)$	$I_{Rx} (mA)$	$V_{Rx} (V)$	$P_{Rx} (W)$	$P_{Tx} (W)$	$Efficiency (\eta)$
1.84	1450	2.67	3.87	5.00	77.4 %
2.38	1325	3.15	4.17	5.00	83.5 %
3.42	1125	3.85	4.33	5.00	86.6 %
4.62	950	4.39	4.17	5.00	83.4 %
4.86	910	4.42	4.02	5.00	80.4 %
5.35	850.1	4.55	3.87	5.00	77.4 %
6.49	750	4.87	3.65	5.00	73.1 %
6.93	700.9	4.86	3.41	5.00	68.1 %
8.83	550.5	4.86	2.68	5.00	53.5 %
10.98	440.9	4.84	2.13	5.00	42.7 %
12.41	390.8	4.85	1.90	5.00	37.9 %
14.21	335	4.76	1.59	5.00	31.9 %
16.46	295.2	4.86	1.43	5.00	28.7 %
17.31	280.2	4.85	1.36	5.00	27.2 %
20.25	240	4.86	1.17	5.00	23.3 %
27.06	180	4.87	0.88	5.00	17.5 %
31.32	155.5	4.87	0.76	5.00	15.2 %
37.51	130.1	4.88	0.63	5.00	12.7 %
42.61	115.7	4.93	0.57	5.00	11.4 %

Table A.10: Efficiency and Receiver's power variation with different Rheostat using Rectangular Coils.

Distance to Rx Coil (cm)	Amplitude (mV)
0	24000
0.5	12400
1	8800
1.5	6800
2	4800
2.5	4000
3	3600
3.5	2000
4	2000
4.5	2000
5	1600
5.5	1600
6	1200

Table A.11: Variation of peak to peak amplitude with vertical distance.

Distance to Rx (cm)	Amplitude (mV)
0	9200
0.5	9200
1	8800
1.5	8400
2	8000
2.5	7600
3	6400
3.5	4800
4	3200
4.5	1600
5	1600
5.5	1600
6	1600

Table A.12: Variation of peak to peak amplitude with horizontal distance.

Distance to Rx Coil (cm)	Amplitude (mV)
0	21800
0.5	8400
1	4400
1.5	3200
2	2400
2.5	2000
3	1400
3.5	1200
4	1000
4.5	800
5	600
5.5	600
6	400

Table A.13: Variation of peak to peak amplitude with vertical distance using an oval coil.

Distance to Rx (cm)	Amplitude (mV)
0	17200
0.5	15600
1	13600
1.5	9400
2	7000
2.5	3400
3	3000
3.5	2600
4	1800
4.5	1200
5	1000
5.5	800
6	600

Table A.14: Variation of peak to peak amplitude with horizontal distance using an oval coil.

Distance to Rx (cm)	Amplitude (mV)
0	4200
0.5	2800
1	2020
1.5	1460
2	1120
2.5	820
3	700
3.5	540
4	400
4.5	340
5	280
5.5	240
6	200

Table A.15: Variation of peak to peak amplitude with vertical distance using a conical coil.

Distance to Rx (cm)	Amplitude (mV)
0	3460
0.5	3240
1	2680
1.5	2060
2	1260
2.5	780
3	380
3.5	200
4	180
4.5	200
5	200
5.5	180
6	180

Table A.16: Variation of peak to peak amplitude with horizontal distance using a conical coil.

Distance to Rx (cm)	Amplitude (mV)
0	2440
0.5	2480
1	2440
1.5	2360
2	2160
2.5	2040
3	1920
3.5	1800
4	1600
4.5	1440
5	1280
5.5	1120
6	960

Table A.17: Variation of peak to peak amplitude with vertical distance using a rectangular coil.

Distance to Rx (cm)	Amplitude (mV)
0	2120
0.5	2120
1	2160
1.5	2180
2	2240
2.5	2280
3	2320
3.5	2320
4	2240
4.5	1840
5	1640
5.5	1400
6	960

Table A.18: Variation of peak to peak amplitude with horizontal distance using a rectangular coil.