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Underwater communications based on resonant inductive links

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Resumo

Em anos mais recentes, os veículos não tripulados têm sofrido um avanço considerável no seu desenvolvimento. Devido ao subsequente aumento de interesse na exploração do oceano, em especial zonas de condições extremas cujo acesso está impossibilitado. Em concreto, nas aplicações subaquáticas, existem problemas substanciais relativos ao carregamento de forma *wireless* dos aparelhos, mais especificamente, à monitorização deste processo, assim como, na transferência dos dados recolhidos. Esta dissertação apresenta uma solução para o controlo de parâmetros associados ao carregamento *wireless*, reaproveitando o acoplamento indutivo ressonante para, além da transferência de potência já implementada, transmitir dados. Denote-se que o estudo e implementação foram desenvolvidos num sistema com um comutador de alta tensão, optimizado para uma resistência de carga igual a $12.5\ \Omega$, uma frequência de ressonância de 240 kHz para uma transferência de potência na ordem dos 80 W com uma eficiência máxima no acoplamento de 94%. O trabalho desenvolvido explora um patamar substancial de corrente disponível, desde 0.5 A a 2.5 A com um conjunto de resistências entre $1\ \Omega$ a $11\ \Omega$. Com estes valores é possível determinar diferentes estados que, por sua vez, permitem uma comunicação *wireless* com um grande alcance dinâmico. A eficiência geral do acoplamento não sofre uma grande alteração para os diferentes estados necessários para o envio de informação. Sabendo que o teor de sal afeta diretamente o acoplamento e, conseqüentemente, os níveis de corrente do sistema, e ainda que os valores de salinidade do mar variam de região para região, é possível regular esta variação mudando o valor da resistência responsável pela modulação da carga, reforçando a modularidade do sistema. Este desenvolvimento apresenta uma solução simples e viável, apresentando-se como uma forte alternativa ao uso de circuitos externos adicionais.

Abstract

During more recent years there has been a considerable advancement in unmanned vehicles, more so in autonomous underwater vehicles, following the increasing interest in exploring unreachable parts of the ocean. Underwater autonomous work poses substantial obstacles when it comes to wirelessly charging the devices and most importantly to the monitoring of such operation, as well as the transfer of the data gathered. This thesis presents a solution for overseeing the parameters that come with the wireless charging of a system, repurposing the resonant inductive link to transmit bits of data in addition to the power transfer already in place. Furthermore, the work was developed on system designed with a high-voltage switching power driver, optimized for load resistance equal to $12.5\ \Omega$, having a resonance frequency of 240 kHz for a power transfer in the order of 80 W with a link efficiency up to 94%. The present work explores the substantial difference in current available at the primary coil, from 0.5 A to 2.5 A with a variation of resistance from $1\ \Omega$ to $11\ \Omega$ seen at the secondary coil. This allows for a detection of different states which provide a wireless communication with a wide dynamic range. The overall efficiency of the link is not greatly affected by the different states necessary to transmit information. Knowing that the salinity value of the sea differs from region to region and in turn, both the levels of current and, subsequently the difference between them, are affected, it is possible to regulate the value of the resistance responsible for the load modulation to atone such difference, which makes for a system with a high level of modularity. This presents a simple and viable solution that is a clear alternative to the need of additional aftermarket circuits to monitor and assist the charging of devices underwater.

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Ricardo Magno

*“We cannot solve our problems with the same thinking
we used when we created them.”*

Albert Einstein

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Acronyms

A4WP	Alliance for Wireless Power
ASK	Amplitude-Shift Keying
BASK	Binary Amplitude-Shift Keying
MASK	Multilevel Amplitude-Shift Keying
BPSK	Bipolar Phase-Shift Keying
IC	Inductive Coupling
ID&C	Identification and Configuration Phase
IEEE	Institute of Electrical and Electronics Engineers
LSK	Load-Shift Keying
PT	Power Transfer
PTU	Power Receiving Unit
PRU	Power Transmitter Unit
PWM	Pulse Width Modulation
Q	Quality Factor
QAM	Quadrature Amplitude Modulation
RIC	Resonant Inductive Coupling
WPT	Wireless Power Transfer
FSK	Frequency-Shift Keying
BFSK	Binary Frequency-Shift Keying
OFDM	Orthogonal Frequency-Division Multiplexing
SPI	Serial Peripheral Interface
PCB	Printed Circuit Board
I2C	Inter-Integrated Circuit
GPIO	General-Purpose Input/Output
RTOS	Real-Time Operating System

Chapter 1

Introduction

The first experiments regarding Wireless Power Transfer were performed by Nicola Tesla in the early 20th century. Since then multiple applications for this type of power transfer were developed, especially in the area of autonomous electronic devices [1, 2, 3, 4].

1.1 Context

More recently, over the years, wireless power transfer has been evolving, finding diverse applications and common uses, such as battery charging of smartphones, medical implants [5], autonomous aerial vehicles and autonomous underwater vehicles [6, 7]. These represent some of the possible scenarios where wireless power transfer can simplify and is revolutionizing the way we interact with the world [8].

Specifically, charging autonomous underwater vehicles, in deep sea water, as seen in figure 1.1, has been increasingly on demand and receiving greater attention in research activities, since it reduces the need of human intervention for plugging in and out electrical connectors in the docking station. Working underwater, however, poses significant problems when working with electronic circuits and performing a transfer of power in seawater. For one, the conditions of the water, such as temperature, salinity and pressure, change, not only from place to place, but even in a matter of hours on the same spot, which gravely affects the link stability. One of the main factors that define the success of missions, such as, ocean and rivers monitoring and ocean floor mapping for mineral exploration, is the vehicle extended operation time. For that reason, several works have been addressing the development of a complete system, from the base station in the device to the docking station, which intend to power such unmanned devices.

However, when it comes to the power receiver side, the scenario is different, that is, in order to regulate the power or voltage of the receiver, the transmitter must track the power at the load side, but such information is not readily available. In addition to this, the regulation voltage on the receiver side can be of beneficial use, in a situation where we pretend to adjust a specific charge rate to a connected battery.

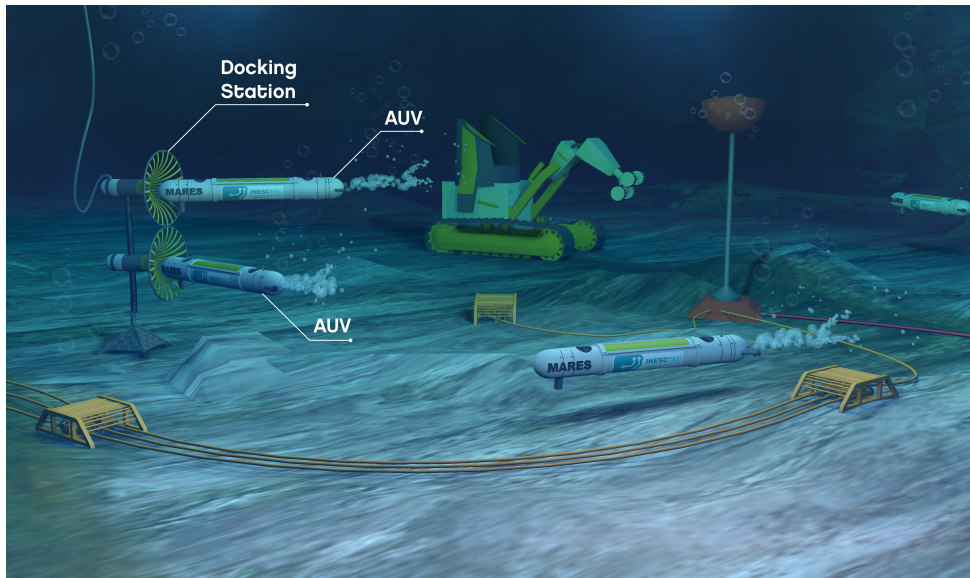


Figure 1.1: Endure System Overview [9]

1.2 Motivation

There are already some works about the Rx voltage regulation, but generally require additional communication links and none of which tested underwater. Under such circumstances, the overall system cost and complexity will increase.

Since the main target for this work will be the autonomous underwater vehicles, the main factors to be considered, when working on the Rx voltage regulation, are the weight, space occupied, temperature, complexity and cost of the system.

The first motivation, in this case, is to reuse different parts of the system, already implemented, such as the power link, to prevent the extra costs and increased complexity that result from using addition communication links and the second one is to develop such a system that works in underwater scenarios. The last motivation is to have a unique and simple communication link for different types of scenarios, vehicle to vehicle, vehicle to docking station and vehicle to sensors.

1.3 Objectives

The objectives of this dissertation are presented next. The main goal is to have a robust communication channel that can be useful in giving quick feedback between the docking station and the vehicle or exchange critical information about the parameters of the link.

- Develop a study of a communication protocol - over a data communication with low data rates.
- Use the power link to transmit data in a robust way.

- Design the Tx side of the protocol to transmit data.
- Design the Rx side of the protocol to transmit data.
- Transmit basic types of information of the system, e.g. battery capacity and power link parameters. Suitable for underwater scenarios.
- Have a suitable communication for underwater for long distances, with a data rate of 100 bits per second.

1.4 Document Outline

In the first part of this dissertation, a study on the state of the art is performed. In this a study of the wireless charging standards for a power transfer over air, including Qi and A4WP, is made, accompanied by an overlook of the communication protocols these standards use. Following suit is the study of different types of signal modulations currently being performed and that are suitable for implementation in the system this dissertation focus on.

The second part focus on the work performed while studying the link used in the underwater power transfer, which shall be used for data transmission. Two solutions on how to send bits from one side to the other emerged, them being a capacitive type of commutation and a resistive type. It is important to understand what the best option is available, so there a careful analysis was performed on how both systems would theoretically behave.

The final part delves more in the transmitter and receiver side, both the hardware and software layers. A study of the hardware is made, since most of it already existed, while the software layer was built around the requisites of the hardware and the project in general. With this, came the final implementation of the data transmission and study on different types of modulation achievable in the system, regarding efficiency, levels of current and how stable the communication can be.

Chapter 2

Background

In this chapter, we will start by explaining what Wireless Power Transfer (WPT) stands for and what the current standards of it are and then present different techniques for data transmission in wireless powering links and communication protocols already implemented in power standards. This thesis focus is on the transmission of data between transmitting and receiving power devices, as well as, the control layer of the data link.

2.1 Underwater Wireless Power Transfer

WPT makes it possible to transfer power through an air gap, without the need of physical connectors or wires [10].

In order to carry energy from a transmitter to a receiver over a air gap, the WPT uses fields, such as an electric field, a magnetic field or electromagnetic waves, which are created by charged particles.

There are different types of wireless power technologies as shown in Table 2.1.

Table 2.1: Wireless power technologies

<i>Technology</i>	<i>Range</i>	<i>Frequency</i>	<i>Antenna</i>	<i>EnergyTransfer</i>
Inductive Coupling	Short	Hz - MHz	Wire Coils	Magnetic Fields
Resonant Inductive Coupling	Mid	kHz - GHz	Resonant Circuits	Magnetic Fields
Capacitive Coupling	Short	kHz - MHz	Conductive Coupling	Electric Fields
Magnetodynamic Coupling	Short	Hz	Rotating Magnets	Magnetic Fields
Microwaves	Long	GHz	Parabolic dishes	Microwaves
Optical Radiation	Long	THz	Lasers	Light

The type of technology focused on this thesis is of resonant inductive coupling type [11, 12, 13, 14].

2.1.1 Inductive Coupling

Inductive coupling or Inductive Power Transfer (IPT) is a technology based on Ampere's law and Faraday's law of induction.

Coils of wire are used to transfer power by a magnetic field. An alternate current in one of the coils creates an oscillating magnetic field, which in turn, when passed through the second coil, creates an alternating current, as seen in figure 2.1.

The current uses include charging in wet environments and transcutaneous recharging of biomedical implants.

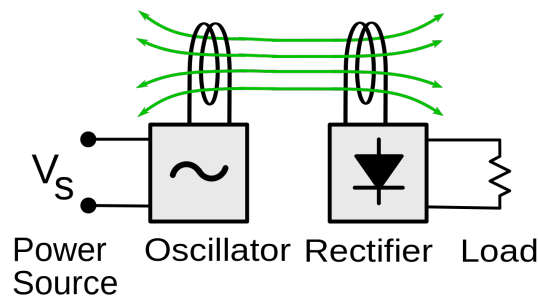


Figure 2.1: Diagram of the most basic IC system

2.1.2 Resonant Inductive Coupling

Resonant Inductive Coupling (RIC) is the phenomenon achieved when the receiver side of the coupled coil resonates, enhancing the coupling.

The most basic system, as seen in figure 2.2 is comprised of a driving coil in the transmitter side and a resonance circuit on the transmitter side.

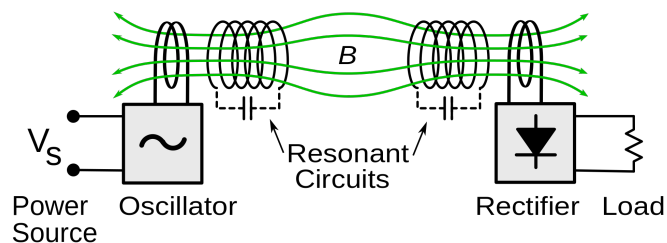


Figure 2.2: Diagram of the most basic RIC system

2.1.3 Capacitive Coupling

Capacitive Coupling is one type of power transfer based on energy being transferred by electric fields.

Both transmitter and receiver are equipped with metal plates, as seen in figure 2.3 in order to form a capacitor, in which, the gap between plates acts as a dielectric.

Alternating voltage is applied to the transmitting plate and the oscillating electric field creates, by means of electrostatic induction, an alternating potential that in the load circuit, on the side of the receiver, is responsible for the flow of an alternating current.

One of the main possibilities for this type is for an area of wireless power coverage.

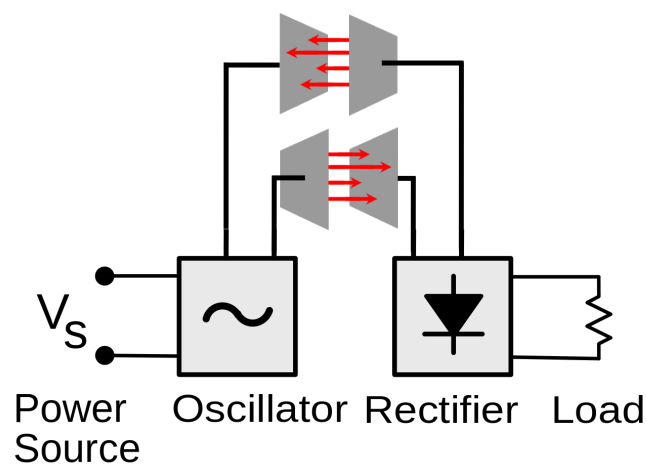


Figure 2.3: Diagram of the most basic CC system

2.1.4 Magnetodynamic Coupling

A model based in two rotating armatures, which rotate synchronously, coupled together by a magnetic field.

If any physical alteration of one of the armatures occurs, the magnetic field exerts torque on the other armature.

This type of power transfer is being tested in harsh environments that need a fairly big gap between stations, to charge unmanned devices and vehicles.

2.1.5 Microwaves

A technology based on the use of shorter wavelengths of electromagnetic radiation and a rectenna to convert microwave energy into electricity.

This solution allows for a longer-distance power beam.

It is a proven concept that it is now being used in conjunction with Wi-Fi to power small cameras and smartphones.

2.1.6 Optical Radiation

Power can also be transmitted by converting electricity into a laser beam aimed at a photovoltaic cell, responsible for converting the laser power.

Currently being tested for space and lunar missions.

2.1.7 Underwater Wireless Power Transfer

Regarding the WPT in an underwater type of scenario, there are a few extra conditions to be considered, such as the salinity of the environment, which is does not have a constant value, the power link degradation over time, which needs constant feedback in order to be stable and the use of nonperfect coils.

2.2 Qi Wireless Power Standard

The Qi wireless power standard was created by the Wireless Power Consortium (WPC) in order to develop an industry standard to achieve interoperability between products using the Qi standard.

Initial decisions regarding this standard, such as the sizing and distance of the coils, had as basis the efficiency of the power transfer, which depends on the coupling between inductors and their quality. The coupling depends both on the distance between the inductors as well as the relative size of the coils. The quality factor, 2.1 depends both on the frequency applied, inductance value and the coil resistance [15].

$$Q = \frac{\omega L}{R} \quad (2.1)$$

When calculating the optimal achievable efficiency of a system with the assumption of a quality factor of 100 in [15], it was observed that the inductive power transfer between coils in proximity are efficient and competitive to wired solutions.

The following system overview and, consequently, coil alignment and communication and control layer are based on the articles [15, 16]. The Qi wireless power system comprises of a charging or base station, containing one or more power transmitters, and one mobile unit, containing a power receiver.

The interface is defined between a transmitter and a receiver and, as seen in figure 2.4 has two basic layers, **power transfer layer** and **communication and control layer** [15].

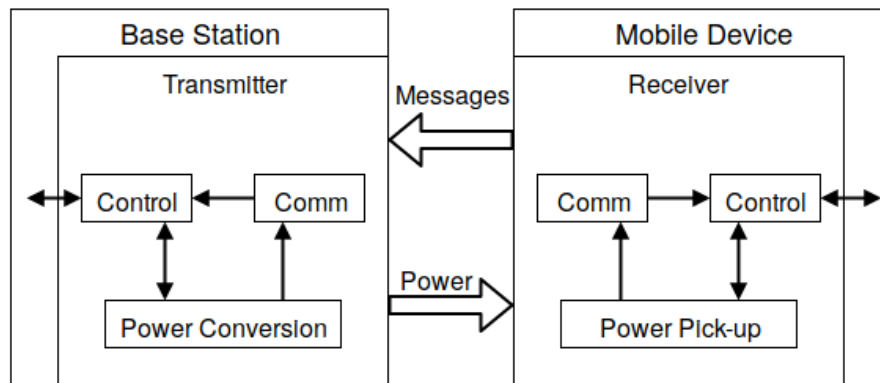


Figure 2.4: System overview of the Qi standard

2.2.1 Power Transfer Layer

In this layer, the transmitter is responsible for providing power to the receiver through magnetic induction. It is also in this layer that the power transfer facilities of both the transmitter and receiver are integrated, as well as the coil alignment of both parties.

2.2.1.1 Coil alignment

Coil alignment, in combination with the same size coils in the receiver and transmitter, close to one another, is of vital importance to achieve a good coupling. Optimal alignment with such restrictions is achieved when both the primary and secondary coils centers are at the same position.

In order to achieve good alignment within the standard, the Qi specification contains 3 basic transmitters types, each one representing a different technique.

- **Guided Positioning** – In this technique the receiver gives feedback regarding the alignment of both coils and acknowledges when a good alignment is achieved. The specification provided an example transmitter on how to implement this technique, which was, using a magnet placed at center of the transmitter coil and a magnetic attractor, the user can be guided through the attraction force between the transmitter and receiver.
- **Free positioning – moving coil** – In this technique, the transmitter is capable of locating the receiver's location and free to move the primary coil to that location. Although, through fine tuning, achieving optimal coupling is possible, accurate alignment of the primary coil requires a specific mechanical implementation.
- **Free positioning – coil matrix** – In this technique, the transmitter is comprised of a matrix of primary coils. Free positioning is achieved by activating and transferring power through the set of three overlapped primary coils closest to the receiver location.

One clear disadvantage when compared with the other two techniques mentioned is the necessity of using more than one primary coil, which can elevate the total cost.

2.2.1.2 Power transfer facilities of transmitter

Both types of positioning presented differ on certain parameters regarding how the coils are powered, but the values for the inductor and resonance capacitors, yet different, are fixed for both the guided positioning and free positioning.

Starting of with guided positioning, figure 2.5, the input voltage is fixed and the frequency is variable. For this type of positioning, a half bridge inverter is used to provide power to the primary coil.

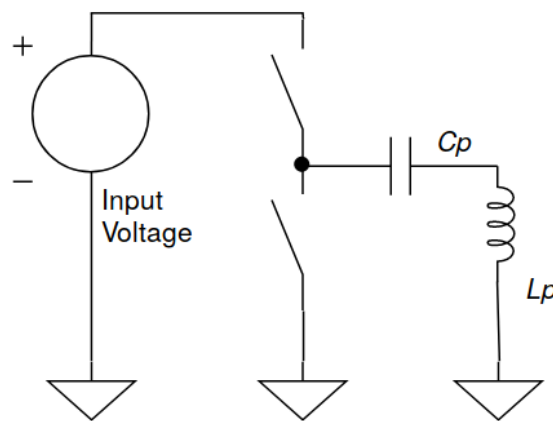


Figure 2.5: Example circuit for guided positioning

The free positioning has a variable input voltage, while the frequency is fixed. In figure figure 2.6, for a moving coil type, a full bridge inverter is used to power the primary coil. For a matrix of coils, a half bridge inverter is used, coupled with a multiplexer for determining which coils will be powered, in parallel, by the inverter.

2.2.1.3 Power transfer facilities of receiver

The design for the receiving part of the power link is free apart from some minor restrictions, including some major requirements for resonance. An example of a dual resonance circuit is provided in figure 2.7.

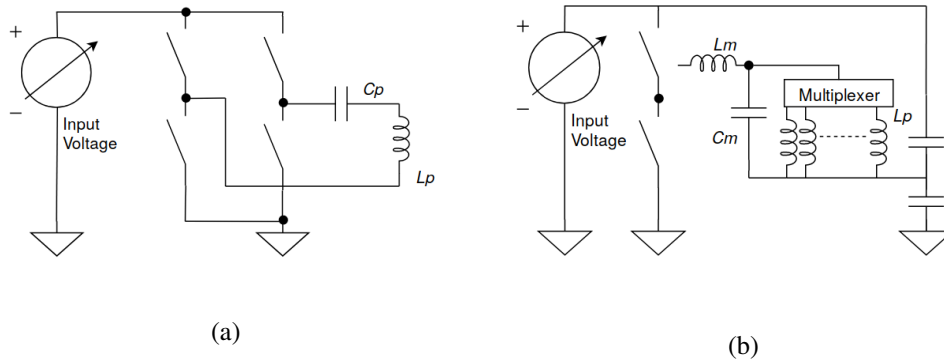


Figure 2.6: Example circuit for free positioning with a matrix, Example circuit for free positioning with a moving coil

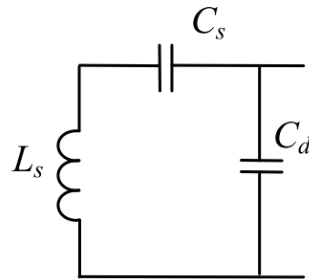


Figure 2.7: Dual resonance circuit

The serial resonance capacitor is used to limit the reactance of the receiver circuit. This brings a limit to the required current in the primary coil and, as a consequence, a reduced system power loss and an improvement to the power transfer efficiency.

The parallel resonant capacitor is useful for the transmitter to detect the presence of a receiver. This is done by exiting a power signal with an equal frequency of the parallel resonance of the circuit, which in turn makes the receiver store some energy. The transmitter then stops the power signal and measures the reflected power signal, stemming from the receiver.

2.2.2 Communication and Control Layer

Regarding the communication between the transmitter and the receiver, since the latter is the one requesting a power service from the former, the receiver is the one in control of initializing the communication system and maintaining the parameters of the power link.

The way a receiver communicates is by means of load modulation. A simple way of achieving the modulation is by switching a small capacitive load between the secondary coil and the rectifier.

2.2.2.1 Data Formatting

Packet format is composed of a pre-amble for bit synchronization, a header for transmitting the type of message, the message data and a checksum to verify the integrity of the data.

Each byte has a start bit, 8-bit data, a parity bit for integrity of the data and a stop bit.

2.2.2.2 System control

The system control has four different phases, as seen in figure 2.8.

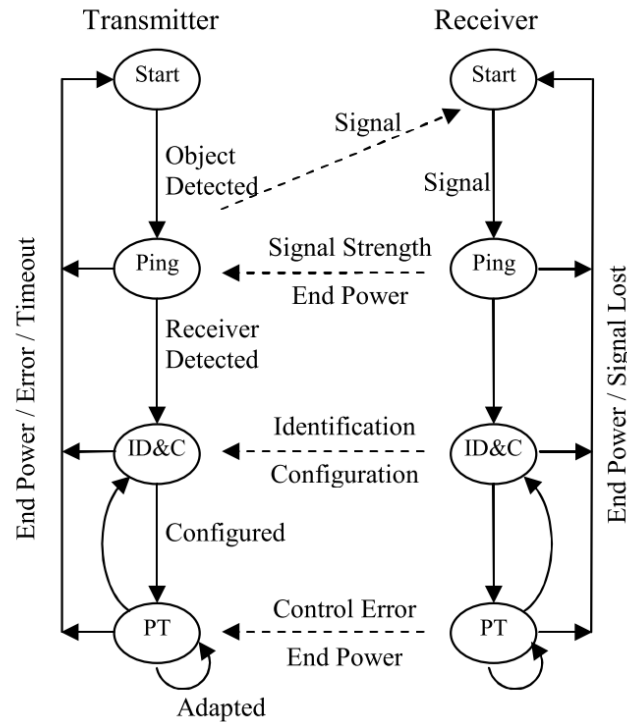


Figure 2.8: System control phases, extracted from [15]

- **Start phase** – The transmitter scans the environment for objects and their location and if an object is found, it proceeds for the next phase.
- **Ping phase** – In this phase the transmitter tries to establish communication with the object. If the object is indeed a receiver in need of power, it answers with the strength of the signal, otherwise, in the case of not needing power, sends a End Power message. After this exchange, the transmitter either passes to the next phase or stops the power signal.
- **ID&C – Identification and configuration phase** – The receiver provides system information in order to prepare the transmitter. At the end of this phase, after the transmitter is aware of all the information necessary to establish the power transfer, it has the right to either accept or refuse to transfer power.

- **Power Transfer phase** – Charging of the receiver. During this phase the receiver has the ability to change the power signal properties, sending "control error" messages with the desired properties, therefore having some control of the transmitter.

2.3 A4WP Wireless Power Standard

The A4WP Wireless Power Standard was developed by the Alliance for Wireless Power. The objective was to generate a larger electromagnetic field with magnetic resonance coupling. The brief description that follows is based on the articles [16, 17].

