Faculty of Engineering of the University of Porto

Printed Electronics Power Supply for IoT Systems

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Abstract

In recent times, connected devices are becoming increasingly more common. Such devices are part of networks usually referred to as IoT (Internet of Things) and are converging to ever-smaller builds. This work aims to contribute to the miniaturization of such devices. To this goal, a power supply is proposed. The project intends to offer an alternative to common power supplies by making use of printed inductors. Such components aim to replace the conventional transformer by providing a reduced volume alternative. Traditionally transformers provide two functions in a power supply, voltage dropping if needed and galvanic isolation. The printed inductors here discussed are used only as a form of isolation providing safety to the system's end-user or any electronic component connected.

An investigation into these inductors is conducted and an implementation is presented. The investigation led to conclude that the inductors may be used to provide isolation but further improvements into the fabrication process are required. Due to the current fabrication process involving impure silver as the conductor, the resulting coils have a resistance excessively high, introducing a great level of losses.

To circumvent this problem, the proposed implementation uses high frequency switching for better results in the receiver side of the system and makes use of a Flyback switching topology with a negative feedback mechanism to regulate the output voltage.

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Abbreviations and Symbols

List of abbreviations

AC	Alternated Current
CeNTI	Center for Nanotechnology and Smart Materials
DC	Direct Current
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
Op-Amp	Operational Amplifier
RMS	Root Mean Square
SMPS	Switched Mode Power Supply
TPS	Transformerless Power Supply
NMOS	nFET Metal Oxide Silicon
WPT	Wireless Power Transfer

List of symbols

H	Henry
F	Farad
Ω	Ohm
µ	micro
W	Watt
V	Volt
A	Ampere

Chapter 1

Introduction

1.1 - Context and Motivation

This thesis is proposed by CeNTI – Center for Nanotechnology and Smart Materials under the guidance of the Eng. João Silva. The project is a joint endeavor with the University of Porto with mentoring by Dr. Vítor Grade Tavares.

In recent years, the connectivity of devices is increasing and becoming an established reality, both in the industrial environment as in personal and domestic technology. These networks, also known as IoT (Internet of Things), allow for greater efficiency and comfort in the system's management. Such devices are capable of sensing, networking, and actuating activities, among others.

The work developed aims to deepen CeNTI's involvement in the development of IoT technologies.

The institute is a research facility focused on the development of technologies involving smart materials and nanotechnology. Such fields allow for the development of innovative solutions. With the institute's equipment, it is possible to design and manufacture circuits using printed electronics to create novel approaches in the development of devices to be integrated into IoT networks.

IoT devices are often small machines that require small amounts of power to function. Sensing devices, generally, do not require much energy, only the necessary amount to perform a measurement and send the information to the processing unit of the network. This transfer can be done directly or through another network node that may be in closer proximity, in its turn the device forwards the information.

Most of these small devices are frequently powered by batteries but in the context of the investigation performed at CeNTI, a wired solution could also be used. Such a solution can be used by drawing power from the electrical grid. This method can be highly effective in dropping and isolating the mains voltage but typically requires a lot of volume due to the bulky nature of such components.

In this document, a solution is presented to make use of printed electronics techniques to design a different form of powering IoT devices.

1.2 - Problem Definition

As referred, in recent times, the use of smart or connected devices is becoming more common. Smartphones are a commodity now that most people can enjoy. The same can be said about the internet.

Most people can afford to have one or more smart devices and the number will keep increasing. Also, the interest or need for network devices goes beyond domestic interest. Companies are increasingly more willing to invest in applications that allow for better control of systems.

The size of a device will always represent an important selling point to a product. In the case of IoT or edge devices, size is of even greater importance. For low power devices, the power supply may represent a considerably large part of the project volume. Especially if the device is very small.

The problem here stated is the volume that most power supplies require and so a solution is investigated that may contribute to further miniaturization of IoT devices.

1.3 - Objectives

The goal of this dissertation is to evaluate the possibility of using printing technologies to construct a power supply solution. Such a device could be used in projects in which volume should be minimized as it is the case for many IoT solutions.

Printed electronics are appealing to use in IoT and edge devices in general because they allow for quick prototyping and could reduce the volume of the device.

The work intends to verify if and in what conditions, printed electronics, can be used to facilitate the model process of electronics design.

The aimed result is a power supply capable of delivering 0.5W of regulated power to a load as low as 50Ω, output 5V and 100mA. For security reasons, the system must also be isolated and regulated. The outcome of the investigation and work developed fulfills these requirements on a simulation base. The designed system performs an AC to DC conversion, the resulting system is then converted to a high frequency AC signal and isolated with a 1:1 transformer, built with printed inductors. The signal is then converted once again to DC to power the load. The voltage on the load is regulated with a feedback system that controls the PWM signal generator.

1.4 - Thesis Structure

This document is divided in five chapters, where firstly, in chapter 2, a literature review and background contextualization are introduced. The core concepts of the thesis are presented and explained. The study of these fields contributed to the final project and each played a part in the final design. It starts with the explanation of the main electronic concepts which are explored within context. The concept of galvanic isolation and possible solutions leads to the concept explored in this work which is the use of printed electronics as magnetic isolation.

Through the investigation performed it is made clear that high frequency is required for better efficiency and so switching methods are also presented in this chapter, as well as the systems required to achieve it.

Following, in chapter 3, there is a presentation of the work developed involving printed coils. Electromagnetic simulations performed in Altair FEKO are presented and lead to the realization that a higher frequency is needed. The fabrication process of the coils is described and followed by the physical experimentation. In the design of the power supply, the coils will represent a vital part due to the isolation they provide.

In chapter 4, a solution is presented making use of the work with inductors. The power supply presented drops the voltage from the mains using a capacitive voltage division. Then the circuit is isolated from the output trough the coils studied. The resulting signal is then rectified and regulated to be presented to the load.

The final chapter concludes the work and presents the unexplored components of the project as well as the optimizations that could optimize the system.

Chapter 2

Background Theory and Literature Review

2.1 - Voltage Drop and Mains Electricity

Mains electricity consists of the electric power available to domestic and entrepreneurial means.

The power grid, at the consumer level, provides the electrical energy of a sinusoidal form with 230V (rms) of nominal voltage at a frequency of 50Hz. These values are the standard for most of the world, yet for North America, the most used combination is 120V and 60Hz [1]. The grid offers an extremely powerful and versatile source of energy for different uses like lighting, appliances, industrial machinery, among others.

These nominal voltage values are given in RMS (Root Mean Squared), which is defined in most literature as the amount of AC power that produces the same heating effect as an equivalent DC power [2].

$$V_{RMS} = \frac{Vpk}{\sqrt{2}} \tag{2.1}$$

When applied to the standard value in Europe (230V), [1] it results in approximately 325V at peak voltage, this value will further be used in this thesis as the reference for the mains DC voltage.

Most electronic devices operate with values much smaller than those delivered by the grid. Devices like a smartphone typically recharge the internal battery with around 5V and 2.0A of direct current, this equals a power transfer of 10W. This voltage value is smaller than the 325V delivered by the wall socket, and so, to effectively charge the device, it is necessary to reduce this voltage using a voltage divider or step-down transformer/converter.

A voltage divider is a circuit configuration that through the impedance of passive components sets a voltage which is a fraction of the input.

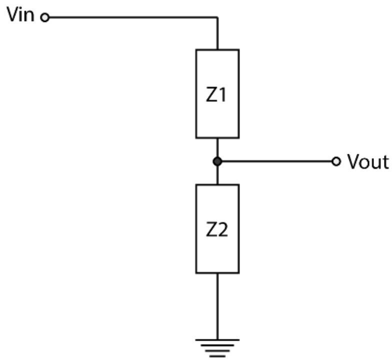

Figure 2.1 - Voltage Divider.