This standard has multiple benefits, such as the precise alignment of coils not being a requirement, as well as, allowing separation, on a scale of several meters, between the charger and the charging devices. Another benefit is that multiple devices can be charged at the same time and that foreign objects can be placed on a charger without interfering with the wireless charging.

The basic architecture type is one of a star topology network, in which one power transmitting unit can interact with one or more power receiving unit.

A4WP assumes two components, a Power Transmitter Unit (PTU), comprised of a power supply, a control processor, a power amplifier matching circuit and a power transmitting resonator, and a Power Receiving Unit (PRU), comprised of a power receiving resonator, a rectifier, regulator and control processor. Wireless Power is controlled by a charging management protocol, where feedback signaling from PRU to PTU helps control the charging.

Session Management States

- **PTU**
 - Configuration State - PTU power on and self-check
 - Power Save State - PTU performs several operations for load detection
 - Low Power State - Establishes a data link
 - PTU Power Transfer State - Power transfer and control of some internal and external conditions of the power transfer
- **PRU**
 - PRU Null State - Check if a certain level of power is received
 - PRU Boot - Establishes a data link for the management protocol
 - PRU On - Power transfer
 - System Error State - Additional states for controlling the power transfer

The communication protocol is composed of three steps, shown in figure 2.9, and capable of supporting wireless charging functionality. It adopts a Bluetooth Low Energy (BLE) link for the control of power levels, identification of valid loads and protection of non-compliant devices.

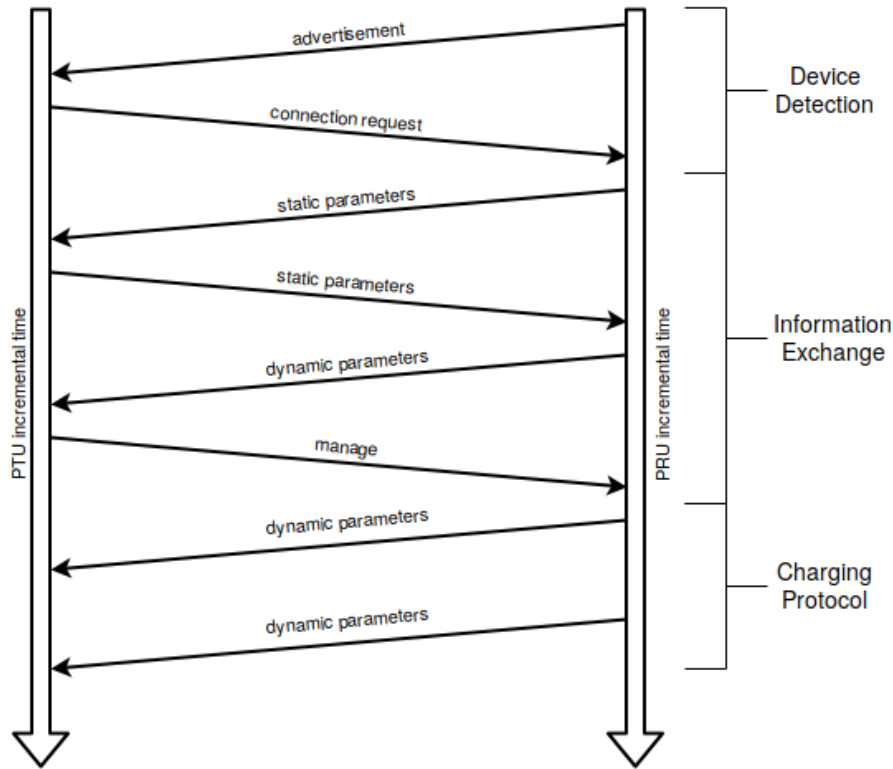


Figure 2.9: A4WP steps

During the device detection phase, the PRU is the one responsible for advertising itself. PTU as it captures the advertisement, replies with a connection request. PRU accepts the connection request by stopping the advertisement. The information exchange phase is composed of an exchange of both Static Parameters and Dynamic Parameters in a preset configuration. The charging control phase is initialized when the PRU control is specified and PTU has enough power to meet the PRU conditions. During this phase, the PRU dynamic Parameters are constantly being updated to inform the PTU with the latest information and readjust the power link. In the case of a System Error or complete charging event the PRU sends alert notification to the PTU.

2.4 Wireless Data Transmission

With regards to the wireless transmission of data, there are a couple of different options already explored, **none of which tested in the conditions this work focuses on.**

The solutions presented can be divided in two different approaches, one being the use of a separated wireless technology standard for the transfer of both data and control parameters of the data link [17], while the other approach makes use of the already implemented power link, in WPT, to transfer, through modulation, data and control parameters.

As previously mentioned, the standard A4WP uses a Bluetooth Low Energy (BLE) profile for the control of power levels. Key elements of the BLE requirements include basic network structure, RF requirements, timing and sequence requirements, and the profile structure itself [17].

A different solution uses RF communication, by having an extra circuit in charge of transmitting and receiving data of the power link, between the transmitter and receiver.

Both of these solutions demand a hardware separation between the WPT and the communication aspect of the power link. This bears some advantages, such as, having a real separation of the actual charging and the control of the power link parameters, which can be considered as having a modular system, resulting in some trade-offs as the extra circuitry necessary, which can lead to an increase in both power consumption, temperature and area.

By using the power link already implemented as a source for the communication level, it is possible to reduce the overall area and temperature of the system but with significant loss in data rate, based on the quality factor of the power transfer system. [18, 19, 20, 21, 22]

2.4.1 ASK Modulation

In this attempt at a simultaneous WPT and communication a ASK modulated signal is used.

At the transmitter, a tunable attenuator is used to transmit the ASK modulated signal by controlling the DC voltage.

In the receiver, for the simultaneous RF-DC conversion and ASK demodulation a power splitting technique is used. The received RF signal is splitted into two branches. One of the branches of the rectifier serves to convert the signal to DC power and the other branch to convert to a baseband signal. The latter uses a envelope detector to perform this [19].

An example of a rectifier output, at a bitrate of 1 Mb/s, after the splitting can be seen in figure 2.10.

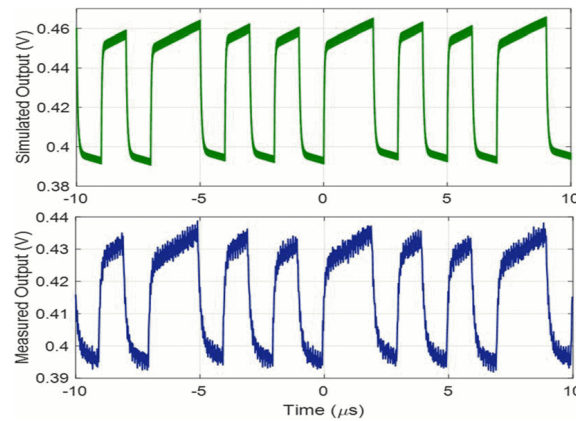


Figure 2.10: Rectifier output signal, extracted from [19]

2.4.1.1 Load Shift Keying Modulation

Within the ASK type of modulations, the Load Shift Keying (LSK) modulation is achieved by shifting an on-off switch based on the data stream. This changes the load of the inductive power link for the data transmission [18].

There are two main disadvantages with this approach. One being that with constant switching of the power link, the power transfer efficiency is decreased due to a frequent mistuning. The second one is that the switch states must be held for a certain period of time to ensure that the system reaches a steady state, decreasing the data rate.

2.4.2 BPSK Modulation

In figure 2.11 it is possible to check a system concept of a communication system using BPSK modulation within a WPT system, using a primary and second coil with an IPT generator.

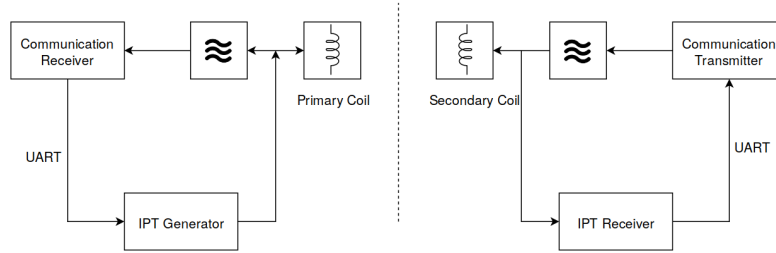


Figure 2.11: System overview of a WPT using BPSK modulation

The transmitter and receiver architecture is based on a I/Q modulation and demodulator for a complex digital modulation schemes. The generated transmit signal is converted from the digital domain to an analog domain, then amplified and pushed into the data channel [20]. In figure 2.12 a representation of a received communication signal is shown.

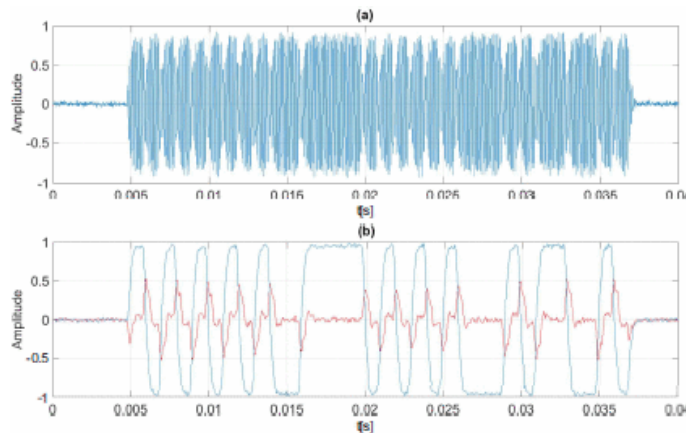


Figure 2.12: BPSK signal, extracted from [20]

At a receiver, the signal is amplified and then sampled. The I/Q symbols are used by the symbol demapper to make a decision based on the chosen modulation scheme

2.4.3 QAM Modulation

Based on the work of an ultra high data rate communication and efficient WPT, it is possible to verify the use of a Quadrature Amplitude Modulation (QAM) in conjunction with a WPT system. The system implemented is shown in figure 2.13. It uses two coils at each end of the link [21, 22].

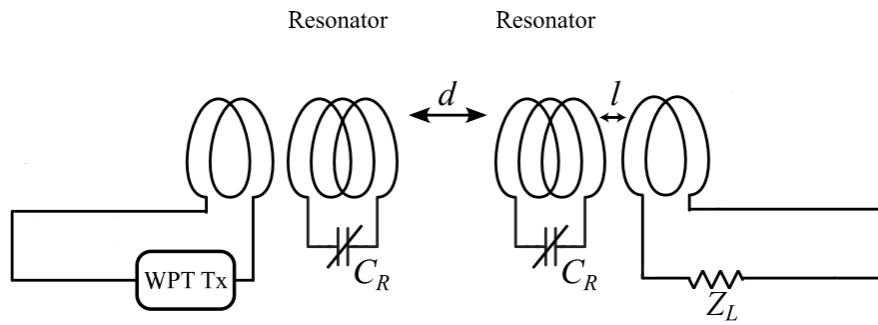


Figure 2.13: System overview

Communication is based on a complex load modulation at the secondary coil and is performed on the same link and coupled through a transformer. This link operates at a carrier frequency of 13.56 MHz with each coil measuring 16.5 cm in diameter [21] [22].

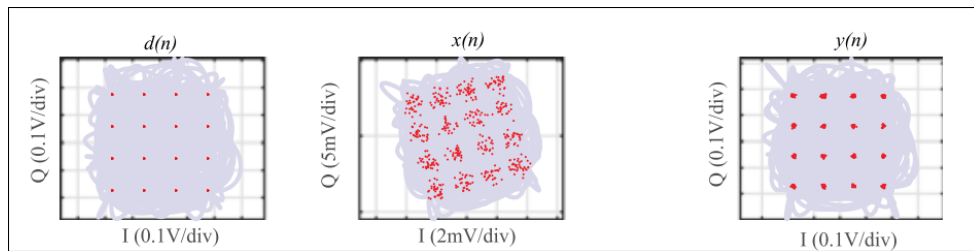


Figure 2.14: Different QAM signals, extracted from [21]

In figure 2.14 it is possible to see an example of an ideal 16 QAM signal as well as a restoration of the original signal in the receiver. One factor to note is that finite bandwidth and the phase shift of the channel results in a significant intersymbol interference of the QAM signal.

2.5 Communication Protocols

Regarding communication in WPT, in which the communication channel is unified with the power link, there are some key deciding factors when setting up the protocol. Questions like which end

of the transmission is in control, which unit begins the communication, what type of information is transmitted and what kind of procedures are followed once we detect a new object [23].

An example of a communication protocol, used in conjunction with the Qi standard, can be seen in article [24]. In this design, the power receiver is in control of the communication. It is possible to distinguish the different phases required by the Qi standard on both ends as well as the types of messages necessary to advance through these.

Since the Qi standard only specifies the method of power transfer and sequence of information transfer, it leaves open the method on which the packet generation and transmission are achieved. For this the power transmitter requires a unit for monitoring incoming packets and the power receiver a unit for generating packets. Additionally the power transmitter requires a unit to change the transmitted signal strength based on the parameters received, and the power transmitter a unit is required to transmit the charge status [24].

2.6 Conclusion

There is no short on alternatives for transmitting data through WPT. Ones with a more extensive list of hardware required, but with better results and less drawback. And others with a simpler approach but possibly slower rates.

For this thesis, the main approach is to implement a ASK type of modulation. In spite of having a negative effect on the power efficiency, i.e. the overall efficiency being lower when transmitting data, it still is a relatively easy method to implement with a high level of detection combined with a decent level of bitrate.

One other alternative is to use a FSK type of modulation. This could present better values of efficiency but, as a trade-off, a much slower transmission rate, when compared to the ASK implementation.

Chapter 3

Study of the data transmission link

This chapter starts with a separation of the entire system in subsystems. This serves as a simplification process, given the sheer size of the project. Next, the focus is on the transmission link used for the underwater power transfer, including an analysis of the circuit currently implemented, as well as an equivalence of circuits in order to simplify the analysis of the current, voltage and efficiency for different points. Following this, a study of the optimal resistance and optimal efficiency for a set of frequencies is shown. The final part revolves around the study on how to achieve communication in this specific system. An in-depth look of the two possible solutions is performed during this phase, including the analysis of several parameters, such as current, voltage and efficiency, in both ends of the link. Finally, given the results, a conclusion is drawn on the best type of commutation, which shall be implemented on the real system.

3.1 System as a whole

Starting off with the overall system, showcased in figure 3.1, one can to organize it into smaller sections. These will be denominated as the transmitter subsystem, power transfer link and receiver subsystem and correspond to the T, L and R marked in the figure.

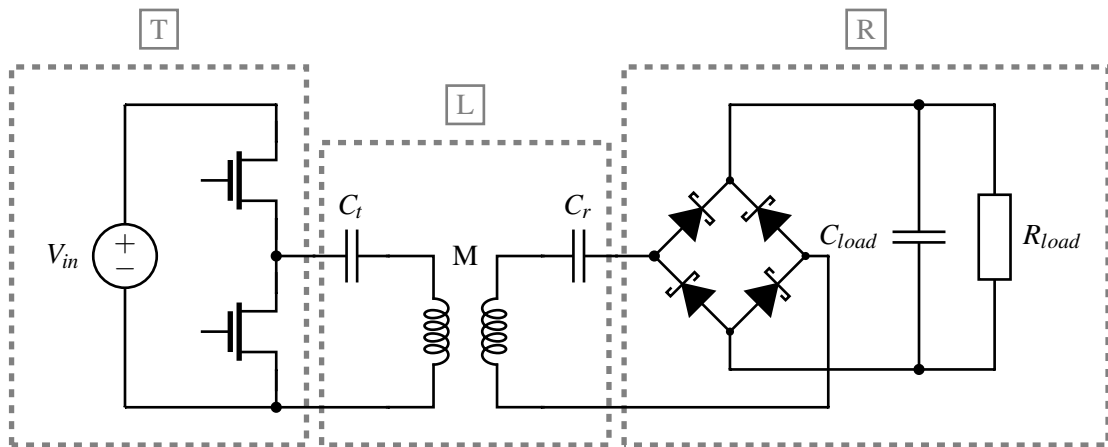


Figure 3.1: System Topology

3.2 Power transfer Link

It is important to note that, in this part of the system, the coils are the central components. As such these coils consist of a 9-turn twisted pair, consisting of a AWG-14 magnet wire, with a 20°C conduction resistance of $8.4\ \Omega$, and polyamide insulation. In figure 3.2 an image of the exact coils being used is shown.

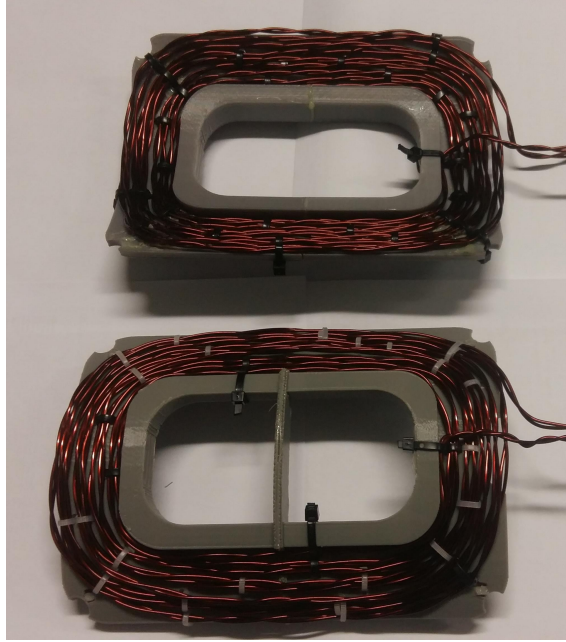


Figure 3.2: Coils [12]

They are housed in a 21 cm by 15 cm boxes, with a thickness varying from 3 cm to 5 cm and a curvature adjusted to the periphery of the AUV to be coupled. They are also filled with epoxy for waterproofness reasons.

In the power transfer link, two capacitors and two coils are used. In order to analyze the coupling coils in the power transfer link, a simplification of the circuit, admitting a T-model, is performed below, where $I_{in'}$ and $V_{in'}$ respectively represent the current and voltage at the transmitter side, $I_{out'}$ and $V_{out'}$ the current and voltage at the receiver side. The coils have a mutual inductance given by $\mathbf{M}$.

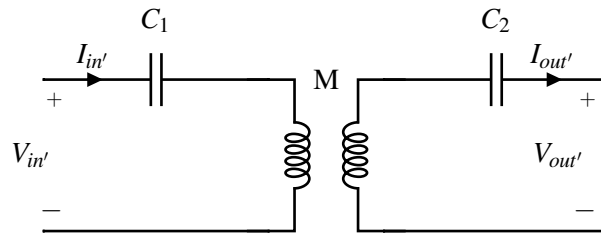


Figure 3.3: Power transfer link

The model, figure 3.4, shows the frequency dependent parasitic resistances, both in the primary and secondary side, respectively $r_1(f)$ and $r_2(f)$, and also the inductance at each side, which is affected by the coupling factor k , given as

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (3.1)$$

where M is the mutual inductance.

The quality factor Q for the power transmitter and receiver, Q_1 and Q_2 respectively, can be defined as follows

$$Q_1(f) = \frac{\omega L_1}{r_1(f)}, \quad Q_2(f) = \frac{\omega L_2}{r_2(f)} \quad (3.2)$$

Apart from the coupling factor, the magnetic coupling is very much dependent on the distance, spacing and alignment of the coils. On figure 3.4, the coils are represented by their real and imaginary components, $r_1(f)$, $r_2(f)$ and L_1 and L_2 , respectively, as well as dependent source supplies, which are dependent on the current of the other end and M .

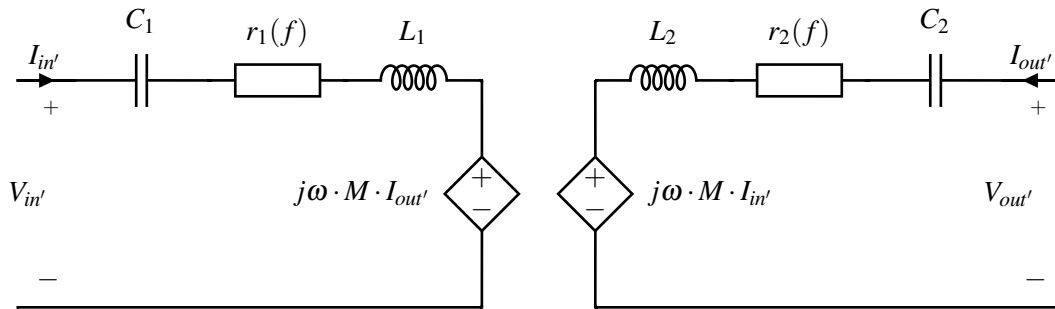


Figure 3.4: Power transfer link equivalent circuit

In order to perform an equivalence of circuits, two complementary coils were added, with a symmetrical value of the mutual inductance as one can see in figure 3.5. This in combination with the dependent power source enables us perform an equivalence of circuits in accordance to both the Thevenin's and Norton's theorems. [25]

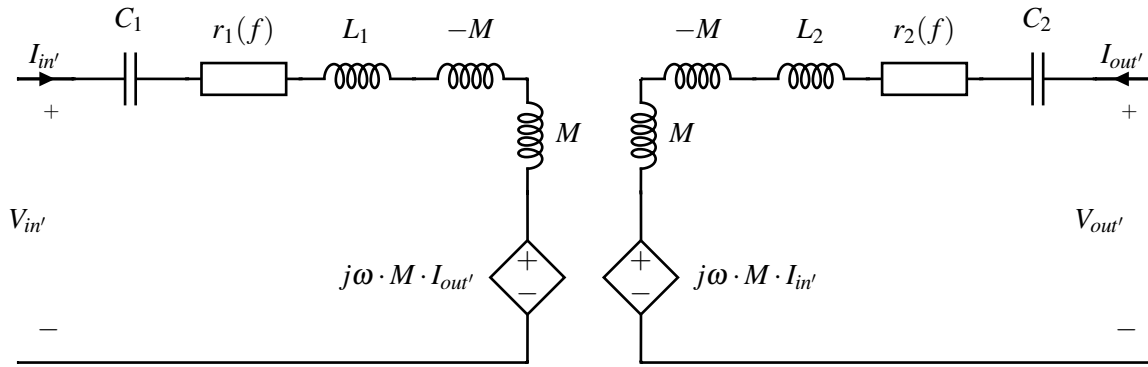


Figure 3.5: Power transfer link simplification

Performing such equivalence results in the following circuit 3.6.

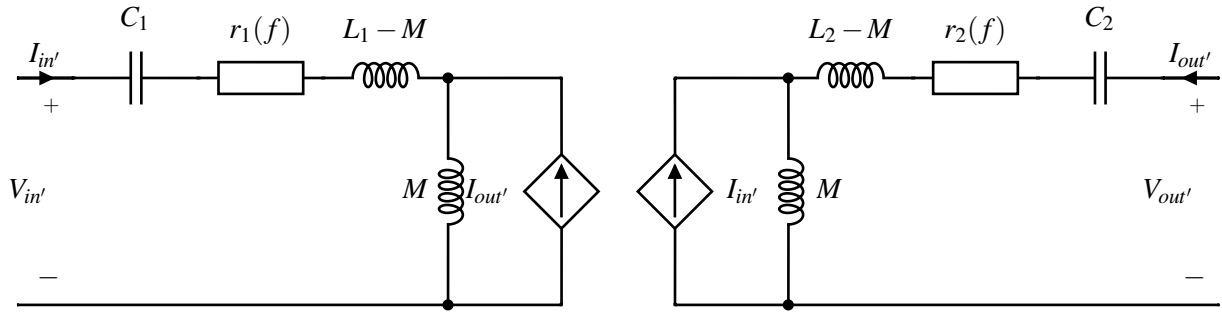


Figure 3.6: Power transfer link - Norton's equivalent circuit

Finally, since the current in M, by the Kirchhoff's junction rule, is equal to $I_{in'}$ plus $I_{out'}$ and the voltage applied to the coils are equal as well, one can conclude that instead of having two different circuits, there is only one circuit 3.7, in which one can admit a T-model of the initial circuit.

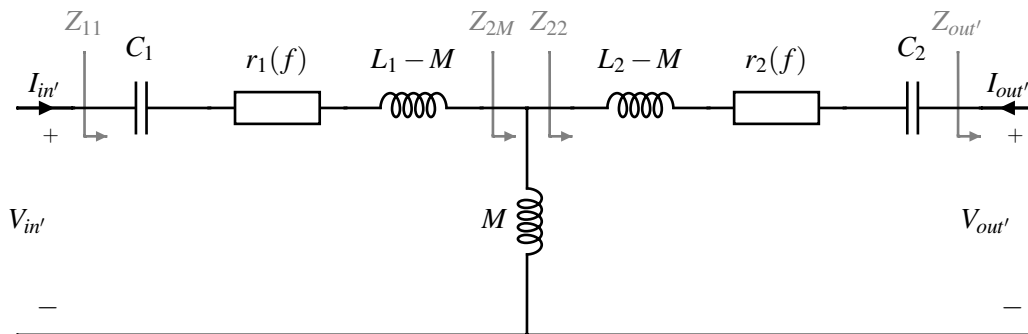


Figure 3.7: Power transfer link - T-model

It is now possible to characterize this part of the system, initially with it being in a non-resonant state, where Z_{11} represents the equivalent impedance seen from the input, Z_{2M} the par-

allel impedance seen from the transmitter of the coils with the receiver side, Z_{22} the equivalent impedance of the receiver side, $Z_{out'}$ the impedance connected to the output of the receiver side.