In the cartesian form the impedance is expressed as:

$$Z = R + jX \tag{2.2}$$

The reciprocal of impedance (Z), which is expressed in Ohms (Ω), is admittance (Y), expressed in Siemens (S). The X is the reactance, the complex component of the impedance.

The reduction in voltage is commonly achieved by connecting two electrical impedances as described in **Figure 2.1**, the voltage is divided proportionally among them.

In the general form:

$$Vout = \frac{Z2}{Z1 + Z2} Vin \tag{2.3}$$

Based on this formula, there are different ways to achieve a voltage division and with these a variety of combinations, the primary methods of voltage division are:

- **Resistive divider:** The resistive divider consists of a circuit composed of two resistors and the relation between both determines the voltage division.
  This method is simpler but is also the one with the highest electrical cost. According to the ohm law, $P = RI^2$, power consumption (W) is proportional to the electrical resistance of the component which means that a voltage division of the mains power will cause energy consumption in the process.

- **Capacitive and inductive dividers:** The capacitive, as well as the inductive dividers, use the same principle of voltage division as the resistive but instead of resistance, it uses the reactance for both capacitive divider inductive divider. Ideally, the capacitive or inductive dividers do not dissipate energy and are more adequate to drop the mains voltage without energy loss, making the system more efficient.

There are also combinations of elements like the low pass RC filter which combines a resistor and a capacitor. These systems combine resistance and reactance to achieve voltage drop and are generally used when there is a need for frequency filtering. In the case of the

RC filter the frequency cut could be high pass or low pass, depending on the purpose intended.

2.2 - Power Supplies

A power supply is an important part of any electric circuit because It provides the energy the circuit needs to operate. Nearly all devices require a constant supply of power, free from major fluctuations.

Transformerless power supplies (TPS) are a type of circuit capable of receiving AC power and convert it to a low voltage DC without the need for a transformer. This type of electrical configuration is usually limited in terms of voltage and current output, normally current is limited to a few tens of milliamps [3].

The supply harvests energy from a source, like grid electricity, and then converts it to a stable and regulated output. Power supplies can be of two types, Linear Regulated Power Supplies (LPS) and Switching Mode Power Supplies (SMPS).

Linear regulators were the most common form of power supply up until the 1970s [4] but in recent times its use is not prevalent.

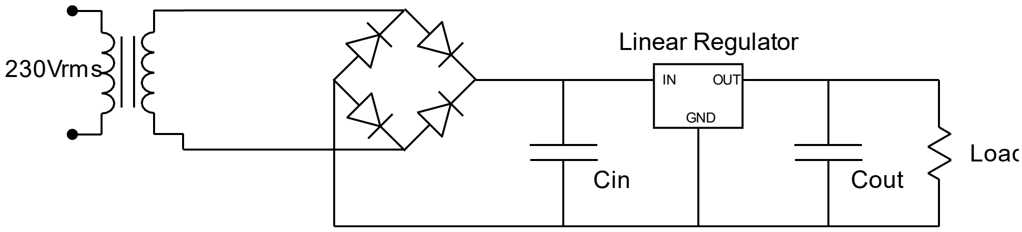

Figure 2.2 – Power Supply With Linear Regulator.

AC voltage is first lowered by the transformer and then rectified by using a diode bridge. The signal is then smoothed to a DC voltage with capacitors. The signal is then regulated with the use of an IC regulator or transistor. In **Figure 2.2**, an example of the supply is demonstrated. The linear regulator acts as a variable resistor. This allows for the resistance value to change to match the power output requirements. One problem introduced by using this type of regulation is the constant power dissipation. Because the voltage regulator is constantly resisting the current to maintain the voltage it also expends energy.

Due to constant power dissipation, such circuit configuration also requires a heatsink. This component will transfer the heat generated by the circuit to a fluid medium like air or liquid coolant.

With the need for the heatsink plus the transformer, this type of power supply is often a very bulky solution.

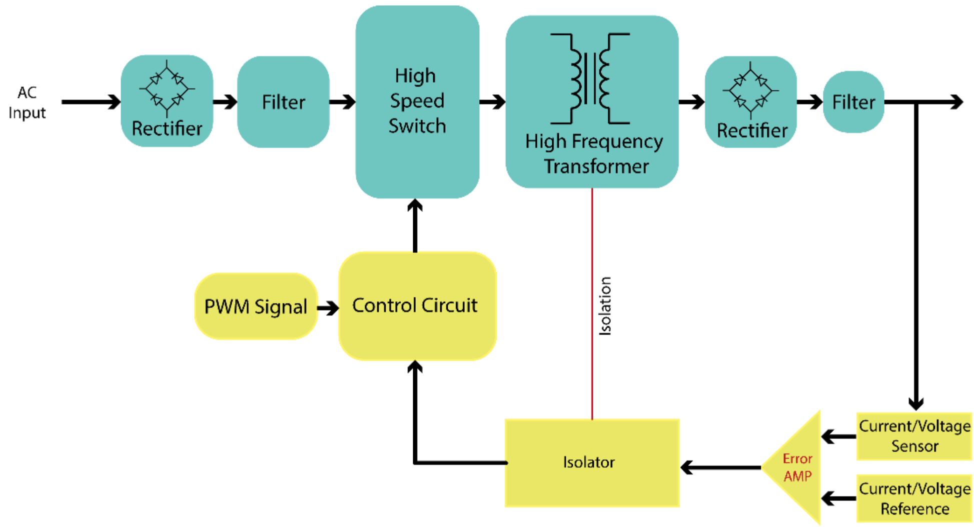

Figure 2.3 - Switched Mode Power Supply.

An SMPS is a type of power source which uses a high-frequency switch to convert the input signal into usable output while also providing regulation. This type of power supply allows choosing if the output signal is a step-up or step-down in relation to the input. The main advantage of SMPS is the stable and regulated DC output with an efficiency of up to 90% or more, depending on the power supply, without the need for lossy linear regulators. In **Figure 2.3**, the block diagram for an AC/DC conversion with an SMPS is represented.

As discussed previously the typical voltage available for domestic consume in Europe is 230V AC which means 325V of DC peak voltage. After a voltage step-down, incorporated in the power supply, the input will be reduced to a smaller value but remain an AC signal like represented in **Figure 2.4**, which is still an improper signal to use in many electronic devices expecting DC power.

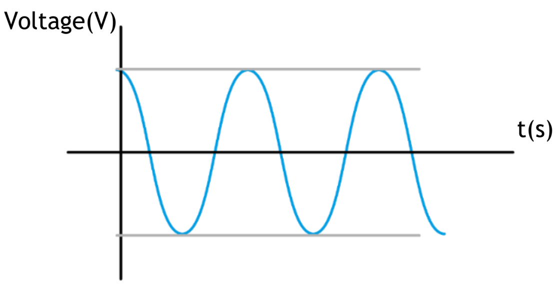

Figure 2.4 - Sine Wave.

After the voltage division, the signal is rectified. This rectification may be full-wave or half-wave depending on the project's needs.

The full-wave rectification employs four diodes to invert the polarity of the negative part of the input, it is possible to accomplish this with diodes because they only allow current in one direction. By combining four, the full input is used. The signal always possesses a return path no matter the current direction.

In **Figure 2.5**, the output signal of a Full-Wave diode bridge is represented. The blue line represents the signal at the terminals of the diode bridge and the red line the same signal, post smoothing. In **Figure 2.6** the circuit which generates that signal is showed. **Figure 2.8** - Half Wave Bridge

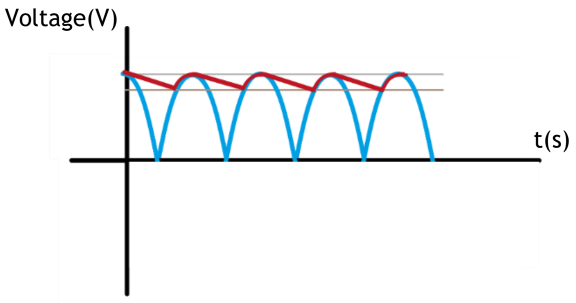

Figure 2.5 - Full Wave Rectification Signal.