Considering then Z_{22} as the series of the coil, resistance, capacitor and impedance seen from the output of the receiver

$$Z_{22} = (L_2 - M) \cdot j\omega_o + r_2(f) + \frac{1}{C_2 \cdot j\omega_o} + Z_{out'} \quad (3.3)$$

And having Z_{22} in parallel with the coil valued at M , one can get to

$$Z_{2M} = Z_{22} || (M \cdot j\omega_o) = \frac{M \cdot \omega_o \cdot (-(L_2 - M)\omega_o + jr_2(f) + (C_2 \cdot \omega_o)^{-1} + jZ_{out'})}{L_2 \cdot j\omega_o + r_2(f) + (C_2 \cdot j\omega_o)^{-1} + Z_{out'}} \quad (3.4)$$

Now since we have a series of capacitor, resistance, coil and Z_{2M} , the impedance seen from the input is equal to

$$\begin{aligned} Z_{11} &= Z_{2M} + r_1(f) + (C_1 \cdot j\omega_o)^{-1} + (L_1 - M) \cdot j\omega_o = \\ &= R1 + (C_1 \cdot j\omega_o)^{-1} + (L_1 - M) \cdot j\omega_o \\ &\quad + \frac{M \cdot \omega_o \cdot (-(L_2 - M)\omega_o + jr_2(f) + (C_2 \cdot \omega_o)^{-1} + jZ_{out'})}{L_2 \cdot j\omega_o + r_2(f) + (C_2 \cdot j\omega_o)^{-1} + Z_{out'}} \end{aligned} \quad (3.5)$$

Considering a sine wave input voltage, one can consider the input current as

$$I_{in'} = \frac{V_{in'}}{Z_{11}} \quad (3.6)$$

And considering the current divider, the current at the output can be defined as

$$I_{out'} = \frac{V_{in'}}{Z_{11}} \cdot \frac{j\omega_o \cdot M}{j\omega_o \cdot M + (L_2 - M) \cdot j\omega_o + r_2(f) + (C_2 \cdot j\omega_o)^{-1} + Z_{out'}} \quad (3.7)$$

Having $V_{in'}$ applied to the system, the power at input can be defined as:

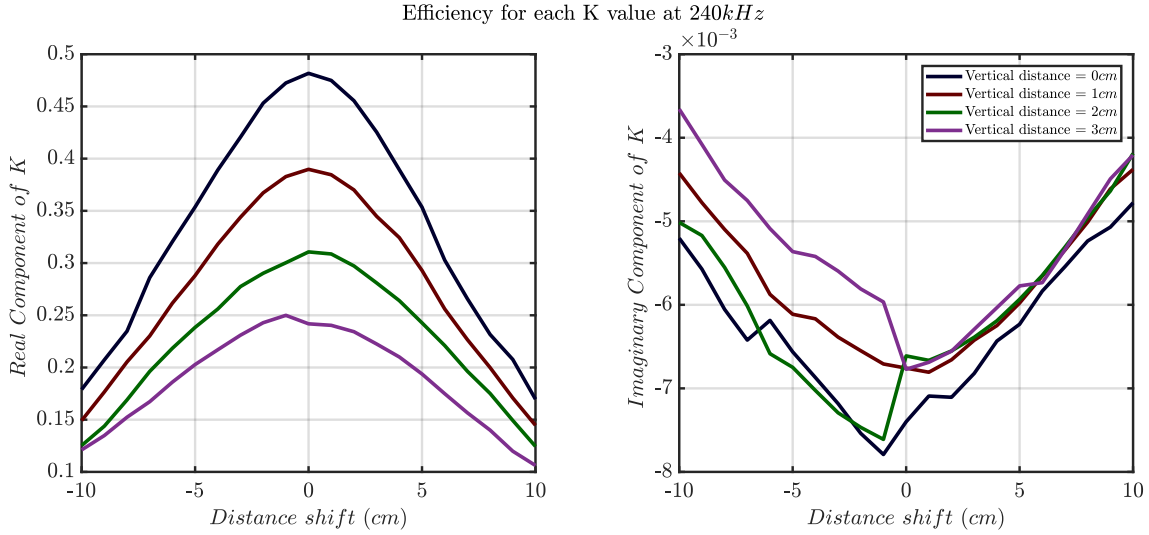
$$P_{in'} = \frac{1}{2} \cdot \frac{|V_{in'}|^2}{Z_{11}} \quad (3.8)$$

And the power at the output as:

$$\begin{aligned} P_{out'} &= \frac{1}{2} \cdot |I_{out'}|^2 \cdot Z_{out'} = \\ &= \frac{Z_{out'}}{2} \cdot \left(\frac{|V_{in'}|}{Z_{11}} \right)^2 \cdot \left(\left| \frac{j\omega_o \cdot M}{j\omega_o \cdot M + (L_2 - M) \cdot j\omega_o + r_2(f) + (C_2 \cdot j\omega_o)^{-1} + Z_{out'}} \right| \right)^2 \end{aligned} \quad (3.9)$$

Considering now the system oscillating at the resonant frequency, where $\omega_o = \frac{1}{\sqrt{LC}}$, as well as having similar sized L values, i.e. $L_1 = L_2 = L$, which implies that $k = \frac{M}{L}$, this lets us simplify

even more the system, as the capacitor and inductor are equal in magnitude and cancel each other. Although such approximation may not be the most adequate when representing the operation, due to inrush currents, it still is relatively accurate in the steady state. To be noted, that, in the case of salt water, the k factor can be seen as a complex quantity to reflect eddy losses, as seen in figure 3.8 for each vertical distance. Given that the housing of the coils already adds 4 cm in distance, one should not that real distances of the figure are from 4 cm to 7 cm.



The final circuit, at the resonant frequency, can be seen in figure 3.9.

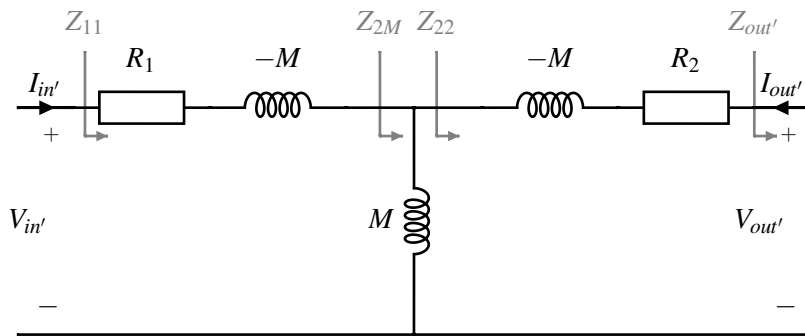


Figure 3.9: Final circuit

Analyzing the system in a similar manner as before, it is possible to define Z_{22} , Z_{2M} , Z_{11} , as well as, $P_{in'}$ and $P_{out'}$.

Considering Z_{22} as

$$Z_{22} = -j\omega_o M + R_2 + Z_{out'} \quad (3.10)$$

and Z_{2M} equal to

$$Z_{2M} = Z_{22} \parallel j\omega_o M = \frac{(Z_{out'} + R_2 - j\omega_o M) \cdot j\omega_o M}{Z_{out'} + R_2 - j\omega_o M + j\omega_o M} = \frac{(Z_{out'} + R_2) \cdot j\omega_o M + (\omega_o M)^2}{Z_{out'} + R_2} \quad (3.11)$$

Finally Z_{11} is equal to

$$Z_{11} = R_1 - j\omega_o M + \frac{(Z_{out'} + R_2) \cdot j\omega_o M + (\omega_o M)^2}{Z_{out'} + R_2} = \frac{R_1 \cdot (Z_{out'} + R_2) + (\omega_o M)^2}{Z_{out'} + R_2} \quad (3.12)$$

Having the input current and output current as

$$I_{in'} = \frac{V_{in'}}{Z_{11}}, I_{out'} = \frac{V_{in'}}{Z_{11}} \cdot \frac{j\omega_o M}{j\omega_o M - j\omega_o M + R_2 + Z_{out'}} = \frac{V_{in'} \cdot j\omega_o M}{R_1 \cdot (Z_{out'} + R_2) + (\omega_o M)^2} \quad (3.13)$$

Considering the input power as

$$P_{in'} = \frac{1}{2} \cdot \frac{|V_{in'}|^2}{Z_{11}} = \frac{1}{2} \cdot \frac{|V_{in'}|^2 \cdot (Z_{out'} + R_2)}{R_1 \cdot (Z_{out'} + R_2) + (\omega_o M)^2} \quad (3.14)$$

And the output power as

$$P_{out'} = \frac{1}{2} \cdot |I_{out'}|^2 \cdot Z_{out'} = \frac{1}{2} \cdot \left(\frac{|V_{in'}| \cdot \omega_o M}{R_1 \cdot (Z_{out'} + R_2) + (\omega_o M)^2} \right)^2 \cdot Z_{out'} \quad (3.15)$$

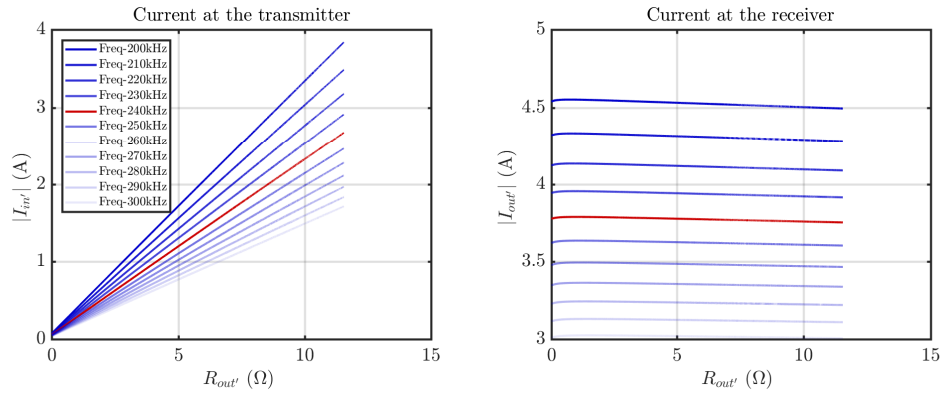


Figure 3.10: Current results for the receiver and transmitter ends. The red line corresponds to the resonance frequency, 240 kHz. For the transmitter, higher values of the resistance or frequency lead to higher values of current, while at the receiver, only the frequency influences the level of current achieved.

Having these definitions, one is able to simulate voltage, current and power values, as well as

efficiency of the power transfer link. Using already acquired values for the link characterization, i.e. impedance values of the coupling coils for each frequency, and with an input voltage equal to 80 V, sweeping the resistance seen from the output from $0\ \Omega$ to $12.5\ \Omega$, the following results were achieved 3.10, 3.11, 3.12.

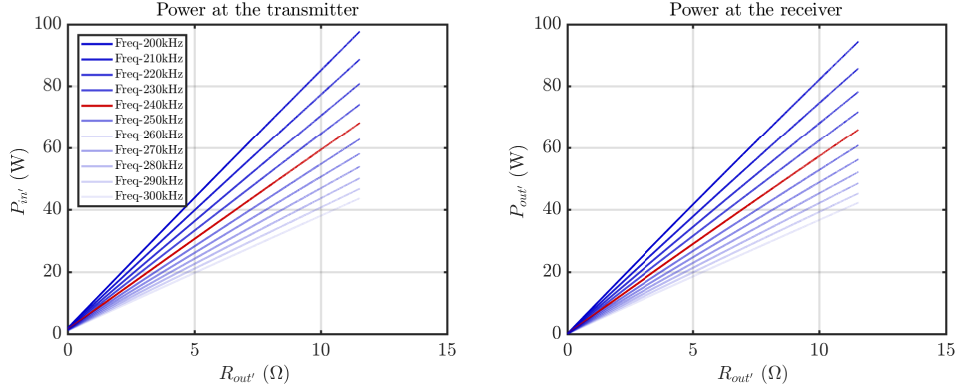


Figure 3.11: Power results for the receiver and transmitter ends. Higher frequencies are able to transmit more power, while lower transmit less. For a $R_{out'} = 10\ \Omega$, the link is able to transmit 60 W of power.

Considering R_{out} as the real part of the load connected to the secondary side, $Z_{out'}$, and due to its variance according to the battery placed at the output, we can define the link efficiency η_{link} for each individual value of $R_{out'}$ as

$$\eta_{link}(R_{out}) = \frac{P_{out'}}{P_{in'}} = \frac{1}{R_{out} + R_2} \cdot \frac{R_{out} \cdot (\omega_o M)^2}{R_1 \cdot (R_{out} + R_2) + (\omega_o M)^2} \quad (3.16)$$

Considering this, it is possible to achieve to following results

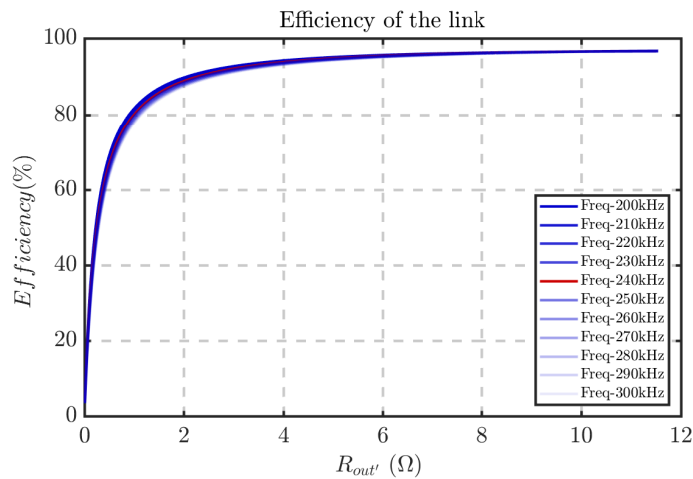


Figure 3.12: Efficiency results between the receiver and transmitter ends. For all levels of frequency, the efficiency remains quite the same, while for higher values of $R_{out'}$ than $4\ \Omega$, the same happens, being close to 90%

There is an optimum load at which the efficiency is maximum. From

$$\frac{\partial \eta_{link}(R_{out})}{\partial R_2} = 0 \quad (3.17)$$

One can obtain such optimum load value. The results are showcased in figure 3.13.

$$R_{out}^{opt} = R_2 \cdot \sqrt{1 + \frac{(\omega_o M)^2}{R_1 R_2}} = R_2 \cdot \sqrt{1 + |k|^2 Q_1 Q_2} \quad (3.18)$$

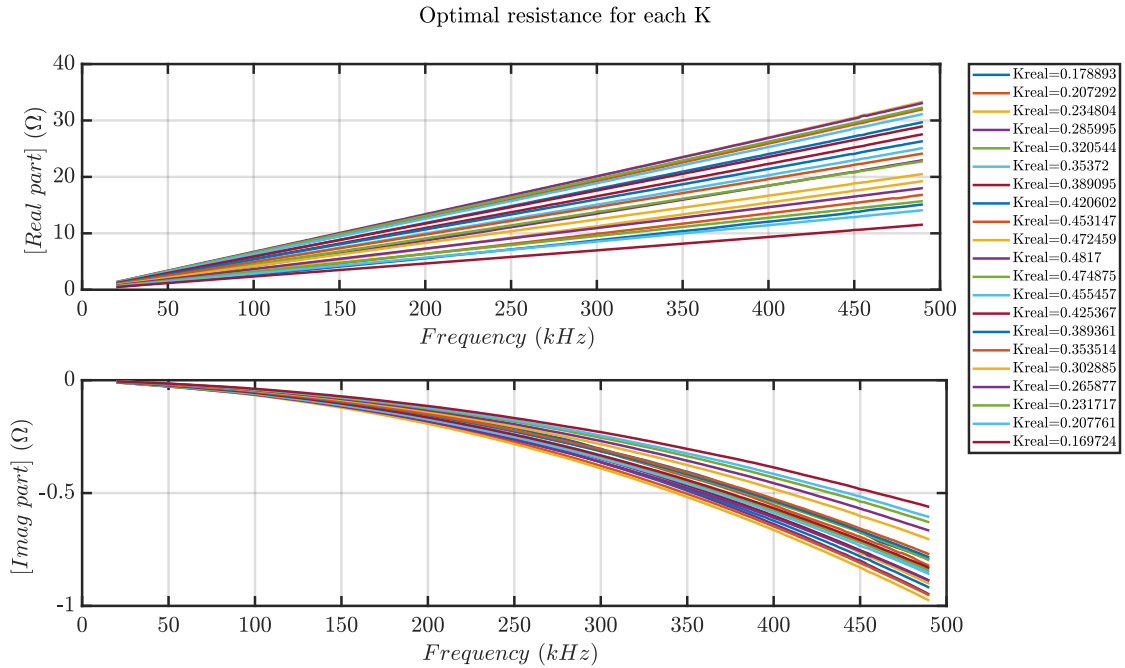


Figure 3.13: Optimal resistance for each value of frequency at different levels of K. This lets us see how the optimal resistance behaves for different positioning of coils and for different frequencies. For a perfect coupling, $K = 0.5$ and at the resonant frequency, the optimal resistance is equal to 12.5Ω

With this, it is now possible to get the optimal link efficiency for each k factor

$$\eta_{link}^{opt} = \frac{|k|^2 Q_1 Q_2}{(1 + \sqrt{1 + |k|^2 Q_1 Q_2})^2} \quad (3.19)$$

Below are the results of the simulation to achieve optimal efficiency for a sweep of both frequency and the k factor.

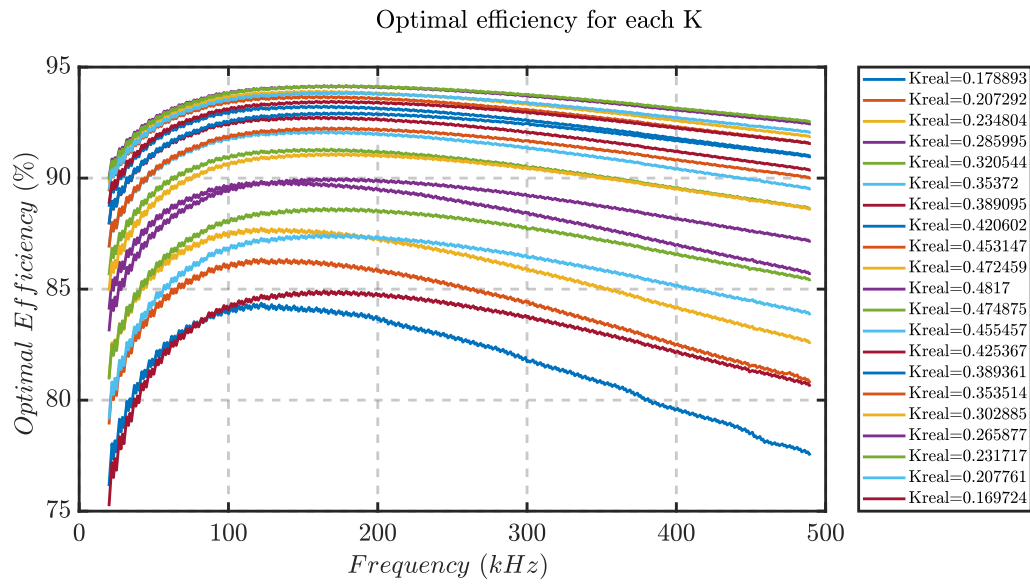


Figure 3.14: Optimal efficiency for each value of K , represented for a different line, and over different frequencies. The peak of efficiency can be hit in the range of 100 kHz to 200 kHz

As one can see, at a frequency of 240 kHz, for an optimal k close to 0.5, which corresponds to a perfect alignment of coils, the optimal resistance is approximately equal to 12.5Ω . For an optimal frequency, one can see that, for the same conditions, that the range between 100 kHz and 250 kHz does not have much variation, being close to an efficiency of 94%.

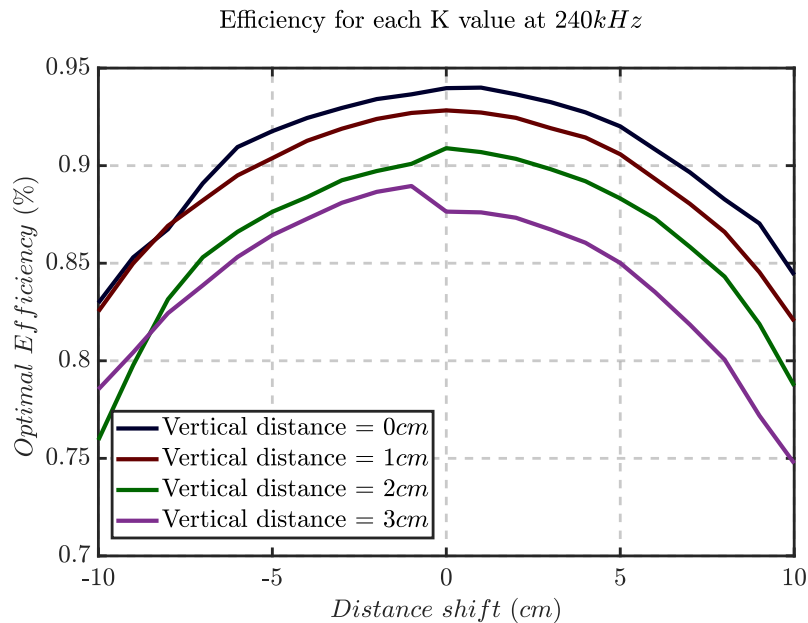


Figure 3.15: Efficiency for each k value

Apart from this initial analysis of the system, a Spectre circuit simulation, within the Cadence

Virtuoso Environment was also on the works. Simulating the schematic in figure 3.7, the results showcased in 3.16 and in 3.17 were achieved.

During the simulation, for each value of resistance $R_{out'}$, from $0\ \Omega$ to $40\ \Omega$, a sweep of frequency was performed. The characteristics of the link transfer were changed accordingly, to accommodate these changes and reflect an accurate representation of the link. The most important thing to notice when comparing the MATLAB simulations with the Virtuoso ones are both the overall efficiency of the link, as well as the optimal resistance based on each frequency.

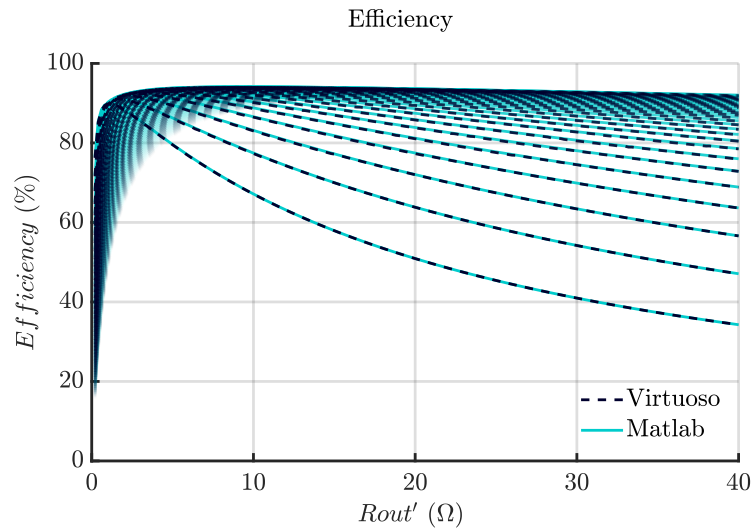


Figure 3.16: Efficiency comparison. The different lines represent frequencies ranging from 50 kHz to 500 kHz

For both figures, the range of frequencies varied from 10 kHz to 500 kHz with an interval of 10 kHz. Looking at figure 3.16 one can analyze how the equation 3.16 compares to the results achieved from the simulation in the Spectre environment.

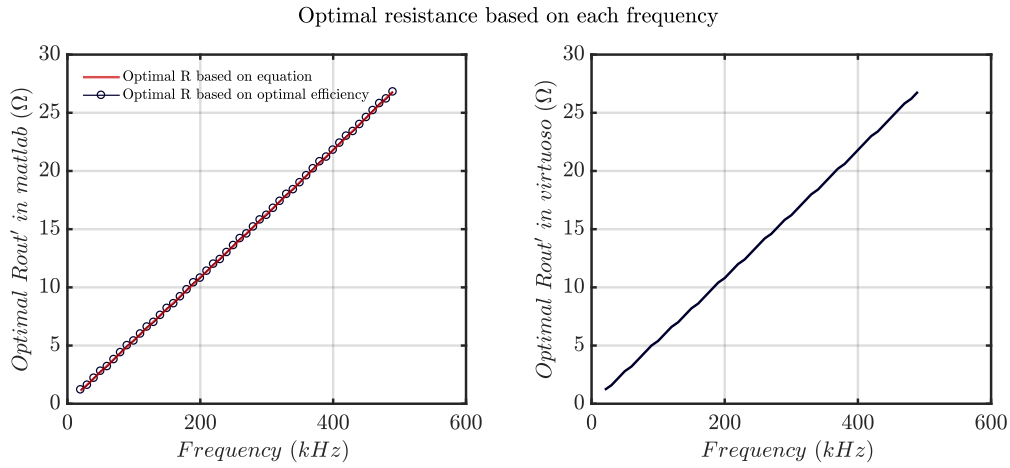


Figure 3.17: Optimal resistance based on each frequency. As before, the optimal resistance for a frequency of 240 kHz, given a perfect coupling between the coils, is of 12.5Ω

Furthermore, when checking the optimal resistance based on the optimal efficiency, considering a frequency of 240 kHz, the best value for a resistance is 12.5Ω .

3.3 Study on how to achieve communication

In order to achieve data transmission, one needs to first sense a change in the receiver on the transmitter side. Given the power transfer link, one possible solution is to switch a part of the receiver subsystem, allowing for a simple detection on the transmitter end.

Continuing this path, there are two possible methods to achieve commutation, resistive and capacitive. For both, the objective is to be able to detect two different states in order to differentiate the binary values a bit can possibly have, 0 and 1. What follows is the study, simulation and results of both alternatives.

3.3.1 Capacitive commutation

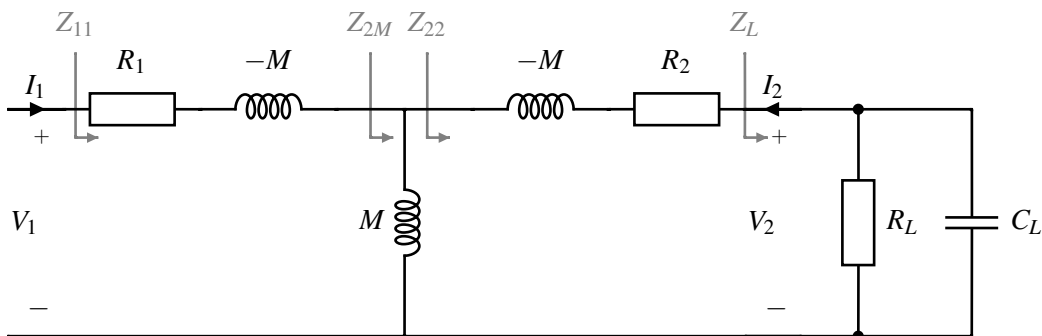


Figure 3.18: System with a capacitive commutation

For a capacitive switching, the present solution was found. Regarding this implementation, one should note that the capacitor should be placed before the rectifier, since in a DC circuit it behaves as a break in the circuit.

Analyzing now the effect it has on the circuit, especially on the impedance and current seen from the input as well as the overall efficiency.

Seeing Z_L as the parallel of R_L and C_L and Z_{22} as the series of this parallel with R_2 and the coil

$$Z_L = \frac{R_L}{1 + j\omega R_L C_L} \quad (3.20)$$

$$Z_{22} = -j\omega M + R_2 + \frac{R_L}{1 + j\omega R_L C_L} \quad (3.21)$$

And considering Z_{2M} as the parallel between the M value coil with Z_{22}

$$\begin{aligned} Z_{2M} &= \frac{-(j\omega M)^2 + j\omega M R_2 + \frac{j\omega M R_L}{1 + j\omega R_L C_L}}{R_2 + \frac{R_L}{1 + j\omega R_L C_L}} \\ &= \frac{(1 + j\omega R_L C_L) \cdot (-(j\omega M)^2 + j\omega M R_2) + j\omega M R_2}{(1 + j\omega R_L C_L) \cdot R_2 + R_L} \end{aligned} \quad (3.22)$$

Z_{11} is equal to

$$\begin{aligned} Z_{11} &= R_1 - j\omega M + \frac{(1 + j\omega R_L C_L) \cdot (-(j\omega M)^2 + j\omega M R_2) + j\omega M R_2}{(1 + j\omega R_L C_L) \cdot R_2 + R_L} \\ &= R_1 + j\omega M \cdot \left(\frac{(1 + j\omega R_L C_L) \cdot (-j\omega M + R_2) + R_L}{(1 + j\omega R_L C_L) \cdot R_2 + R_L} - 1 \right) \\ &= R_1 - (j\omega M)^2 \cdot \left(\frac{1 + j\omega R_L C_L}{(1 + j\omega R_L C_L) \cdot R_2 + R_L} \right) \end{aligned} \quad (3.23)$$

Considering now the two currents at each end as

$$\begin{aligned} I_1 &= \frac{V_1}{Z_{11}} \\ &= \frac{V_1}{R_1 - (j\omega M)^2 \cdot \left(\frac{1 + j\omega R_L C_L}{(1 + j\omega R_L C_L) \cdot R_2 + R_L} \right)} \end{aligned} \quad (3.24)$$

$$I_2 = \frac{j\omega M}{R_2 + Z_L} \cdot I_1 \quad (3.25)$$

For the current that flows through R_L , performing a current division operation

$$\begin{aligned} I_o &= \frac{1}{1 + j\omega C_L R_L} \cdot \frac{j\omega M}{R_2 + Z_L} \cdot I_1 \\ &= \frac{j\omega M \cdot I_1}{(1 + j\omega C_L R_L) \cdot R_2 + R_L} \end{aligned} \quad (3.26)$$

From 3.24 the input power can be defined as

$$P_1 = \frac{V_1^2}{R_1 - (j\omega M)^2 \cdot \left(\frac{1 + j\omega R_L C_L}{(1 + j\omega R_L C_L) \cdot R_2 + R_L} \right)} \quad (3.27)$$

And from 3.26 the output power can be defined as

$$\begin{aligned} P_o &= I_o^2 \cdot R_L \\ &= \left(\frac{j\omega M I_1}{R_L + R_2 \cdot (j\omega C_L R_L + 1)} \right) \cdot R_L \end{aligned} \quad (3.28)$$

In order to test this hypothesis, the equations were simulated in the MATLAB environment. These occurred with an input voltage equal to 80 V, considering a load resistance of 12.5 Ω and a range from 5 nF to 30 nF for the capacitor value. What follows are the current results of the simulations, for each end.

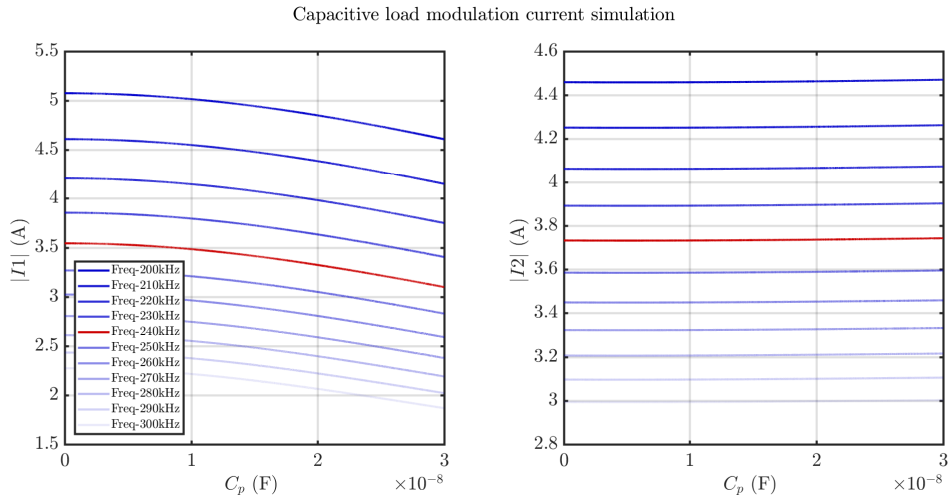


Figure 3.19: Results of the current for a capacitive commutation. At the transmitter side, the current does not seem to greatly vary for different values of C_p , For the frequency of 240 kHz, one can get a difference of 0.5 A between having a capacitor switched or not, which is a sufficient value

As one can see, the current at the transmitter side, I_1 , has a slight variation of current, enough for the microcontroller to detect. Following next is the analysis of power for the transmitter and receiver.

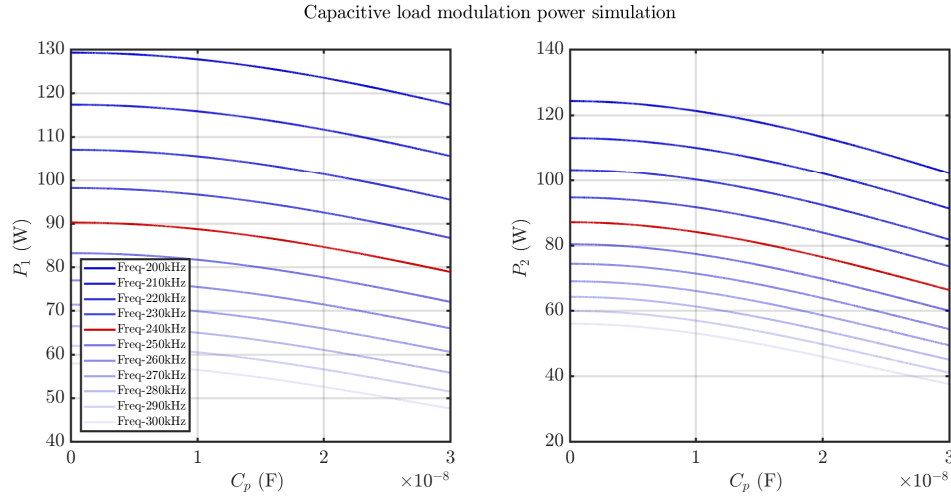


Figure 3.20: Results of power for a capacitive commutation

Results of power for a capacitive commutation. For this type of commutation the system is able to transfer power equal to 90 W, but it seems to suffer a loss in the power received for bigger values of C_p

Having in mind the results of figure 3.19, we can conclude that for a higher level of current to detect between two different states, there seems to be less power being transferred. Ultimately there needs to be a trade-off between the power being transferred and the amount of ΔI for detection available. One can note how the power at the receiver side, P_2 , has a steeper slope for higher values of the capacitor, when compared with P_1 . This becomes much more evident looking at figure 3.21.

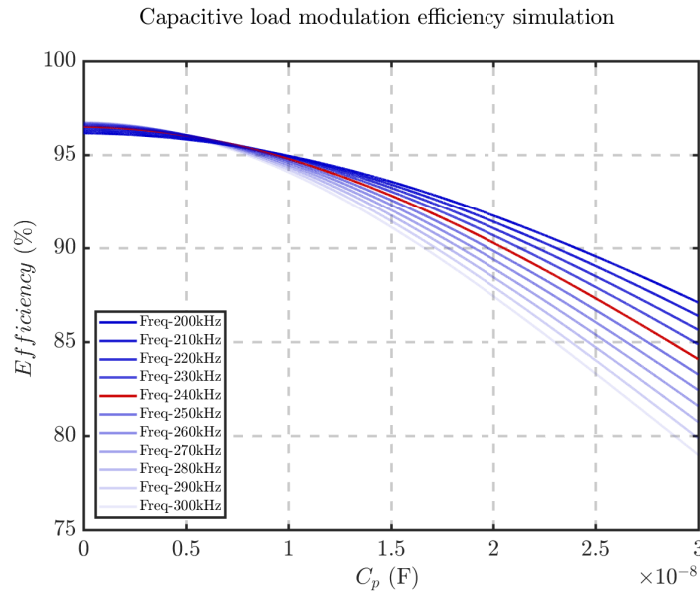


Figure 3.21: Results of efficiency. For bigger values of C_p the efficiency tends to suffer, up to a difference of 10%

A clear conclusion of these simulation results is that it is indeed possible to detect two different states, with a sufficient ΔI , at a cost of, not only having less power being transferred, but the efficiency of such transfer being much lower for higher values of ΔI .

3.3.2 Resistive commutation

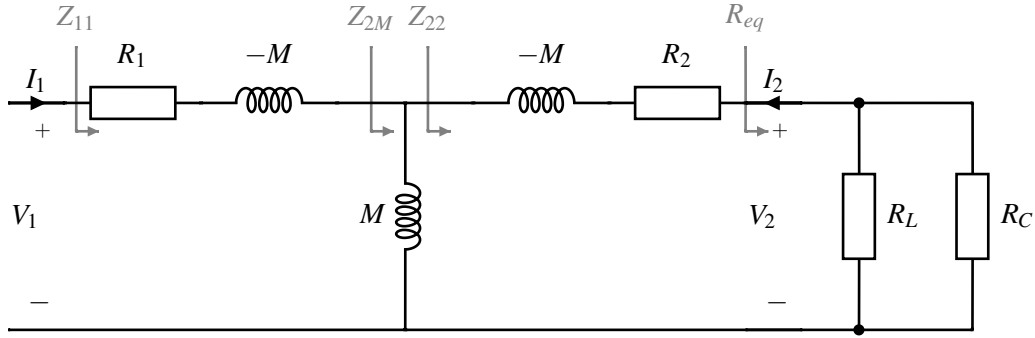


Figure 3.22: System with a capacitive commutation

For the resistive commutation, the resistance shall be placed after the rectifier, in parallel with the load resistance. In the following chapter, a thorough explanation, 4.11, is presented on how the resistance is seen at the input of the rectifier. For simplification reasons, such resistance is represented as R_{eq} .

$$R_{eq} = \frac{R_L \cdot R_C}{R_L + R_C} \quad (3.29)$$

And since it is in series with the $-M$ valued coil and R_2 , Z_{22} can be seen as

$$Z_{22} = -j\omega M + R_2 + R_{eq} \quad (3.30)$$

Consequently, since the M value coil is in parallel with Z_{22}

$$Z_{2M} = \frac{-(j\omega M)^2 + j\omega M R_2 + R_{eq}}{R_2 + R_{eq}} \quad (3.31)$$

Finally, the impedance seen from the input can be defined as

$$\begin{aligned} Z_{11} &= R_1 - j\omega M + \frac{j\omega M \cdot (-j\omega M + R_2 + R_{eq})}{R_2 + R_{eq}} \\ &= R_1 + j\omega M \cdot \left(\frac{-j\omega M + R_2 + R_{eq}}{R_2 + R_{eq}} - 1 \right) \\ &= R_1 + j\omega M \cdot \left(\frac{-j\omega M}{R_2 + R_{eq}} \right) \end{aligned} \quad (3.32)$$

From 3.32 one can obtain the input power

$$\begin{aligned} I_1 &= \frac{V_1}{Z_{11}} \\ &= \frac{V_1}{R_1 + j\omega M \cdot \left(\frac{-j\omega M}{R_2 + R_{eq}} \right)} \end{aligned} \quad (3.33)$$

And the current at the output power, dividing the current, as

$$I_2 = \frac{j\omega M}{R_2 + R_{eq}} \cdot I_1 \quad (3.34)$$

From 3.34 the current at the load is equal to

$$\begin{aligned} I_L &= \frac{R_C}{R_C R_L} \cdot \frac{j\omega M}{R_2 + R_{eq}} \cdot I_1 \\ &= \frac{R_C \cdot j\omega M}{R_2 \cdot (R_C + R_L) + R_C R_L} \cdot I_1 \end{aligned} \quad (3.35)$$

Finally both powers are defined below

$$P_1 = \frac{V_1^2}{R_1 + j\omega M \cdot \left(\frac{-j\omega M}{R_2 + R_{eq}} \right)} \quad (3.36)$$

$$\begin{aligned} P_o &= I_L^2 \cdot R_L \\ &= \left(\frac{R_C \cdot j\omega M}{R_2 \cdot (R_C + R_L) + R_C R_L} \cdot I_1 \right) \cdot R_L \end{aligned} \quad (3.37)$$

It is now possible to simulate this approach in a MATLAB environment. What follows are the results of a simulation with 80 V of input voltage, a load resistance equal to 12.5 Ω and a range comprised between 0 Ω and 12.5 Ω for the resistance to be switched.

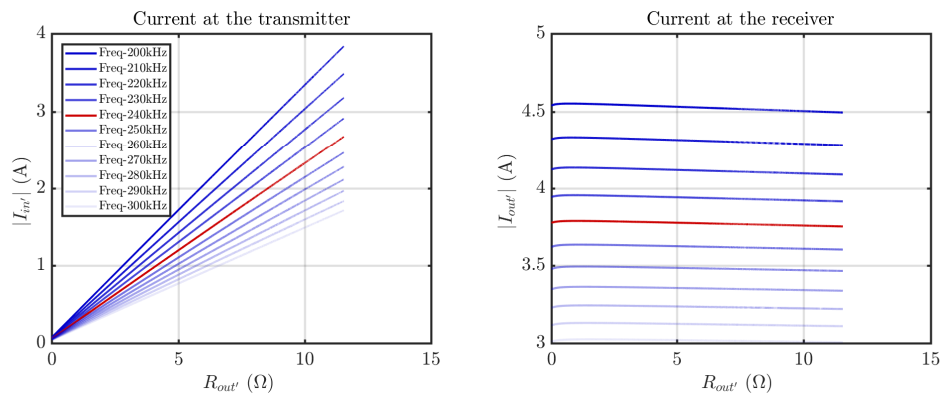


Figure 3.23: Results of the current for a resistive commutation. From these results, one can see how the current seems to suffer a huge impact by varying $R_{out'}$, while the current at the receiver, remains the same. This for equal frequencies.

As one can observe from figure 3.23, there is a significant difference in current available. When comparing the parallel of the two resistances, R_L and R_C and when R_{eq} is simply equal to R_L , i.e. equal to 12.5Ω , the difference in current can be as high as 4 A, for an input voltage of 80 V. The following results correspond to the comparison of these two currents mentioned. Let us define this difference between the two states as ΔI .

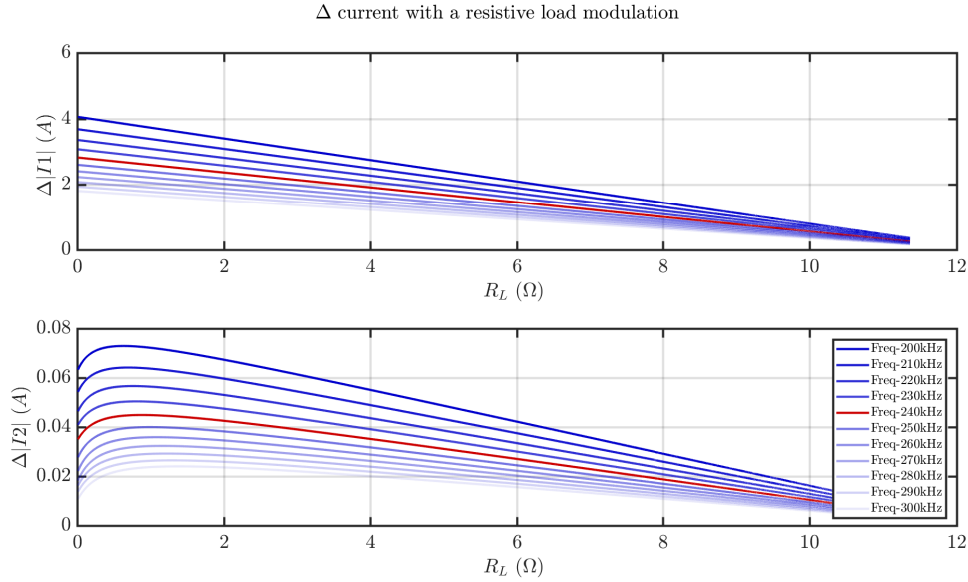


Figure 3.24: Results of the ΔI based on the switching resistance. It is possible to see how much difference there is between the two states of the resistance being switched

From these simulations, one is able to perceive how much difference in current there is between the two states of commutation. For a parallel resistance equal to 11Ω , the system is able to achieve up to 0.5 A of ΔI , which is quite noticeable.

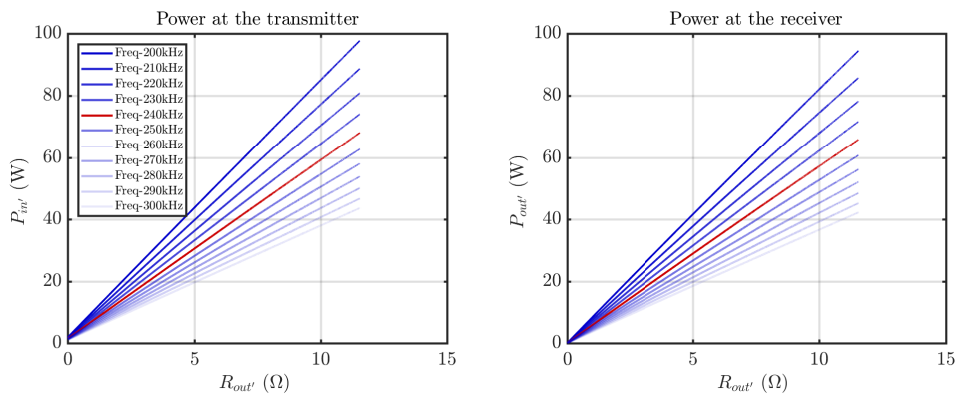


Figure 3.25: Results of power for a resistive commutation. These results indicate that while there is enough difference in current, the power at the transmitter and receiver suffer according to the value of $R_{out'}$

Since the ΔI is high enough for there to be a detection of different states, the power and consequently efficiency are analyzed. The power results are shown in figure 3.25. As one can see there is a loss in the power being transferred as the relation with the available Δ being one that for a bigger value of ΔI , there is also a bigger drop in the power transfer.

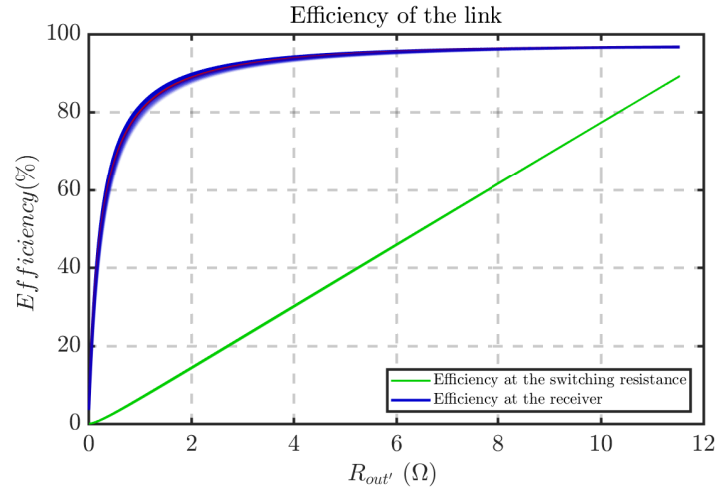


Figure 3.26: Results of efficiency for a resistive commutation. Here one can compare how the efficiency at the receiver compares against the one at the switching resistance. For a value of $R_{out'}$ the difference is close to 15%

In spite of such drop in power, the efficiency remains quite the same for a significant range of equivalent resistance values, meaning that even when the value of power is diminished, the total amount of power being lost in the link remains similar in percentage.

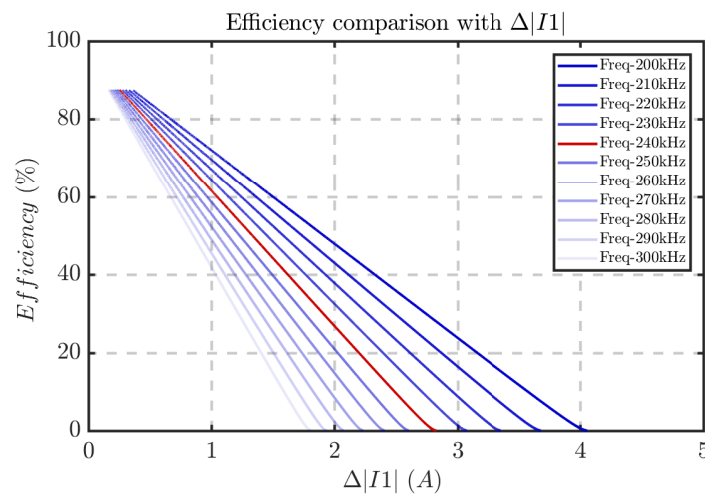


Figure 3.27: Results of the power efficiency based on the ΔI available. Now one can compare the efficiency against the level of Δ available. This quite clearly shows that in order to have a better efficiency, one needs to suffer a loss in the Δ available.

Figure 3.27 is the comparison between the efficiency and the ΔI available. One can conclude that for higher levels of efficiency, the total ΔI available diminishes, i.e. if one needs to have higher levels of Δ , the link efficiency will effectively take a toll.

3.4 Conclusion

Concluding the chapter, a few observations can be made regarding the results achieved.

Starting off with the capacitive commutation, a small ΔI can be achieved at a cost of diminishing quite heavily the efficiency of the power transfer and when there is no significant drop in efficiency, the ΔI is non-existent. Considering the objective set, this is a significant trade-off that does not hold its position when compared to a resistive commutation.

In the second study performed, with a resistance in parallel with the load, there is a significant ΔI for the transmitter to detect with little to no change in the efficiency of the power transfer. The trade-off in this case is within the loss of power being transferred. Since this is a prominent behaviour in both techniques, and that the resistive commutation does not have any other main drawback, this was the technique chosen for the system to transmit data.

Chapter 4

Characterization and system development

This chapter consists on the work performed on the extremities of the system. Firstly, a look on the transmitter subsystem is made. A study on the boost converter was performed. It is important to notice that, although this component was being developed by the supervisor, the posterior soldering and testing of the PCB were at my charge. This was all while the study of the rest of the system was being performed, simultaneously. For the inverter, one other thing to note, is that the hardware layer was already implemented, only being performed the study of such circuitry and the development of the software side, including programming the microcontrollers, which involved setting up the I2C bus driver layer, website layer and python functions. A in-depth explanation is performed during this section of the chapter. Next the receiver subsystem is studied, including the characterization of the diode bridge rectifier, both for the ideal model in a virtuoso simulation and the real model in experimental tests. For this part, the software involved an ESP32, as well as a XMC hexagon controller board and an in-depth explanation of the software layer, including the SPI communication is made. Finally the whole system can be seen assembled, including the transmitter and receiver side, as well as a characterization of the individual components in terms of efficiency and power.

4.1 Transmitter subsystem

The transmitter side is composed of a DC voltage power supply, a boost converter and a half-bridge converter. The objective of this subsystem is to output a squared wave, which corresponds to the input of the power transfer link.

4.1.1 Boost Converter

A boost converter is a DC-to-DC power converter able to step up a voltage applied to its input. A simple example of a boost converter, with the necessary components, is presented in [4.1 \[26\]](#).

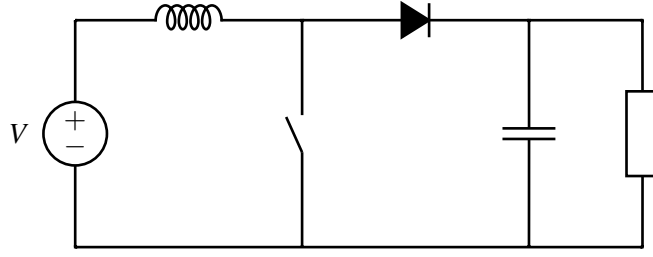


Figure 4.1: Basic circuit of a Boost Converter

The boost converter operation, in continuous mode, has two clear states, depending whether the switch is on or off. During the period in which the switch is closed, creating a short circuit, the inductor stores energy in its magnetic field and, because of the higher impedance on the rest of the circuit, almost all of the current flows through the switch. During this time the charge C is being drained away through the load, supplying it with a constant voltage of $V_{in} + V_L$, as explained next [26]. The current flowing through the inductor suffers a variation during this time period (t), given by:

$$\frac{\Delta I_L}{\Delta t} = \frac{V_i}{L} \quad (4.1)$$

Where L corresponds to the inductor value.

And with D being the duty cycle, representing the time, during the commutation period T, when the switch is on, the increase in current is equal to:

$$\Delta I_{L_{closed}} = \frac{1}{L} \cdot \int_0^{DT} V_i dt = \frac{DT}{L} V_i \quad (4.2)$$

When the switch is turned off, the coil returns energy to the circuit, acting as a power source in series, making the voltage at the load be $V_{in} + V_L$ and, simultaneously, charging the capacitor C. If we consider this capacitor large enough for the voltage to remain constant and a zero voltage drop in the diode, the evolution of I_L is given by:

$$V_i - V_o = L \frac{dI_L}{dt} \quad (4.3)$$

And, therefore, the variation of I_L , during this period is:

$$\Delta I_{L_{open}} = \int_{DT}^T \frac{(V_i - V_o) dt}{L} = \frac{(V_i - V_o)(1 - D)T}{L} \quad (4.4)$$

The amount of energy stored in each component has to be the same at the beginning and the end of a commutation cycle, and since the energy stored in the inductor is given by:

$$E = \frac{1}{2} L I_L^2 \quad (4.5)$$

The current has to be the same at the starting and ending points of the commutation cycle, meaning:

$$\Delta I_{L_{closed}} + \Delta I_{L_{open}} = \frac{V_i DT}{L} + \frac{(V_i - V_o)(1-D)T}{L} = 0 \quad (4.6)$$

Which, in essence, is equal to:

$$\frac{V_o}{V_i} = \frac{1}{1-D} \quad (4.7)$$

The the boost converter already in use was dimensioned to achieve an output voltage of 40 V, given that the input voltage is supplied by a set of lithium batteries able to output 13.2 V. The maximum and minimum input voltage is comprised between 12 V and 14.4 V, while the output current is able to withstand up to 2.8 A.