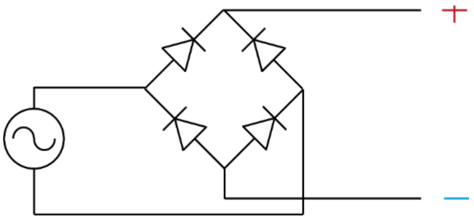

Figure 2.6 - Full Wave Rectification.

The half-wave rectifier only uses the positive part of the signal, excluding the negative part. A representation of this effect is represented in **Figure 2.5**, and the respective circuit in **Figure 2.7**.

In both rectifications, the smoothed signal (red line) is obtained by placing a capacitor in parallel with the load. In **Figure 2.9** the complete configuration is presented. The capacitor discharges as the signal begins to decrease, limiting the drop to an expected ripple, see **Figure 2.6** and **Figure 2.5**.

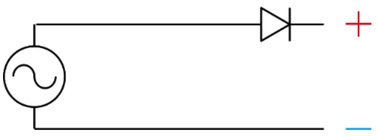

Figure 2.7 - Half Wave Rectification

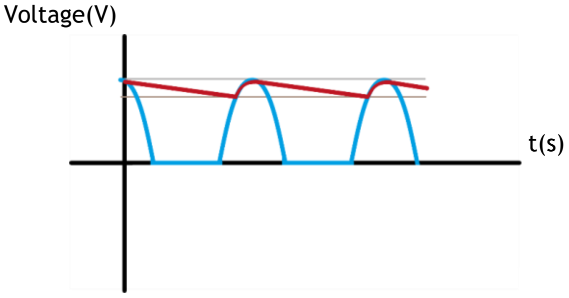

Figure 2.8 - Half Wave Bridge

Ripple is the ratio of the maximum variation below the expected voltage. It is calculated by measuring the maximum value and the minimum value post smoothing. The calculation is then performed as presented in equation (2.4).

$$Ripple(\%) = \frac{Vmax - Vmin}{Vmax} 100 \quad (2.4)$$

The calculation of the rectifier capacitor depends on the frequency the input signal and the connected load. The time required for the voltage at the capacitor's terminals to drop to V_0/e is equal to RC. The greater RC in relation to the frequency the more effective the rectification will be, and less ripple will remain.

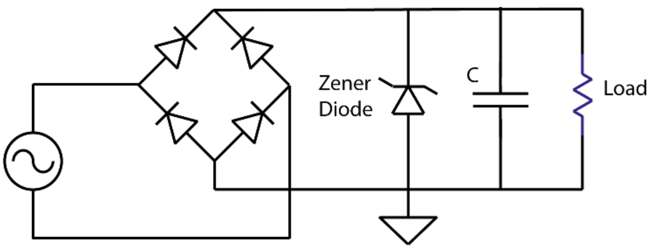

Figure 2.9 - Full bridge Rectification.

2.3 - Galvanic Isolation

Galvanic isolation is the convention used when different electrical parts of an electrical circuit have different ground potentials.

Isolation is of importance when it comes to safety, both of human operators as to other devices which the original circuit might need to communicate or transfer energy to.

When dealing with devices like the transformerless power supply that are directly using the mains electricity there's no true ground associated with it, and so if at any point some "real" ground comes in contact with the circuit's return path, the circuit will close through it which represents an electrocution hazard.

Isolation may refer to signal or power isolation [5]. While both depend on the complete isolation of the input from the output the concept appears in different forms depending on its need. The concept is referred to especially when there is a need to transfer information or power across the isolation.

When referring to signal isolators the main purpose is to transfer the signal and not power. Such isolation is often used in communication technologies.