This approach uses the Texas Instrument LM5022 Low-Side controller, [27], in order to, not only command the switch, but also monitor the output voltage. The PWM controller embedded is designed to have a switching frequency given by:

$$f_{sw} = (R_T \cdot 5.77 \cdot 10^{-11} + 8 \cdot 10^{-8})^{-1} \quad (4.8)$$

Where the current value of R_T is dimensioned to be 73.2Ω , which corresponds to a switching frequency of 232 kHz.

Other components include the Coilcraft shielded power inductor, SER2918H-153KL, [28] which has an inductance equal to $15 \mu\text{H}$ ($\pm 10\%$) and a self-resonant frequency of 16 MHz, as well as a Schottky diode, the MBR40250, [29] with a voltage drop of 0.86 V.

The final PCB is shown below, in figure 4.2



Figure 4.2: Production PCB of the boost converter

In order to fully analyze the efficiency of the system, an electronic load was used at the output to achieve a full sweep of current, from 0.2 A to 3 A with fixed intervals of 0.2 A, as well as a DC voltage power supply, at the input, in order to test different voltage values, more specifically 12 V, 13.2 V and 14.4 V. An image of the setup can be seen in figure 4.3

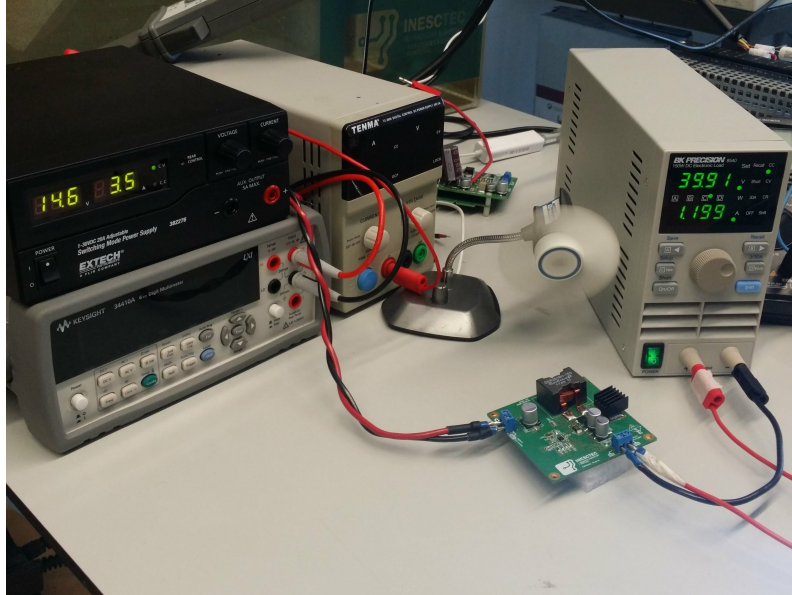


Figure 4.3: Boost testing setup

Below are present two graphs regarding the efficiency and overall values, such as voltage and current of the system.

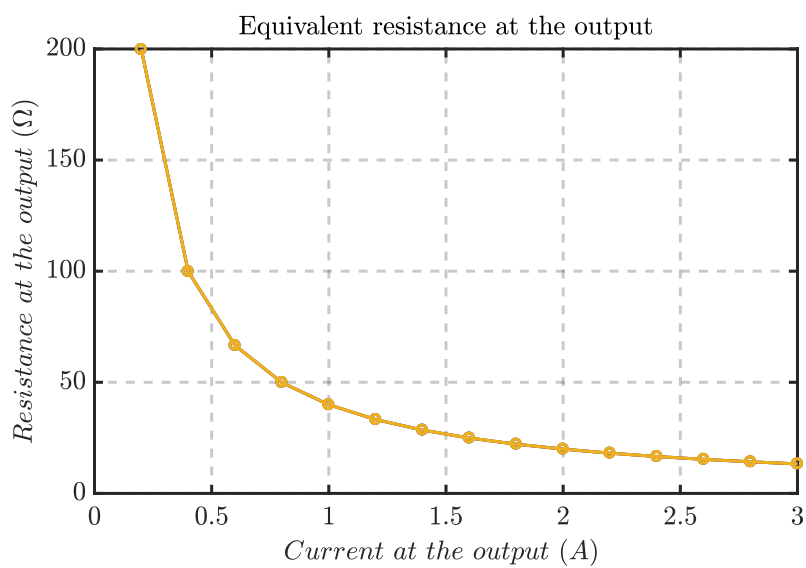


Figure 4.4: Boost analysis - Equivalent resistance at the output

The values of the equivalent resistance when sweeping the current can be seen in the figure above, 4.4, considering an output of 40 V.

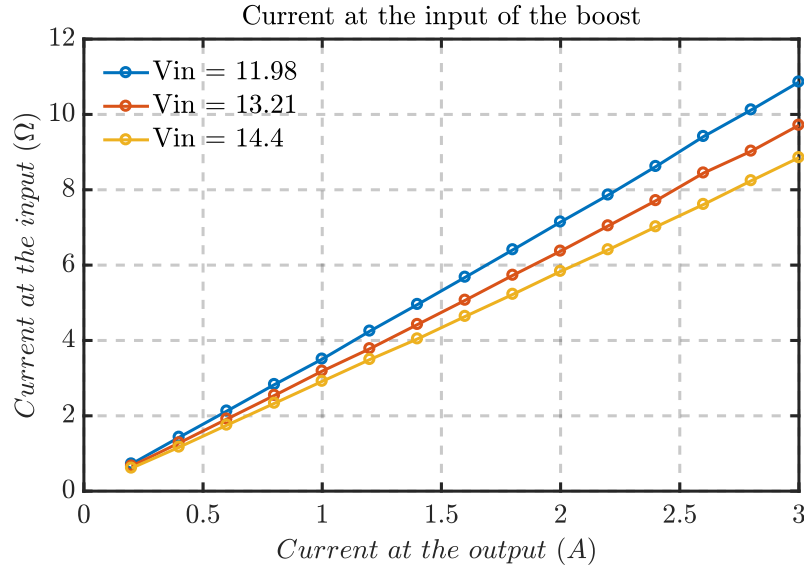


Figure 4.5: Boost analysis - Current at the input

There is not a significant change when checking the input current in 4.5.

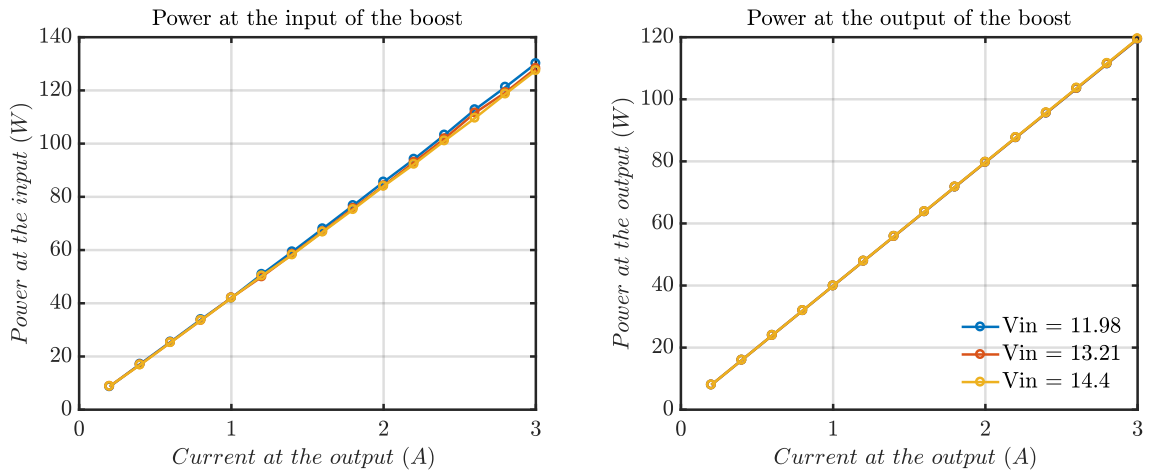


Figure 4.6: Boost analysis - Power at the input and output

When comparing both the transmitter power and receiver power, the behaviour is quite similar, with a small loss in the power received, the link having an efficiency close to 94%, as represented in 4.7.

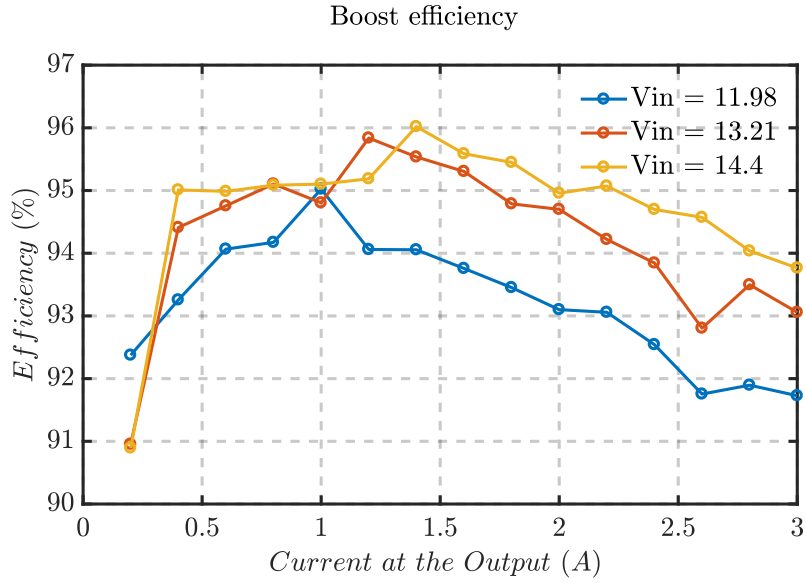


Figure 4.7: Boost efficiency results for multiple input voltages and a current sweep

4.1.2 Inverter

An inverter is a DC-to-AC power converter. Depending on the configuration and design, different frequencies and output voltages, as well as output waveforms, can be achieved [30].

4.1.2.1 Half-Bridge

Among the different designs available, the one in use is of the type Half-Bridge DC-AC inverter, which consists of two switches, in a cascode configuration, working alternately to output a square wave [30]. A simple design sample is presented in figure 4.8.

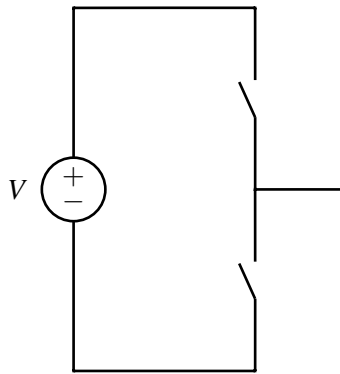


Figure 4.8: Basic circuit of a Half-Bridge inverter

The switches are turned on and off in a complementary manner, which result in a squared-wave at the output, that alternates between the DC high voltage and ground. As it is possible to analyze, the AC current flows in each switch depending on which one is closed or open, resulting

in two clear states represented which will be denominated ON state and OFF state, where the former corresponds to 4.9a and the latter to 4.9b.

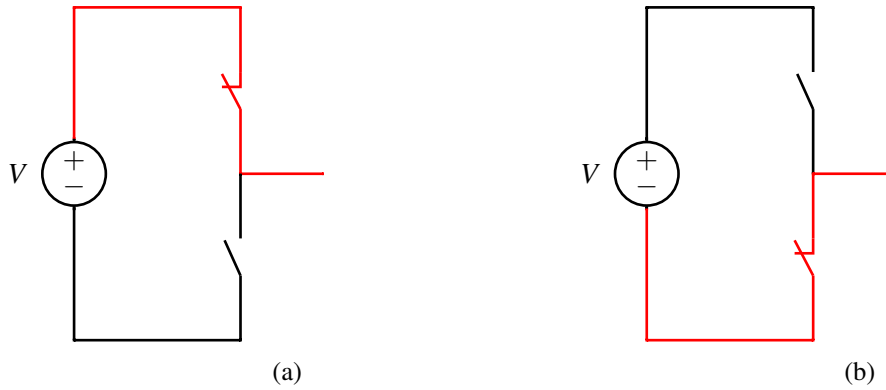


Figure 4.9: Current flow when one switch is open and the other closed

Overall, considering that there is a set dead-time between the control signals of each switch, there are four different operational states, as seen in figure 4.10.

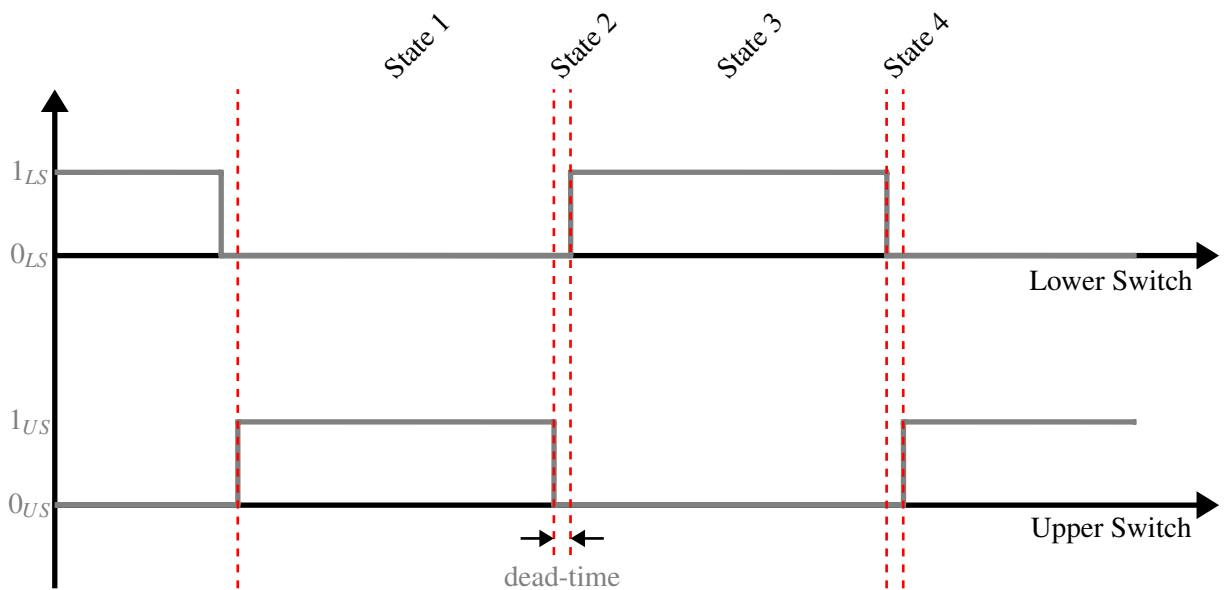


Figure 4.10: Half-Bridge Inverter - Different states

In state 1, the upper switch is turned on and, in turn, the mid-point is connected to the higher DC voltage, and since the lower switch is turned off, all the current flows through the upper switch and onto the load. This is considered to be the ON state of the system.

In state 2, during the dead-time in which both switches are turned off, the current continues to flow through the load, coming from, in equal parts, from both the intrinsic capacitor of both the upper switch and lower switch. As a result, the voltage at the load slews down to ground, with a set rate dependent on the total capacitance of the switches at the output.

In state 3, the lower switch turns on, making the current flow through it and, in turn, switching the direction of the current at the load. At this point, the mid-point is connected to ground, being the voltage at the load equal to ground. Since the upper switch is turned off, no current flows through it. This is considered to be the OFF state of the system.

In state 4, both switches are turned off and since current continues to flow into the mid-point, both capacitors of each switch are equally charged and the voltage at the output slews up at a rate equal to one in state 2.

4.1.2.2 Gatedriver

For this implementation of the inverter, a low-side gate driver circuit, which is referenced to ground, is necessary for the lower switch to alternate between on and off. Same principle applies to the upper switch with a high-side driver. For this a dedicated gatedriver is used, which accepts a low-power input from an external source and produces a high-current drive input for the gate of each high powered transistor.

In order to activate the upper switch, i.e. having a sufficient voltage at the gate, a bootstrap implementation is needed.

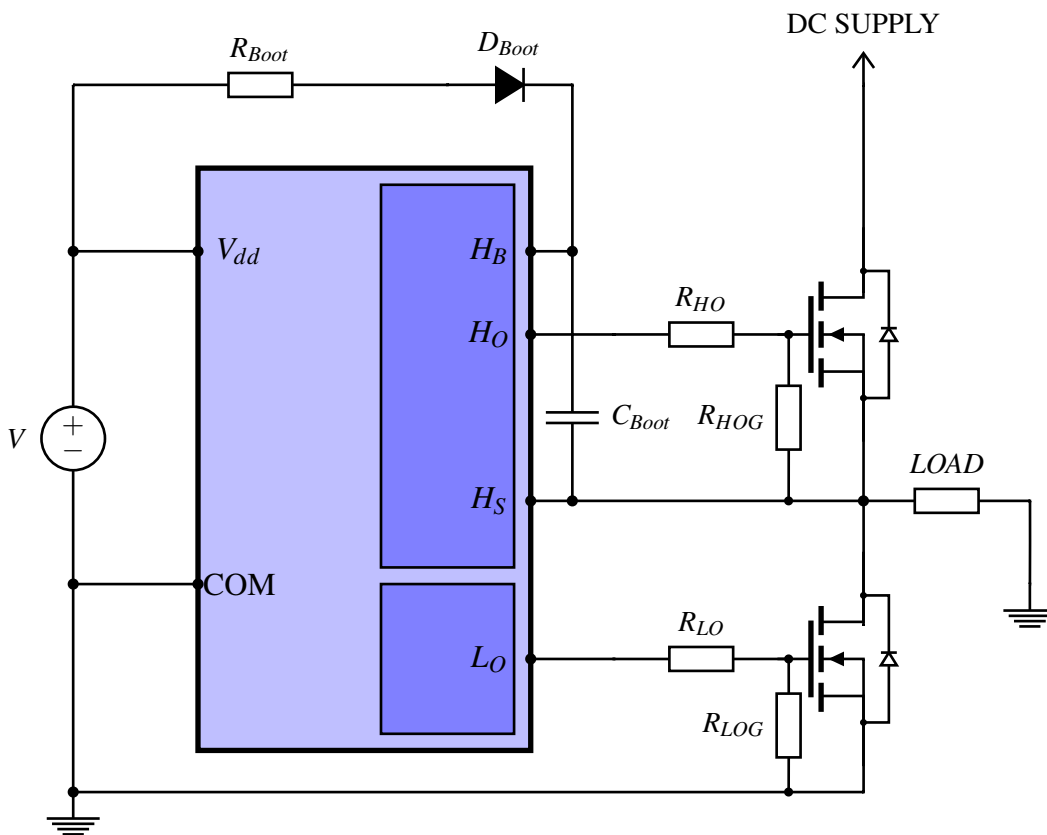


Figure 4.11: Bootstrap Power Supply Circuit

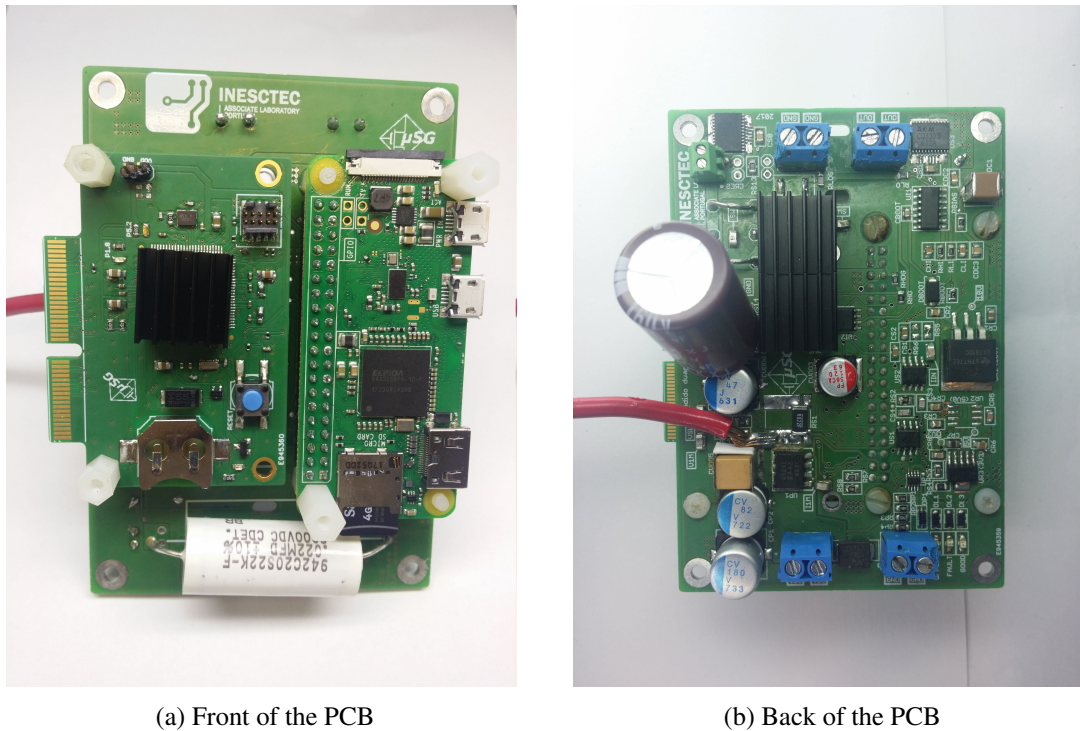
A general example of a bootstrap implementation can be seen in figure 4.11. It operates as follows. When the voltage at H_S goes below the supply voltage V or the lower switch is turned on and the higher switch is turned off, pulling it down to ground, the bootstrap capacitor, C_{BOOT} , charges through both the bootstrap resistor and the bootstrap diode, R_{BOOT} and D_{BOOT} respectively. When the voltage at H_S goes above the supply voltage, the V_{BS} floats and the bootstrap diode reverses and blocks the current from flowing [31].

For the implementation already in use, the gatedriver is the UCC27714, from Texas Instruments, where R_{HO} , R_{HOG} , R_{LO} , R_{LOG} are sized to reduce ringing and to limit the current coming out of the gate driver [31].

Both MOSFETS are from Texas Instruments as well, of type CSD18536KTT. In addition to this, a buffer was used to handle the high current, and at the output of it, R_{HI} , C_{HI} , R_{LI} , C_{LI} act as a low pass filters [32].

4.1.3 Microcontrollers

In order to control the system, as well as monitor voltage and current at specific nodes in the circuit, a XMC microcontroller is used, more specifically a XMC4400 hexagon board [33, 34]. On top of this, an I2C bus driver [35] between the XMC and a Raspberry Pi [36] was adopted to establish real time communication with the microcontroller and control it. The full system can be seen in figure 4.12.



(a) Front of the PCB

(b) Back of the PCB

Figure 4.12: Testing for different positions

Within this part of the project, quite a few software modifications were required to both test further the system, as well as to improve some parts of it.

4.1.4 Software

Delving now into the software layer developed and built to control the transmitter side, the I2C bus driver communication between the XMC and Raspberry Pi has been developed, as well as the control algorithm of the XMC in order to prepare and activate the system to transfer power, controlling certain aspects of such transmission. Apart from this, a web page combined with a database, was also implemented so that one can control the system and get real time values during the power transfer operation.

In order to program the XMC one can use the DAVe app, a C/C++ software development and code generation tool, provided by Infineon. The Raspberry Pi has the official Raspbian operating system installed and is programmed to be the master on the I2C and hosting both the web page and database [37]. For this, the software tools necessary can be summarized as Python scripting, CSS, HTML, SQL and JavaScript. In figure 4.13 a small diagram summarizes the software layer implemented.

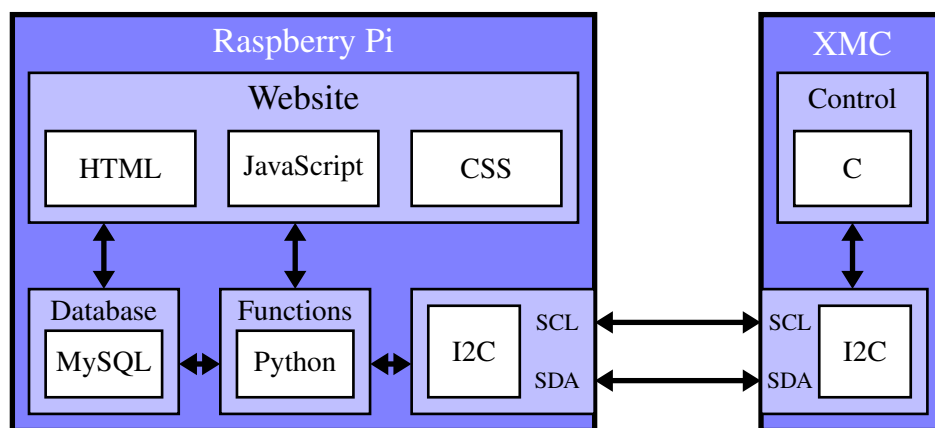


Figure 4.13: Diagram of the transmitter side

Explaining now the algorithm behind the control of the XMC and, in turn, of the power transfer operation. In the XMC device there are 3 distinct states, *sleep*, *wake* and *charge*. In the first one, the system is in a stand by mode, waiting to be activated. In the second one the system is powered one and awaiting for additional commands. The third one is set when the power is being transfered, i.e. the system is actively switching the inverter.

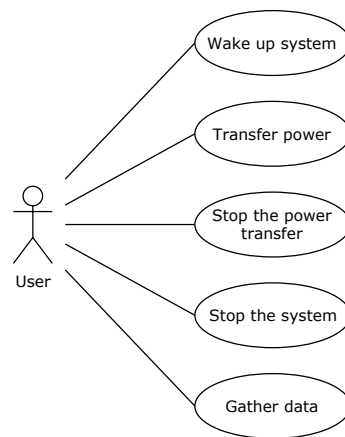


Figure 4.14: Use case diagram of the transmitter side

To control this state machine, with the Raspberry Pi, a series of scripting functions were created to transfer commands and send information to the XMC, through an I2C bus.

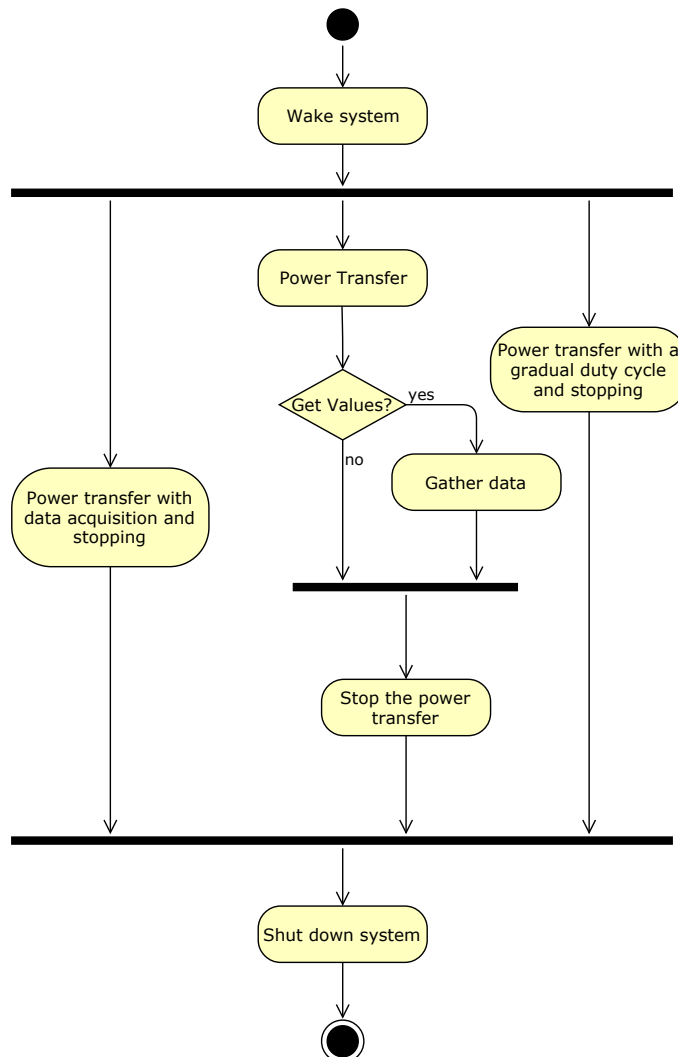


Figure 4.15: Activity diagram of the transmitter side

These were scripted using the Python language.

- A wake function is used to start the system, `wakeI2C.py`, and act as a safe mechanism, i.e. the system can only perform actions, such as start the power transfer process if it is in a wake state. This accepts no arguments and is just to prepare the system.
- A function to start the power transfer process, `chargeI2C.py`, which activates a gradually increasing PWM wave, until the defined duty cycle is achieved. It accepts frequency -in kHz-, duty cycle -in %-, the gradual increasing step -in %-, and the dead time of the PWM -in ns-. System needs to be in a wake state and is set to a charging state while it is transferring power.
- A stop function to slowly halt the power transfer, `stopI2C.py`, in which, if the system is in a charging process, it gradually draws the PWM wave to a stop and sets the system in a wake state.
- A function to immediately halt the system, `sleepI2C.py`. Sets the system from a wake to a sleep state.
- A function to quickly access the voltage and current values of different nodes of the system, `dataI2C.py`. Returns six values, including the voltage and current at the input, voltage at the output of the switching node, current at the input of the coil.
- A function to continuously gather data of the voltages and currents mentioned above, `gatherData.py`. This is useful when trying to acquire a significant portion of values to store in the database.
- A testing function in order to start the charging process, setting different duty cycles for a period of time that is defined by the user, acquire values to compare and finally halt the process, with no need to use additional functions.
- A testing function to start the charging process with a frequency defined by the user, and quickly acquire values during a predefined period of time, and immediately stop the charging process. This is useful to check the different values at the input and check if any difference is captured.
- The last function, `askI2C.py`, is one which serves the purpose of acquiring the current state of the system, for debugging reasons.

For an easier control of the XMC and a more pleasant interface, it was opted for the creation of website and a database to store values.

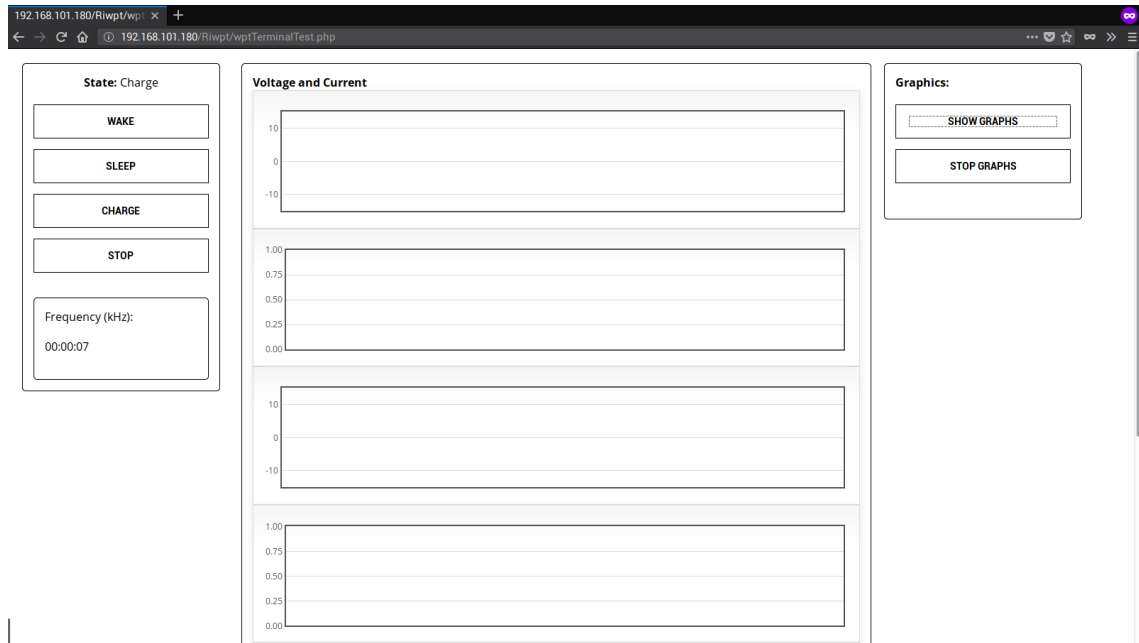


Figure 4.16: Screenshot of the website

A screenshot of the website can be seen in figure 4.16. This allows for the same level of control, using buttons, since it reuses the Python functions to achieve the same results. On top of this, one additional feature that enables users to check the wave in real time was explored.

4.2 Receiver subsystem

The receiver subsystem is composed of a full-bridge rectifier, as well as, a capacitor and a resistance, both in parallel. On this part of the subsystem, a study on the hardware was performed, as well as selecting the microcontrollers used to control the receiver side combined with the development of the software layer.

4.2.1 Diode Bridge Rectifier

In the receiver side of the system, the input signal is rectified through a full wave bridge rectifier. In this implementation, in each half cycle, two diodes conduct current, outputting a half rectified wave and dropping, in voltage, two times each diode's V_{drop} . As seen in figure 4.17, during the positive half cycle of the input wave, diodes D_1 and D_3 are conducting current, while D_2 and D_4 are reverse biased. During the negative half cycle, both D_2 and D_4 are at work while D_1 and D_3 are reverse biased. On both cases, a positive half wave is achieved at the output [38]. Furthermore, to achieve a smoother DC output a capacitor can be used.

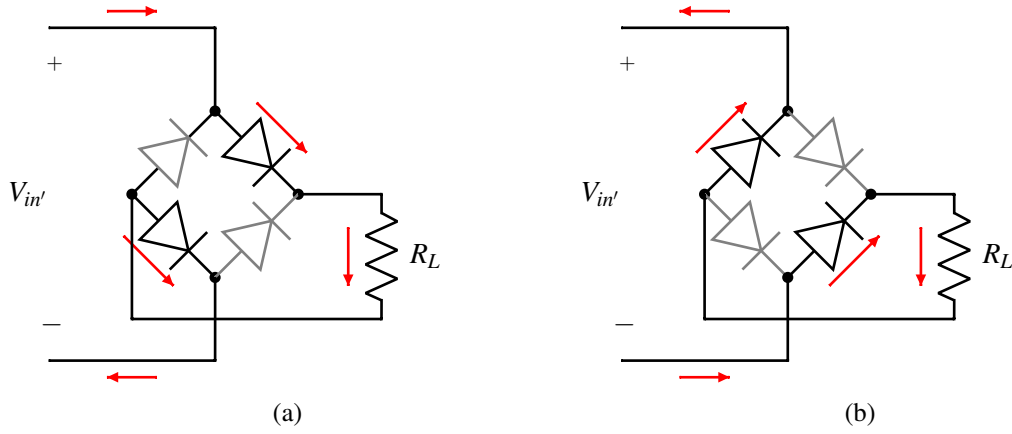


Figure 4.17: Current flow for each stage

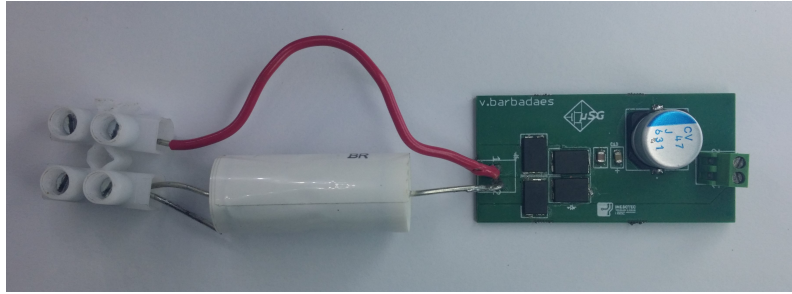


Figure 4.18: Rectifier PCB

The rectifier used in figure 4.18 uses Schottky diodes to provide fast switching and a low forward voltage drop, V_D [39]. Considering that the value of V_D can be despised when compared to the value of the voltage at R_L and assuming a reduced diode conduction resistance, the rectification efficiency tends to unity, i.e.

$$R_{i,2}|I_2|^2 = 2R_L I_R^2 \quad (4.9)$$

Since each half cycle carries a half sinusoidal current, the output current will be twice the average of the input current, i.e.

$$\frac{I_R}{I_2} = \frac{2}{\pi} \quad (4.10)$$

From (4.9) and (4.10)

$$R_{i,2} = \frac{8}{\pi^2} R_L \simeq 0.811 \cdot R_L \quad (4.11)$$

In order to achieve the best performance, tests were conducted in two different types of diodes, PMEG and SVF. For this, a virtuoso simulation was performed with the ideal components, as well as an experimental test with which version of the diodes. The following figures show the results

for a comparison of each. Since the real circuit has a resonant frequency of 240 kHz, one could only test the real system at this frequency.

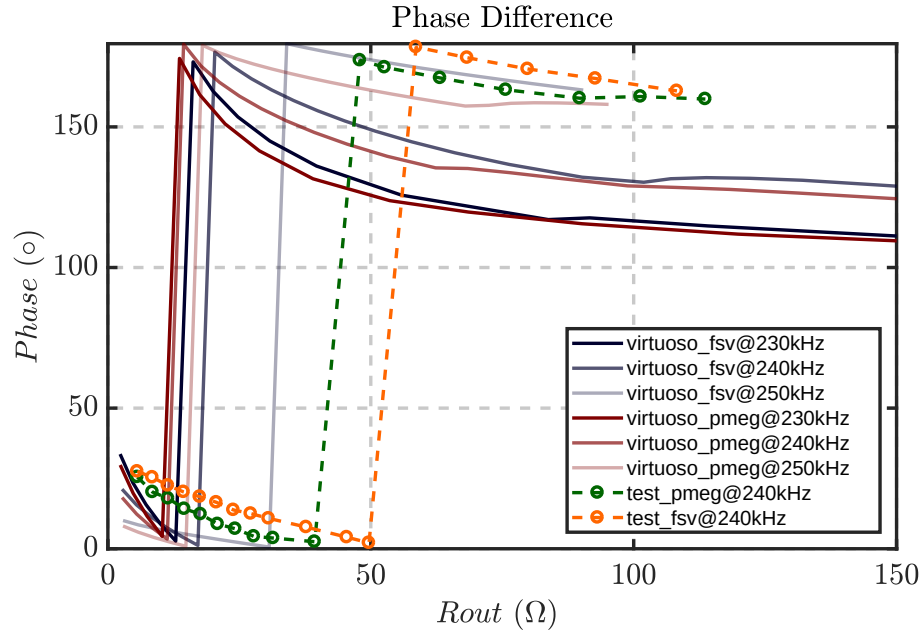


Figure 4.19: Comparison of phase at the input of the coils

In figure 4.19 one can see the difference in phase between the input of the coils and the input of the diodes for different resistance values and for different experimental tests, as well as simulations.

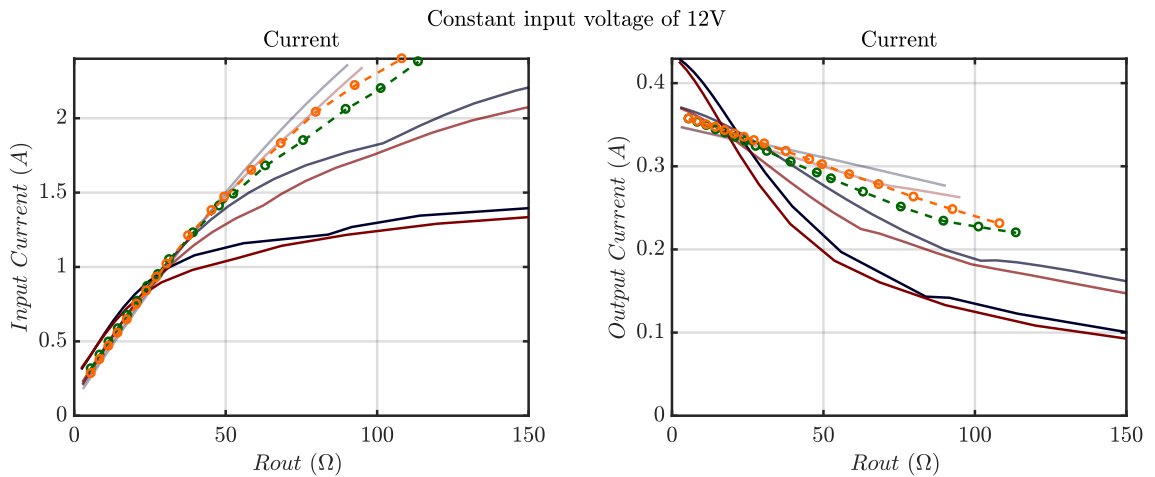


Figure 4.20: Comparison of the current at the input of coils and at the output of the rectifier

Analyzing the results of figure 4.20 and 4.21 we can see how there's a shift in frequencies between the virtuosio simulations and the experimental tests. One possible explanation for this

shift can be because of the difference between the ideal model of the diode simulated and real life model used.

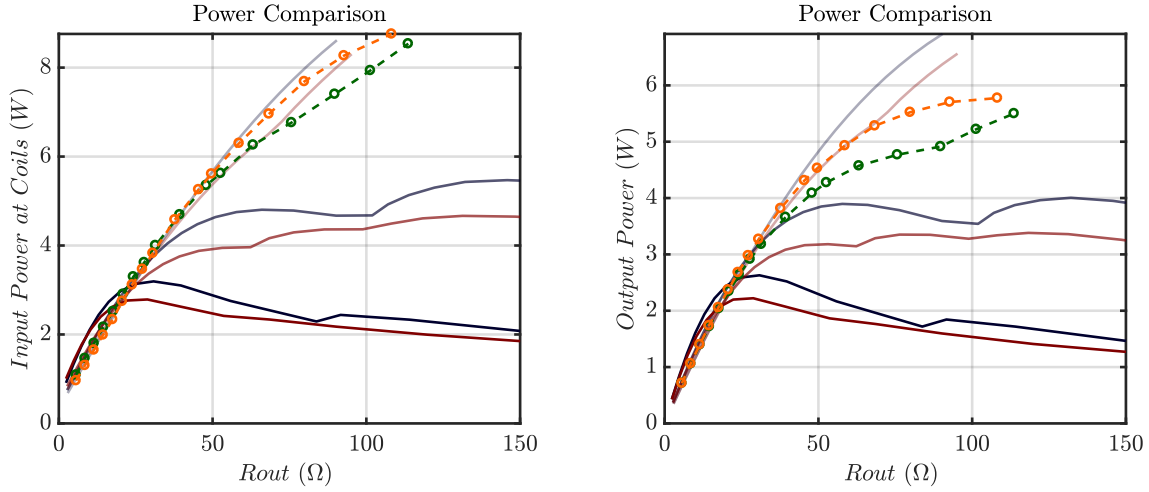


Figure 4.21: Comparison of the power at the input of coils and at the output of the rectifier

The efficiency results, figure 4.22, show how the experimental results has the same type of model as the simulation results, and to expect an efficiency close to 80% in the rectifier.

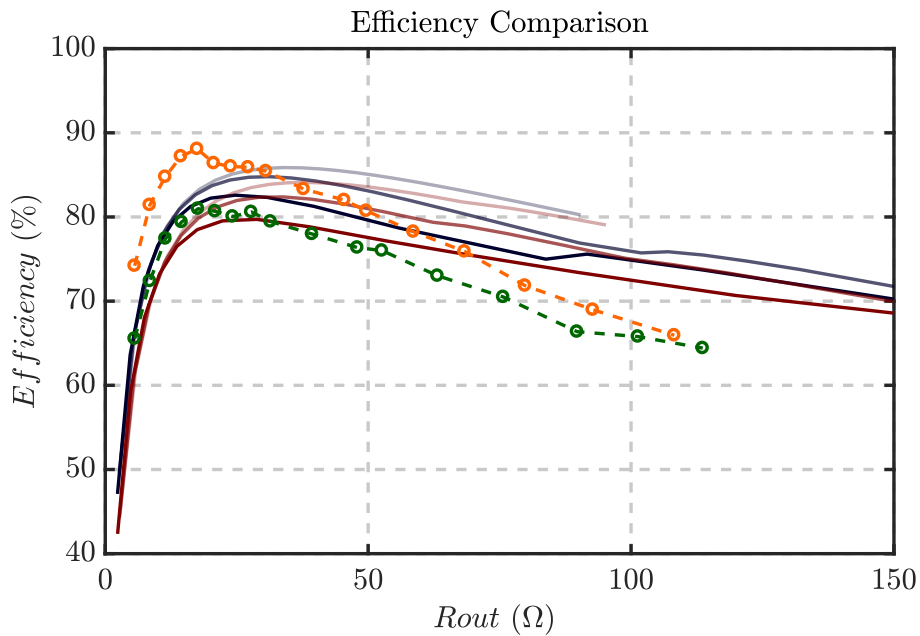


Figure 4.22: Efficiency of the rectifier

Finally, the implementation of this subsystem is shown in figure 4.23.



Figure 4.23: Final implementation on the receiver

An adaptation of this board was made, using the EAGLE CAD software, to try to implement a symbol based communication, with multiple resistance in parallel to achieve this. The schematic of this adaptation can be seen in figure 4.24.

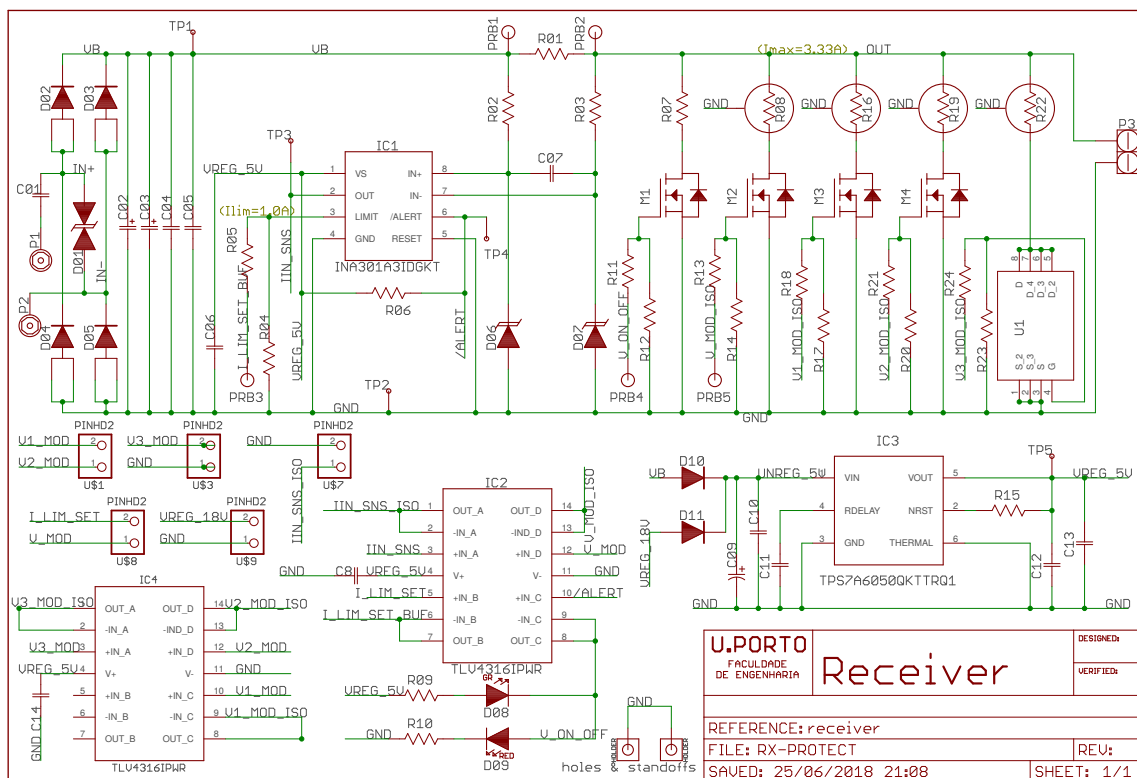


Figure 4.24: Adaptation of the receiver already designed

4.2.2 Software

On the receiver side, apart from the components mentioned above, it was decided that two microcontrollers should be used. An ESP32 microcontroller, [40] suitable for WiFi connections, therefore giving the option to control the receiver in a wireless manner, and, since the options available to obtain communication between the link revolve around a resistive commutation or a capacitive commutation, it should be noted that there should be an extra controller in order to control a switcher responsible for either option, therefore the XMC4400 was chosen, with far more precision in order to toggle a set of GPIOs at higher frequencies and have an ADC in case one is needed in the future. A picture of the system interconnected is shown in figure 4.25.

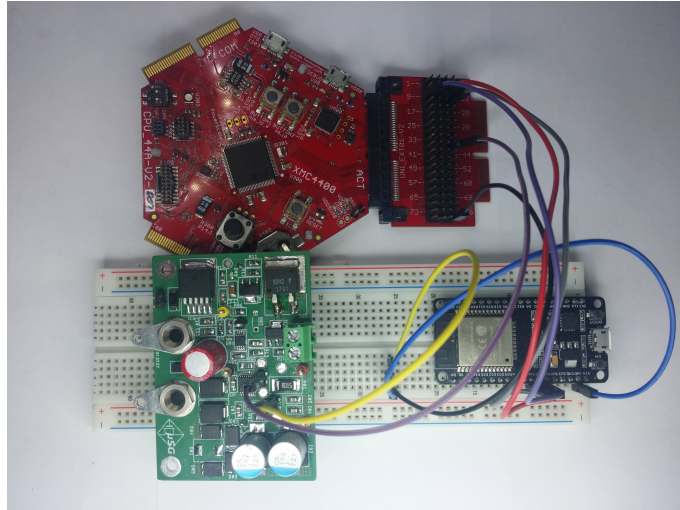


Figure 4.25: Receiver with the microcontrollers

For these two modules to communicate, the SPI bus driver was chosen for its simplicity and for being available, with predefined functions, in both the ESP, as a master, and the XMC, as a slave [41, 42]. With the bus driver selected, an algorithm was developed.

The ESP32 was flashed with the Lua RTOS, which is a real-time operating system designed to run on embedded systems [43]. One can program it with the Lua programming language. For the extra microcontroller, two options were available: a XMC microcontroller, similar to the one on the transmitter side, or a PIC32 microcontroller. Both of which are programmed within a C/C++ software development.

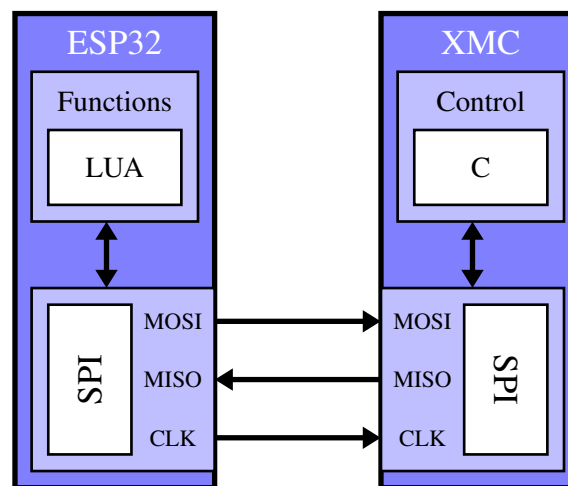


Figure 4.26: Diagram of the receiver side

With the ESP32 configured to be the master of the SPI communication, a set of functions to communicate and control the XMC were developed.

The functions created, using the Lua scripting language, can be resumed as follows.

- One function to activate a PWM in the XMC, the only argument being the frequency in which to set the PWM. This enables the option to continuously switch a GPIO between 0 and 1.
- A function to stop the PWM and set the GPIO to low.
- A function to check if the GPIO is set to high or low.
- Accepts a byte as an argument and, in a loop, the XMC switches the GPIO according to the bits it has received, i.e. a bit with the value of 1 corresponds to setting the GPIO in a high state, while a value of 0 sets the GPIO to a low state.
- Order the XMC to activate a state in which it sends bits of data through a frequency shift modulation, i.e. a 1 corresponds to a f_1 and a 0 to a f_2 . Each bit has a duration equal to 5 times the period of the lower frequency.