Power isolation in its turn aims to transfer energy while also protecting the output of the circuit.

2.4 - Signal Isolators

With signal isolators, there is generally no concern with the amount of power transfer because the purpose is to transfer data, in the sense of bits or just the raw analog signal.

Its need arises, usually, when the two circuits involved are using different power sources and if they were to communicate directly it could result in damaged circuits.

The most used types are optical and electromagnetic isolators, but other types may be achieved.

2.4.1 - Optical Isolator

The optical isolator, or optocoupler, uses light to communicate between two independent

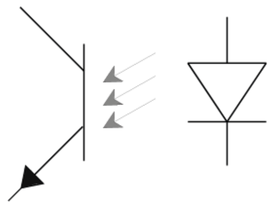

Figure 2.10 - Optocoupler.

circuits.

The most common form of optocoupler consists of a LED and a phototransistor; in **Figure 2.10** a representation of such a device can be observed. When the system is ON, the LED (component to the right) activates and starts transmitting information as light. The receiving phototransistor (component to the left) in its turn receives the energy in its Base port which then allows for current to flow from the Collector to the Emitter. On the receiver side frequently, the phototransistor is used as a gate. When the transistor begins conducting the gate opens. In this manner, the signal is passed from one circuit to the other.

Other types of optical isolators exist using other methods to receive signals. Among them there is the LED-photodiode which uses a diode sensor, the LED-LASCR using a thyristor on the receiver, and lamp-photoresistors in which the receiver changes its resistance based on the received signal.

2.4.2 - Hall effect sensor

The Hall effect sensor is an isolator device that responds to the fluctuation of magnetic fields. Its output voltage is directly proportional to the magnetic field flowing across the sensor.

Such sensors are often used for proximity sensing, positioning, speed detection and current sensing [6].

The working principle of the sensor is the effect that gives it its name, the Hall effect. Inside de sensor, a strip of metal has a current flowing across it, in the presence of a magnetic field the electrons in the said strip are deflected toward one edge producing a voltage gradient across the strip.

The main advantages of the Hall effect sensor as an electronic switch are its cost, the high-frequency tolerance and potential for low volume. Yet cannot provide much measuring accuracy.

2.4.3 - Capacitive coupling

Capacitive coupling is another type of signal isolator in which the signal is transmitted through electric induction. The system consists of two electrodes like metal plates, an anode and a cathode separated by a dielectric material such as air. The alternating voltage applied to the transmitter side induces an alternating potential on the receiver by electrostatic induction.

2.5 - Power Isolators

Power isolation consists of the separation of low power-sensitive devices from greater power lines. The topic of power isolation if of higher importance for this dissertation because there is a need for isolation, for security reasons while maintaining power transfer.

2.5.1 - Transformer

The most common and effective form of power isolation is the transformer.

A transformer is a passive electrical device that transfers electrical energy from one circuit to another. The working principle of the transformer is electromagnetic induction [7].

Electromagnetic induction is the phenomenon that occurs when DC current flows through a conductor, creating a magnetic field around it, **Figure 2.11**. This effect can be magnified if the wire is twisted into a coil. The magnetic field is proportional to the amount of current flowing through the coil and the number of turns.

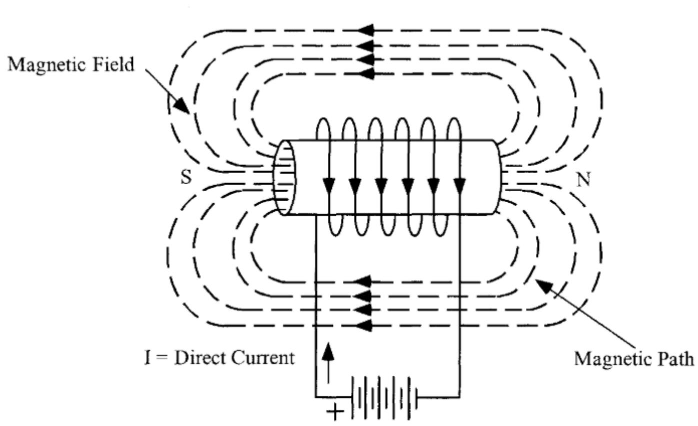

Figure 2.11 - Air-Core Coil with dc excitation, reprinted from [39].