The XMC is set to continuously check if it has received any SPI MOSI signal from the master and act according to the message received.

4.3 Final Setup and Testing

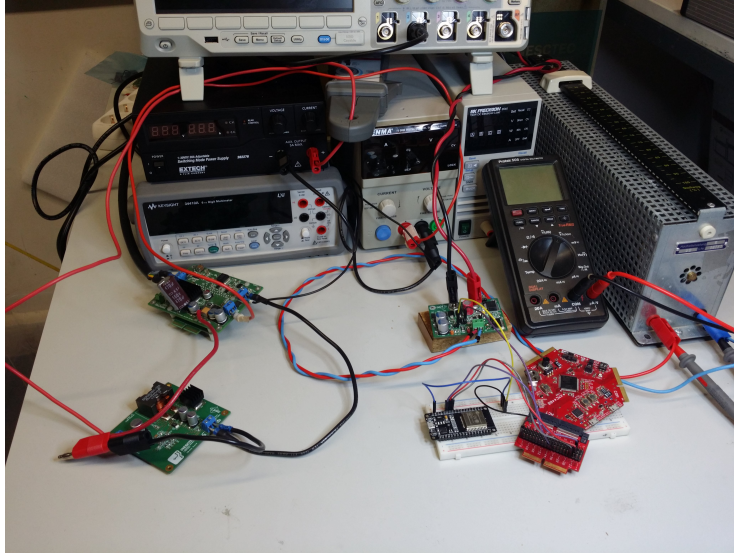


Figure 4.27: Mounted test setup

Figure 4.27 displays the full system mounted, including the salt water tank. Up close, in figures 4.28 and 4.29 one can see the transmitter side and receiver side, respectively.

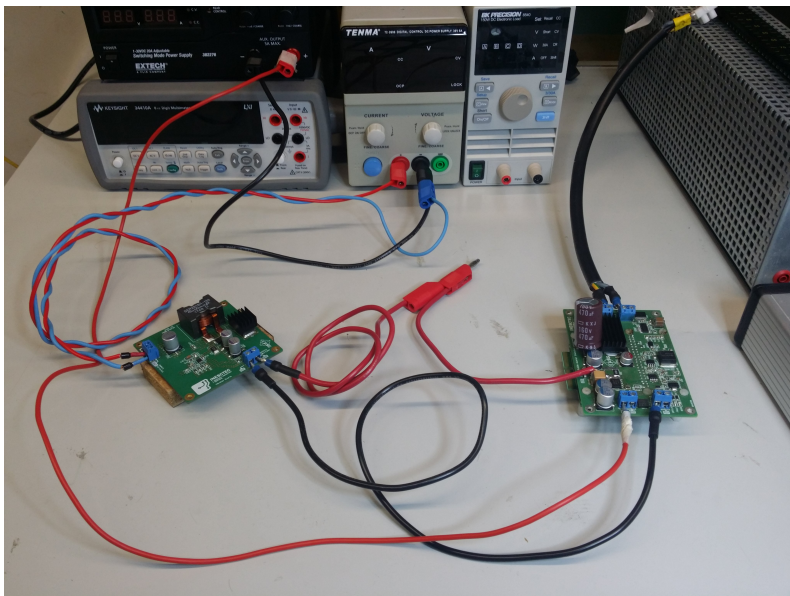


Figure 4.28: Transmitter side of the mounted test setup

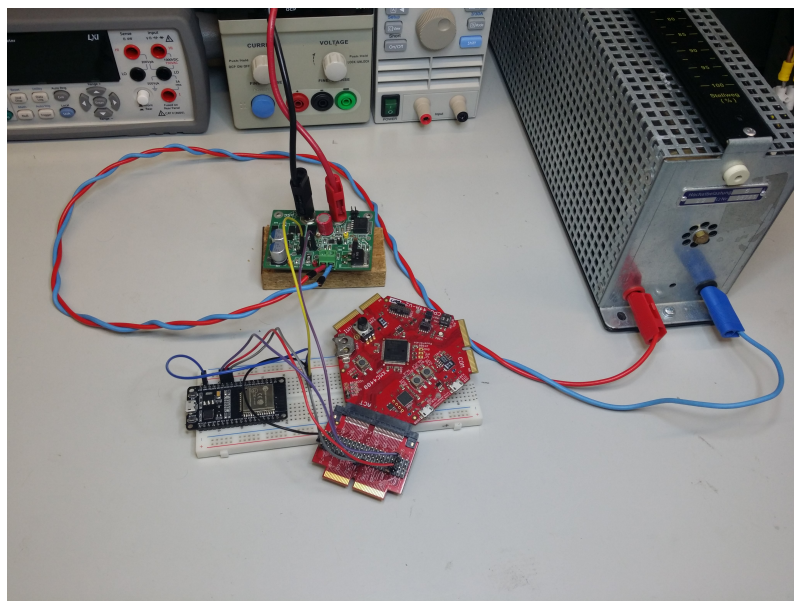


Figure 4.29: Receiver side of the mounted test setup

Experimental results of the efficiency and power of the test setup, at different points of the system, can be seen in figures 4.30 and 4.31. The tests were performed with a PWM wave set to 240 kHz and a 50-50 duty cycle.

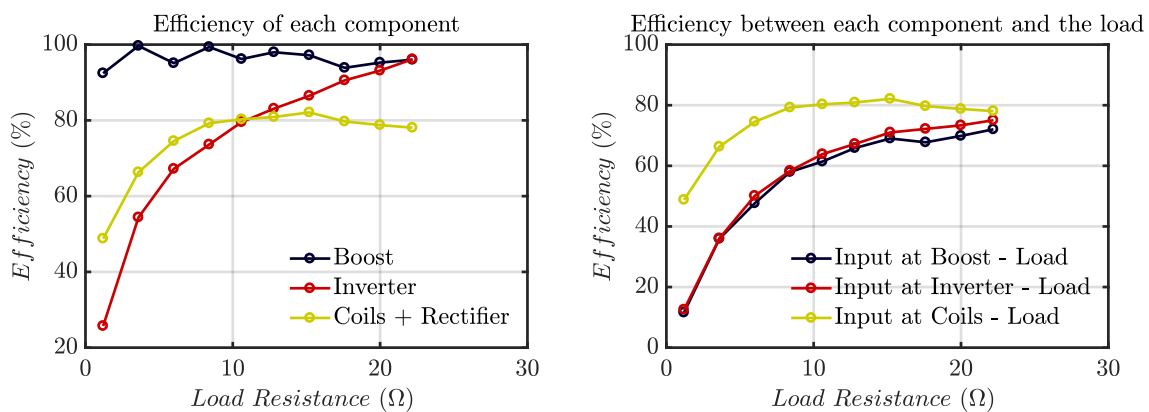


Figure 4.30: Efficiency of both each component and between the output and different points of the system

It is interesting to note, in figure 4.30, how each individual part of the system behaves in terms of efficiency and how the biggest loss of power transmitted occurs between the coils and the rectifier. One other conclusion is that the overall efficiency of the system is close to 70% when considering the ideal resistance for the frequency tested, 12.5 Ω for 240 kHz.

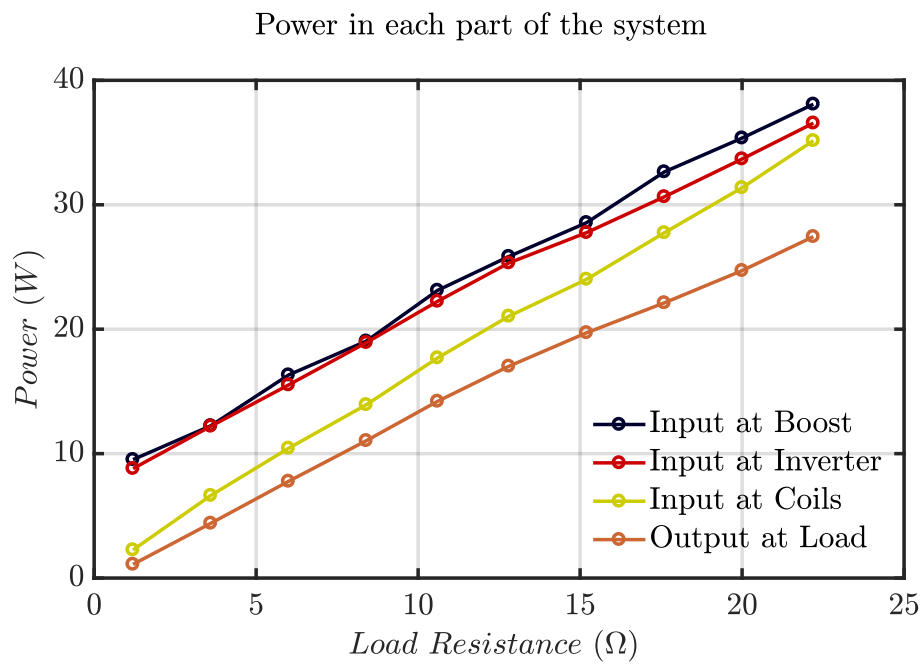


Figure 4.31: Power at different points of the system. The biggest drop in power is from the input at the coils to the output of the load, which basically corresponds to the receiver side.

Finally, on figure 4.31, we can see how much power there is at the input of each component and, in easy way, visually understand how much power is being lost in each part.

Chapter 5

Modulation

This chapter consists on the results and conclusions taken of several tests performed on the system. Initially, it was performed a test which verified, as proof of concept, that the transmitter could detect the changes in the transmitter, first seen using an oscilloscope and then using the current sense at the circuit. After this, a quick test using different load resistances was performed to check how the efficiency and ΔI were affected. The next part focus on the type of displacement available in the coils, especially when in real use case scenarios. By shifting the horizontal and vertical positions, one can simulate this behaviour and get an idea of the different levels of efficiency and ΔI to expect. Finally an analysis of the level of ΔI is performed, including how it behaves for different frequencies, as well as for the different positions testes.

5.1 Initial testing and limits

Starting off by explaining the procedure used for the testing performed. Initially, having setup up the system as figure 4.27 shows and using the functions developed on the receiver side to control the switcher and consequently the resistance to transmit data. For the tests performed, a resistance with a value of $25\ \Omega$ was used for the R_C . For the load, the resistance was changed according to the tests, being displayed as legend on the plots. On top of these configurations, a frequency sweep was performed for different positioning of the coils. Before proceeding with more intensive tests, we first need to ensure that the resistance switching is detected on the transmitter side, checking the current values over time. For a very low frequency, the system was first tested to prove the concept of data transmission by continuously sending zeros and ones. The results of such validation are presented in 5.1, for 1 Hz and 10 Hz.

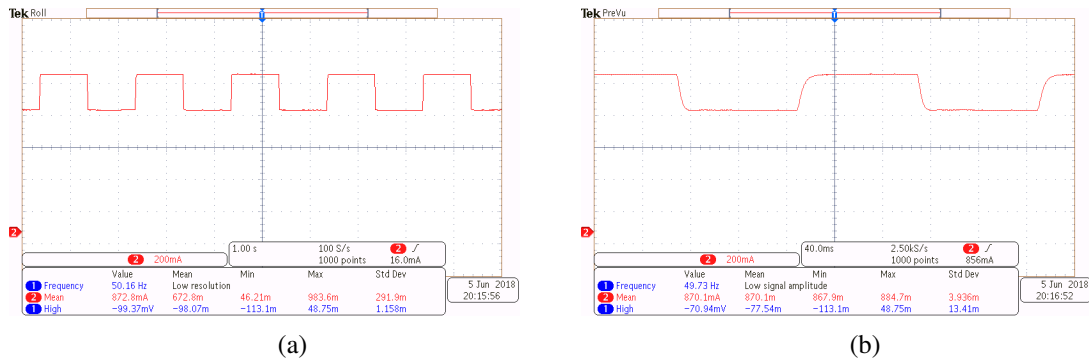


Figure 5.1: Simple test to verify that the transmitter senses the change in current

Further analysis of the sensed current at the input of the transmitter, one can see how the wave behaves according to the data being transmitted. The current peaks can be explained by the XMC microcontroller being connected at the receiver and introducing this effect to the system.

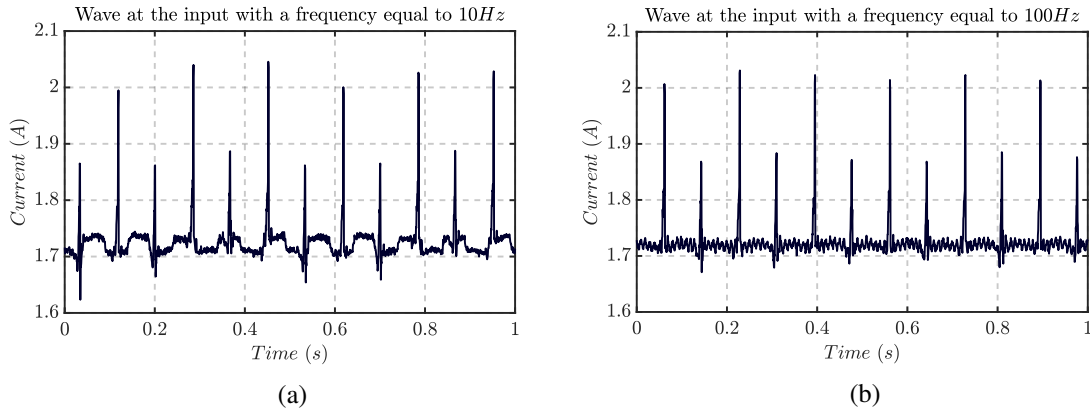


Figure 5.2: Sample of the signal sensed at the input

And lastly, how analyzing the sample with a Fast-Fourier Transform (FFT) algorithm, the frequencies at which the bits are being sent can be easily determined.

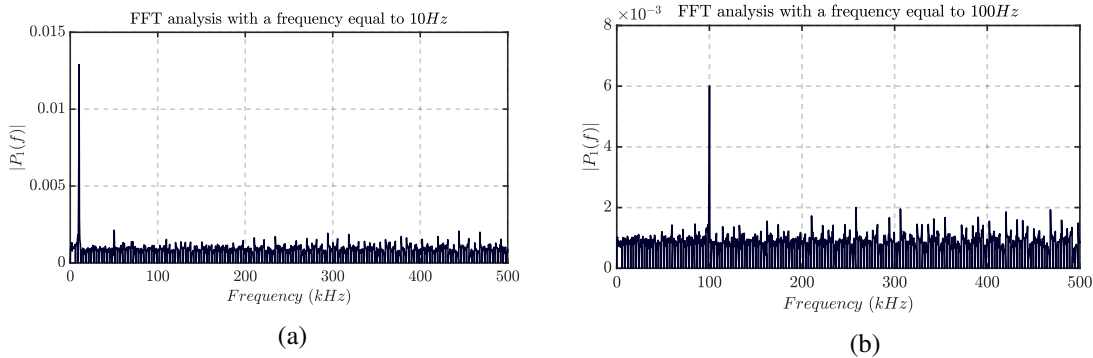
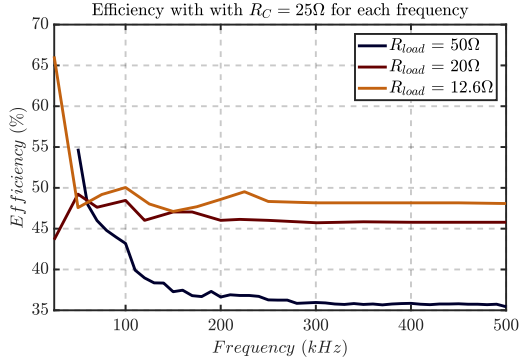


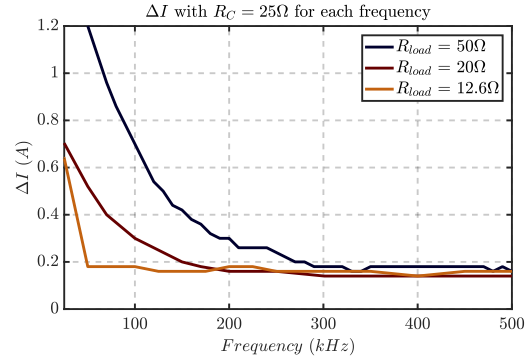
Figure 5.3: FFT analysis of the sampled signal

The most important aspects of the system to analyze and characterize are the input ΔI levels, overall efficiency over different frequencies and how it behaves for different values of k , i.e. varying the horizontal and vertical alignment of the coils. This way we can determine the maximum value of frequency that the system can achieve for communication purposes.

Firstly, beginning with a perfect positioning of the coils and varying R_{load} with 3 values, 12.6Ω , 20Ω , 50Ω . The efficiency, 5.4a, and levels of current, 5.4b, are presented next.



(a) Efficiency for each frequency

(b) ΔI current for each frequency

Taking a closer look at the results shown, one can see how having a lower value of R_{load} affects the efficiency positively and the ΔI negatively. There is a clear trade off in terms of these two specifications of the system.

For now, one needs to understand how the system behaves for different levels of positioning. Since we now have an idea on how the load resistance affects the system, for the next tests, the value of R_{load} was set to 20Ω and a sweep of frequencies were performed. Figure 5.5 shows the planned setup for this experiment, this is, to move the coils in a horizontal and vertical manner to achieve different levels of positioning and, therefore, different values of k .

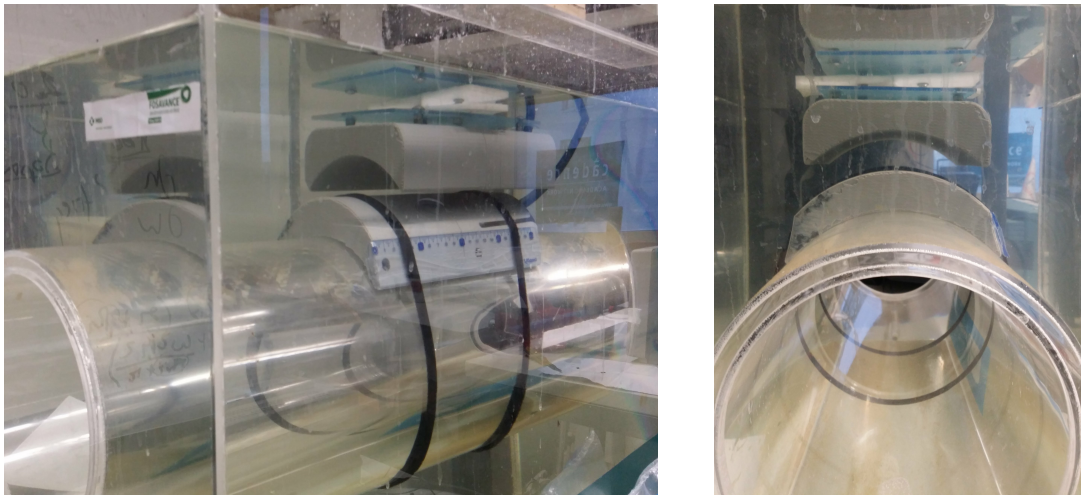


Figure 5.5: Testing for different positions

What follows are the results of the efficiency and ΔI for every position. Note that, based on 3.8, one can assume that the system behaves in a similar manner for complementary values on the horizontal shift performed and expect identical values for a negative shift. Bear in mind that the vertical distance corresponds to the difference between the casing of the coils. For the true distance value between coils one needs to add 4 cm to the vertical position.

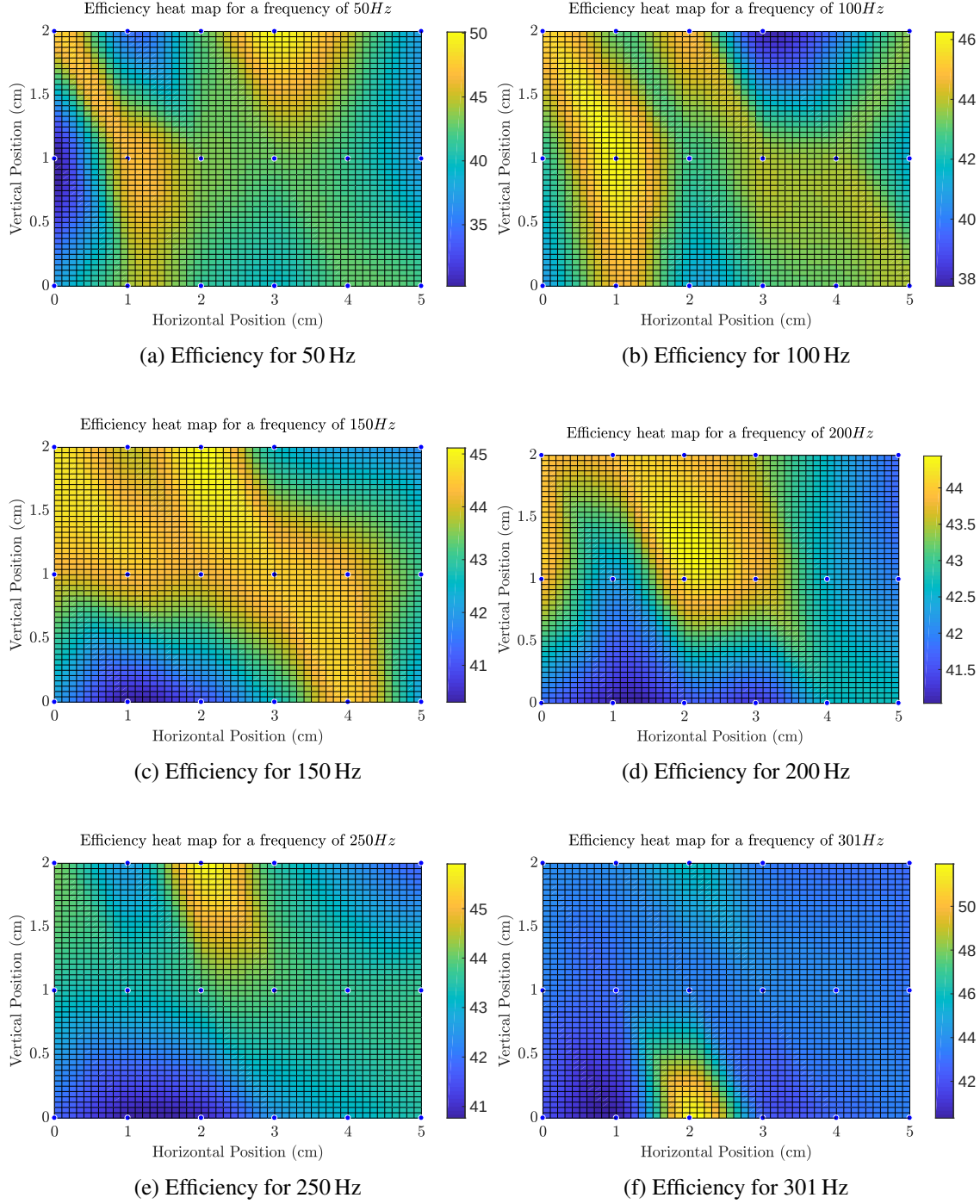


Figure 5.6: Efficiency heat map for different frequencies

Analyzing the results in figure 5.6, it is possible to see how the best efficiencies are achieved in the lowest frequencies, having a higher level of area covered as well, and that having a smaller distance between the coils improves the power transfer efficiency.

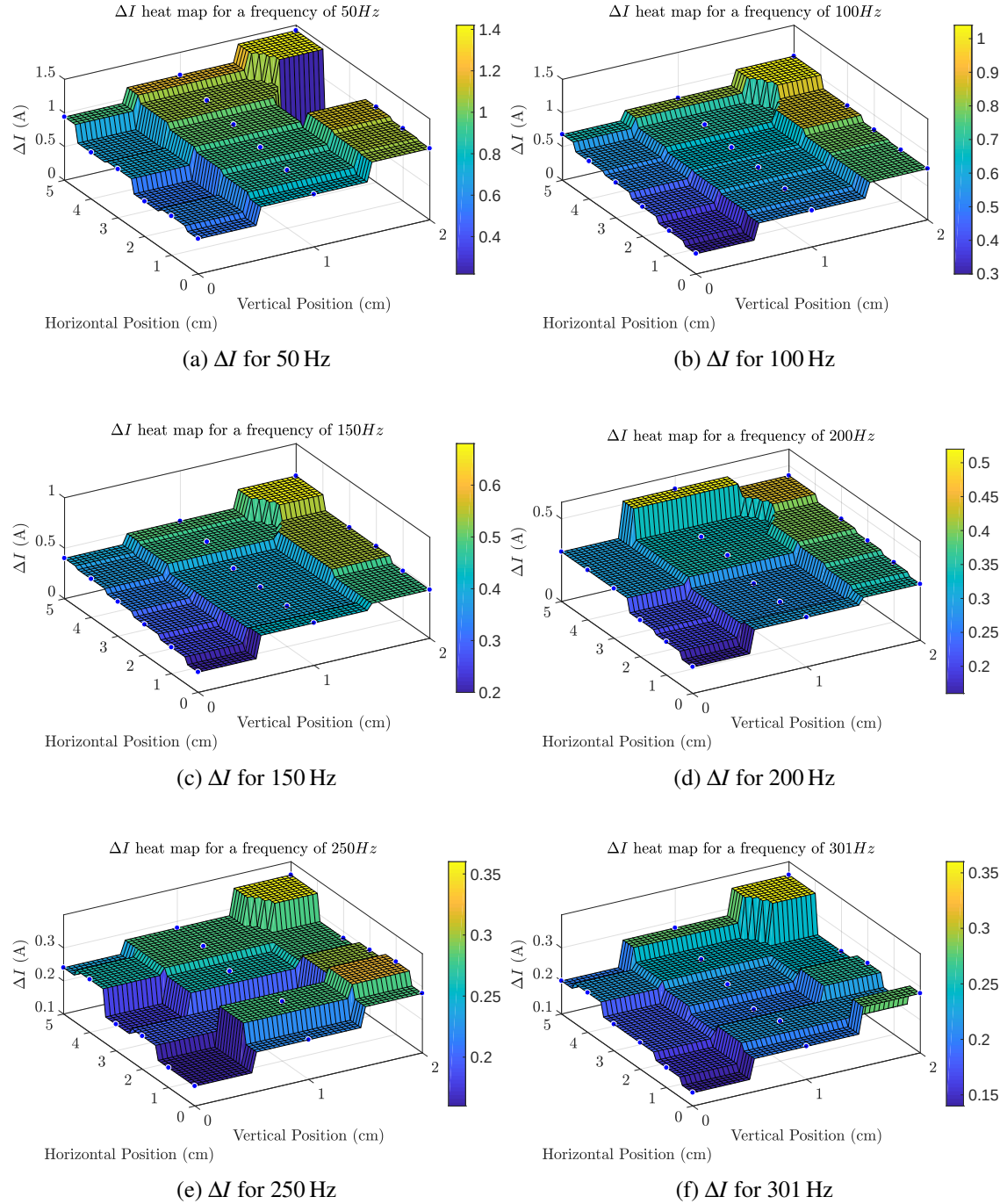


Figure 5.7: ΔI heat map for different frequencies

Looking at the results presented in figure 5.8, each line corresponds to different values of misalignment between the coils, ranging from 0cm to 5cm. The blue toned lines are when the

current is on a 1 state and the red toned represent a 0 state. For this one can see how farther away the coils are, the higher ΔI is. Delving on the current values for different vertical distances, performing a frequency sweep, one gets.

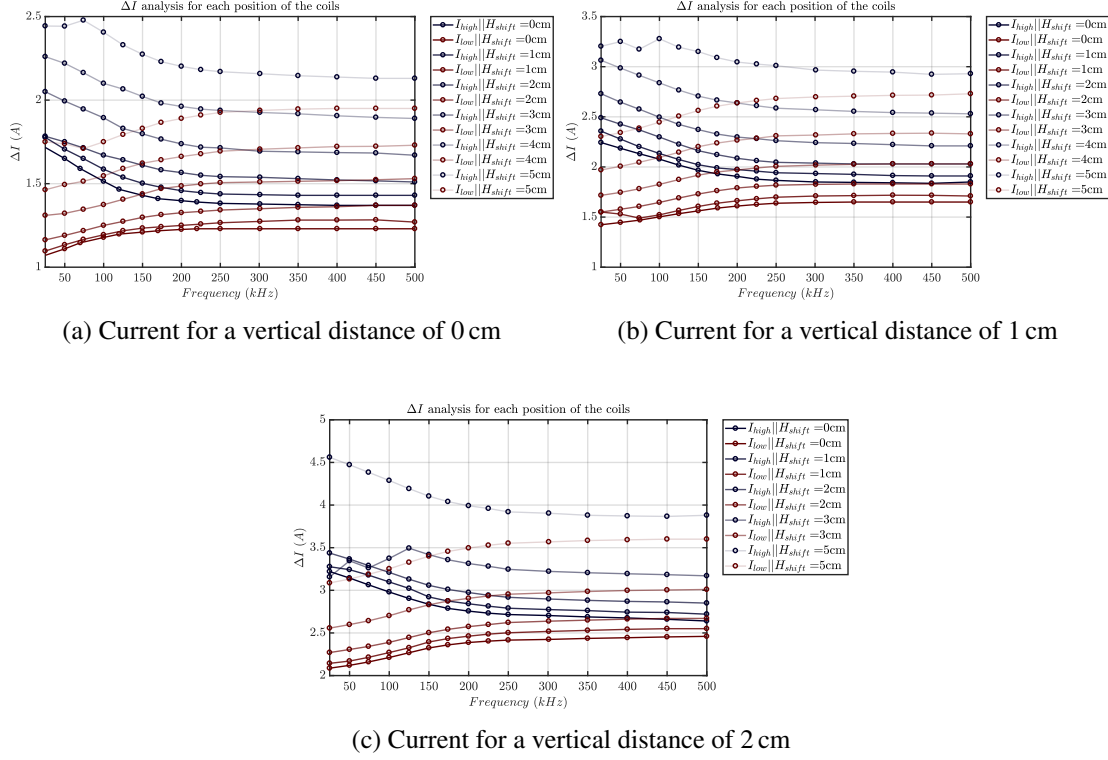


Figure 5.8: Current for the two different states for every position

Looking now at the distribution of results for both each position and frequency in a box plot. One can see how the efficiency has very little change in value and variation when the coils are misaligned, remaining in the 40% to 45% range.

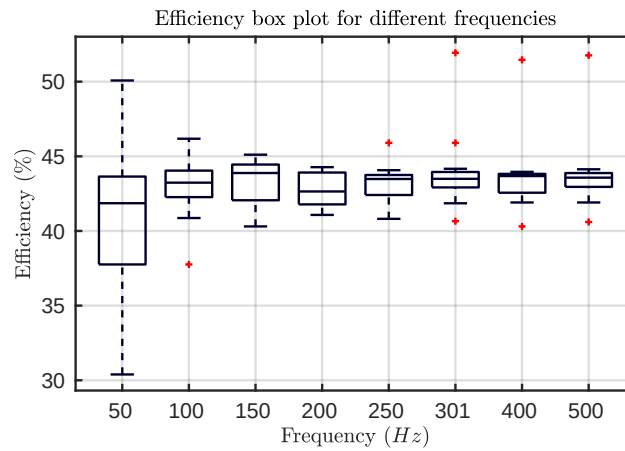


Figure 5.9: Efficiency box plot for each frequency

One can see the slight tendency for the system to have a 1% to 2% gain in efficiency when farther away the coils are, but overall for each position, the value of efficiency remains in the 40% to 45% range.

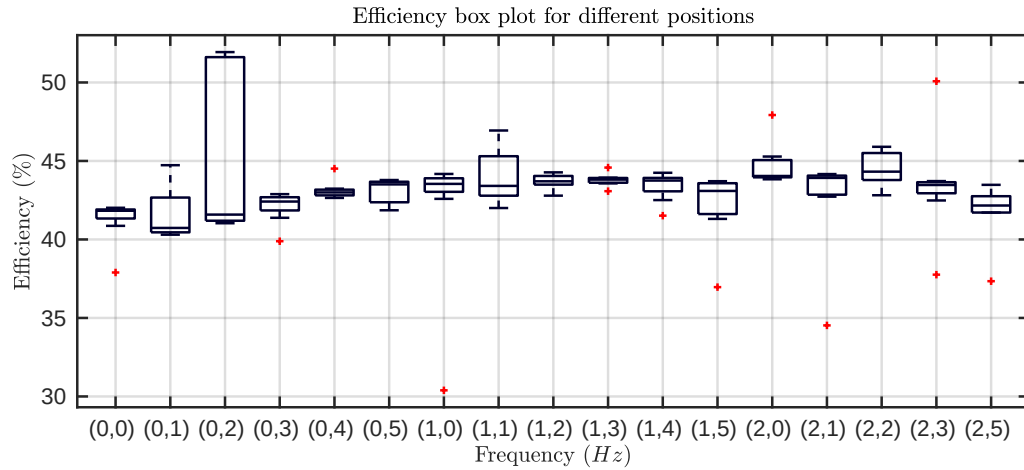


Figure 5.10: Efficiency box plot for each frequency

Finally, comparing the ΔI for each frequency, one can conclude that, the higher the frequency in which the data is being sent, there is less dispersion, being concatenated in a ΔI close to 0.2 A. For lower frequencies, the dispersion is quite big. There being a difference of 1.2 A between the point with the highest ΔI and the lowest for a frequency of 50 Hz.

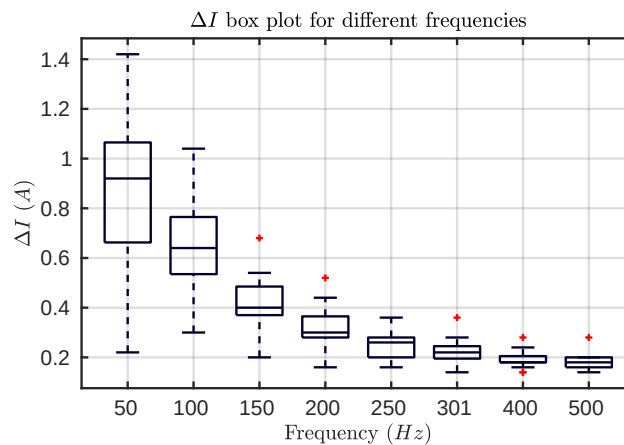
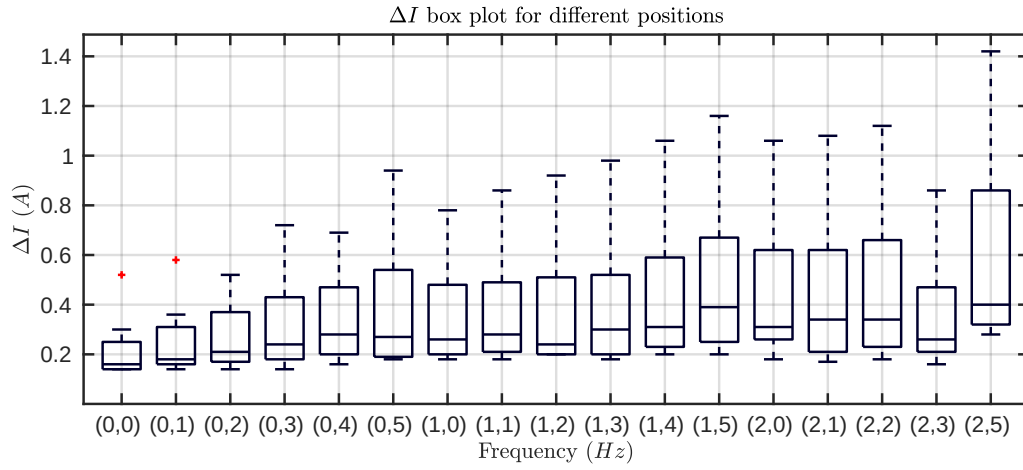
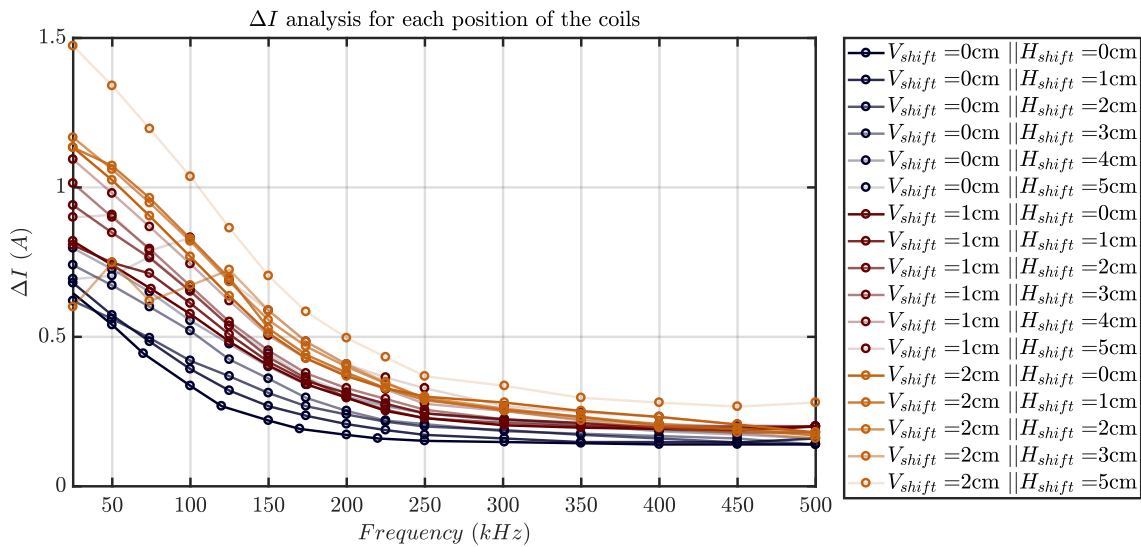


Figure 5.11: ΔI box plot for each frequency

When comparing the values of figure 5.12, one can see the trend of having bigger values of ΔI for higher distances between the coils. The explanation of this is below.

Figure 5.12: ΔI box plot for each position

Two important conclusions can be drawn from these plots. The levels of the input current are higher when the coils are distant from one another, which can be explained by the much smaller mutual inductance value. And also that the current values tend to stabilize after 200 Hz. This can be also explained by a bigger squared wave frequency, which leads to less time for the capacitors of the system to charge and discharge, leading to less of a ΔI available. Ultimately these conclusions can be further supported by the following results of ΔI for each frequency. Every line corresponds to a different positioning of the coils, being that the yellow lines correspond to all points with a vertical distance of 0 cm, red to a vertical distance of 1 cm and blue to 2 cm. Each individual line, having the same color, represents a different value for the horizontal misalignment.

Figure 5.13: ΔI for each frequency for each position

5.1.1 Conclusions

From these results alone, one can comprehend how the communication can be achieved from two distinct characteristics of the system, the amplitude of the current at the input or the frequency at which the resistance is switching, meaning one is not restricted to just one way of sending data [44].

In terms of amplitude modulation, it is affected by the distance and displacement between the coils, but can achieve higher transmission rates than the Frequency-Shift Keying (FSK) alternative. For this option two distinct options are available, one based on the transmission of bits, Binary Amplitude-Shift Keying (**BASK**), in which only one resistance is needed, while the other works with a symbol transmission basis, Multilevel Amplitude-Shift Keying (**MASK**), with a γ -parallel set of resistances to achieve γ^2 symbols.

Using the frequency modulation lets us have a more reliable and stable level of communication, since the K value has no affect whatsoever on the switching frequency. The downside is that since we need more than one period of the lowest frequency in order to be able to sample the signal and divide into its different frequencies, the overall transmission rate shall be slower than the Amplitude-Shift Keying (ASK) alternative. For the frequency modulation options available, the same concept applies, in which we have a binary data transmission based off the frequency, Binary Frequency-Shift Keying (**BFSK**), as well as a symbol based transmission link, Orthogonal Frequency-Division Multiplexing (**OFDM**).

5.2 Binary Amplitude-Shift Keying

Using the BASK digital modulation technique for transmitting bits of data, in which the switching resistance is alternated according to the binary data, which affects the amplitude of the input current.

In order to achieve this, a byte, $0xD2$ is sent, from the receiver, in an infinite loop. What follows are the results for different bit times.

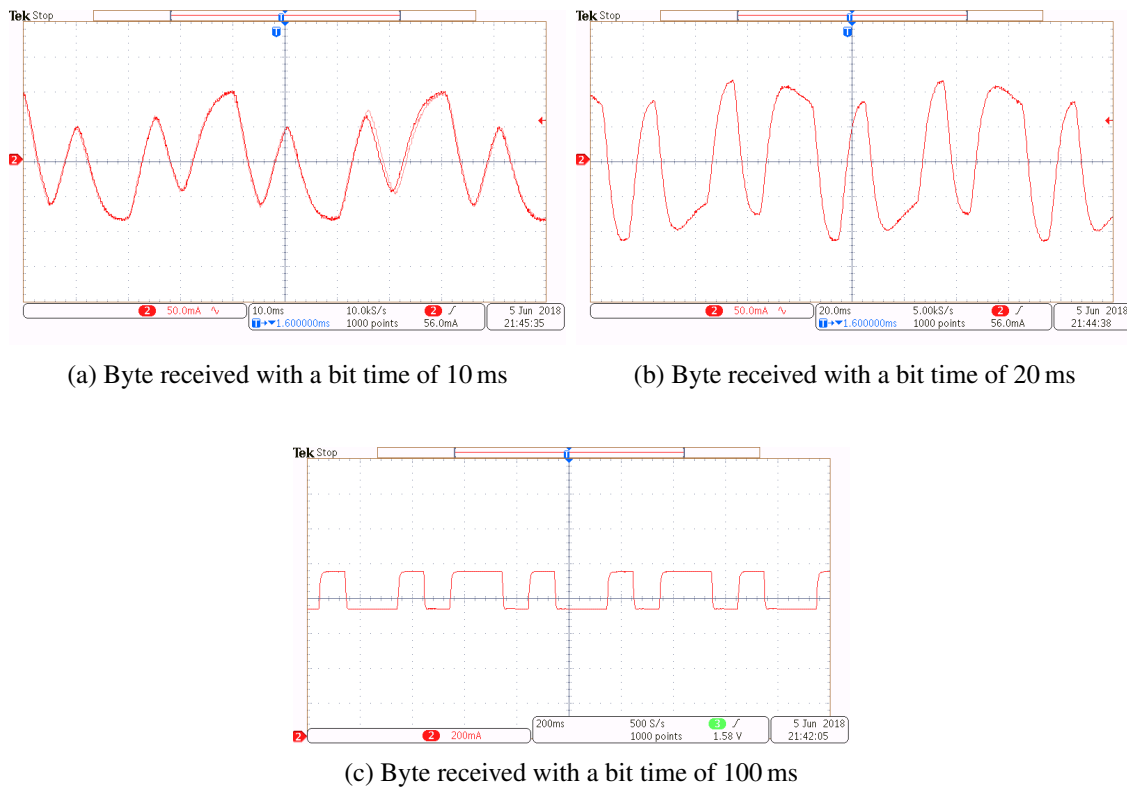


Figure 5.14: Byte $0xD2$ received for multiple bit times

It is possible to conclude that the transmitter can detect and demodulate signals with a bit time of 10 ms.

5.3 Frequency-Shift Keying

For this implementation, a decision was made to consider 100 Hz and 200 Hz as the frequencies of the BSFK technique, with a bit time equal to five times the lowest of frequencies. This is to test the detection and distinction of the two frequencies at various levels of positioning, the results of which are shown next.

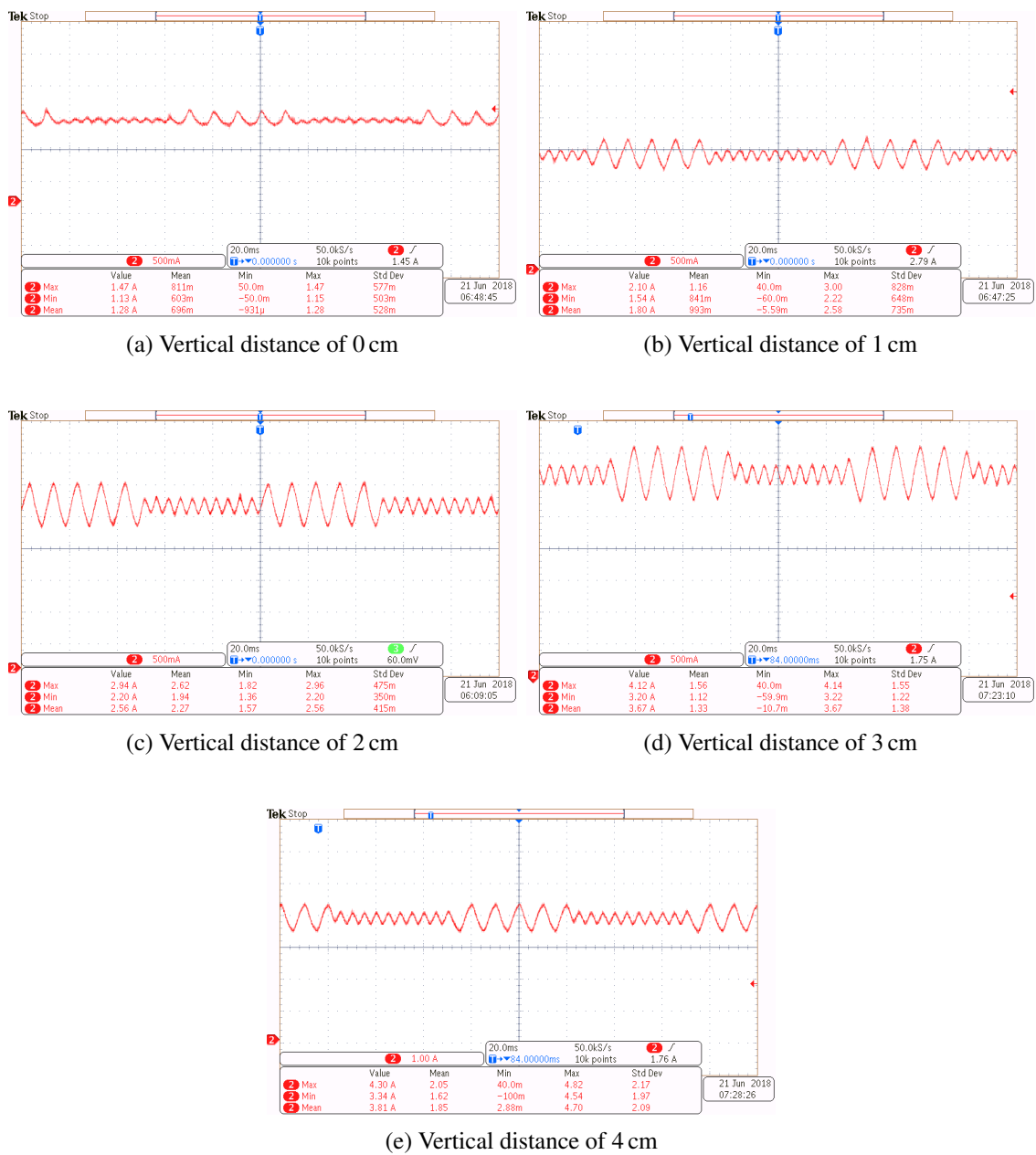


Figure 5.15: FSK analysis with centered coils

As it is possible to see, there is sufficient difference in frequency, as well as bit time, to detect two different states. This further strengthens the option for a FSK based communication.

The test performed next was similar to one mentioned in the BASK sub chapter. This was to send a full byte, more specifically `0xD2` and check the behaviour of the current at the input of the transmitter. First the control signal that comes out of the XMC is presented in figure 5.16.

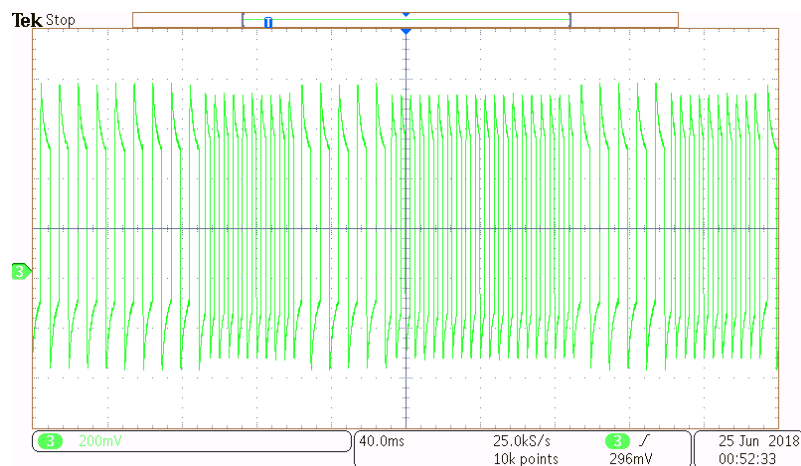


Figure 5.16: Control signal waveform at the receiver

The next image, 5.17 contains the results of the message received at the transmitter.

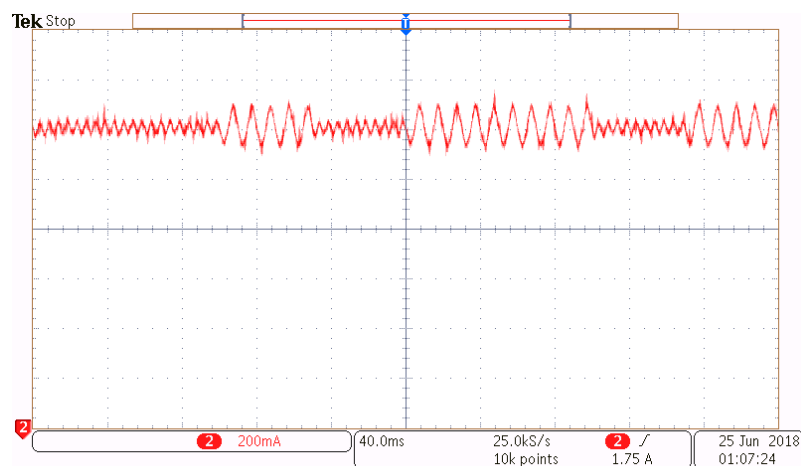


Figure 5.17: Current waveform at the transmitter

5.4 Conclusion

We now have sufficient data to verify that the transmitter can sense differences in the receiver side and this can be used to transmit data, through multiple types of modulation. For an ASK type of modulation, the max bit time achieved for a stable communication was of 100 ms, but it was verified that this modulation is affected by how coils are positioned. The FSK modulation solves this issue, but it is slower. For the testing performed, one could achieve up to 20 ms of bit time. On top of this, we were able to send and detect a byte at the transmitter, proving that the communication between the receiver and the transmitter has been achieved.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The original objective that was established was meant to study and implement an alternative way of transmitting data, while using the power transfer link in use in the system. The contribution of this work can be summarized as follows.

- Achieved data transmission with a low data rates which does not require extra equipment
- Transmitter and receiver software layers built
- Have a suitable type of communication for long distances underwater, with a decent data rate, better used when used in a vehicle–sensor case.
- A ASK modulation was achieved using the underwater wireless power transfer link, with decent levels of data rate for close distances
- A FSK modulation was fulfilled using the underwater wireless power transfer link, with decent levels of data rate for long distances

The work flow passed from the study and analysis of the system and different possibilities of achieving data transmission, continuing after with the implementation and testing of different feasible possibilities.

The results presented leave a broad spectrum of viable options to which the data transmission can be made. Either on a ASK type of modulation or a FSK type, there is enough of data that proves that one can achieve a sufficient data rate, as high as $10ms$ of bit time, provided with a stable detection.

In the ASK modulation, one could achieve a high bitrate, $10ms$, which varies greatly with the positioning of the coils. For the FSK modulation, there was a maximum bitrate of $20ms$, which varies with the amount of periods necessary for the frequency detection, but is immune to the positioning of the coils, being that frequency does not vary with it. Both these modulations offer

efficiencies in the order of 40% to 50%, which is not a major loss compared to when the system is single handedly charging.

With this, one can use wireless power transfer for both transfer energy as well as communicating and transmitting vital information of the system, which is crucial to reduce the amount of extra systems on a tight spaces, such as the one in the AUVs.

6.2 Future work

Having achieved data transmission, with more than one viable type of data modulation and having designed the PCB for a symbol based data transmission, the next step shall be to test this type of communication and check its reliability and then to build the upper layer of the transmission protocol that serves as a control algorithm, in order to achieve the level of autonomy on the charging process this project aspires. This should act on top of the more preliminary layer, knowing the type of modulation used, decode messages and act accordingly.

References

- [1] Nikola Tesla. Art of transmitting electrical energy through the natural mediums, 1905.
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