In transformers, there's an input side and an output, from here forward to be referred to as the primary and secondary respectively, **Figure 2.12**. The primary receives a varying electrical current that by electromagnetic induction creates an oscillating magnetic field. On the secondary side, the reverse principle occurs. The magnetic field generates within the coil an alternating current if connected to a load. The induced current can then be used to power electronics.

The relationship between the magnetic flux density, B, and the magnetizing force, H, for an air-core coil is given by:

$$B = \mu_0 H \tag{2.5}$$

Where μ_0 is the permeability in a vacuum. The relationship between B and H is linear and is the greatest advantage of air-core coils.

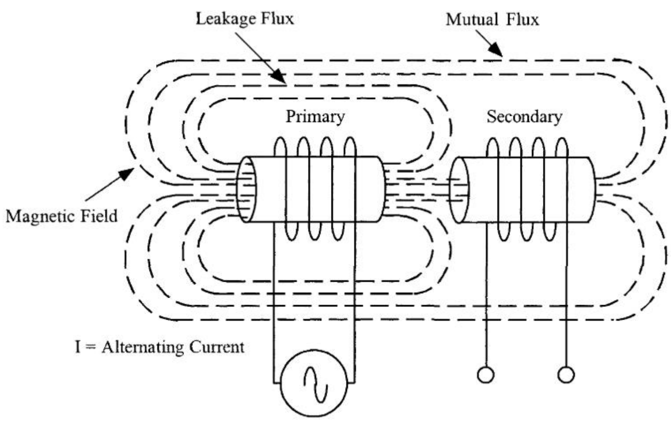

Figure 2.12 - Simplest Type of Transformer, reprinted from [39].

2.5.1.1 Magnetic cores

Most materials possess poor permeability due to low magnetic flux conduction. The permeability of every material is measured relative to vacuum/air. So, relative to itself the vacuum has a permeability of 1.0. Many non-magnetic materials like air, paper and copper have permeabilities in that order. Some materials, however, have a high permeability, like iron, ferrite, nickel, cobalt, and alloys created for that purpose, ranging from hundreds to thousands. These sorts of materials can be used to achieve better results than those achieved with an air-core, **Figure 2.14**.

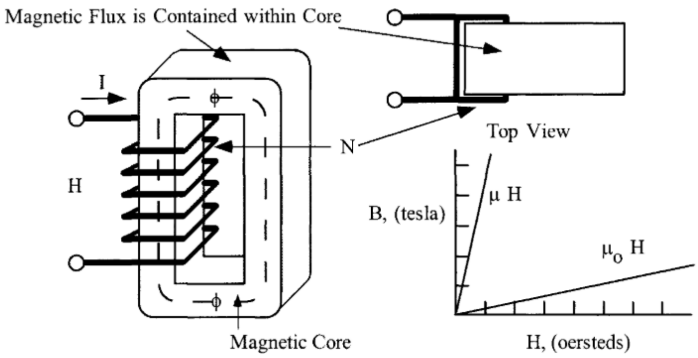

Figure 2.14 - Introduction of a Magnetic Core, reprinted from [39].

When discussing the role of a magnetic core is important to consider the equivalent circuit of the system. Two models are used to represent the circuit, the π model and the T model. The most used system is the T model [8] due to its simplicity. It describes the electrical operation of the transformer to low frequencies. This model has the leakage inductance (L_s) divided into two branches, one associated with the primary (L_{s1}) and the other with the secondary (L_{s2}), also a shunt magnetizing branch composed by the parallel between R_m and L_m. The reviewed model is shown in **Figure 2.13**.

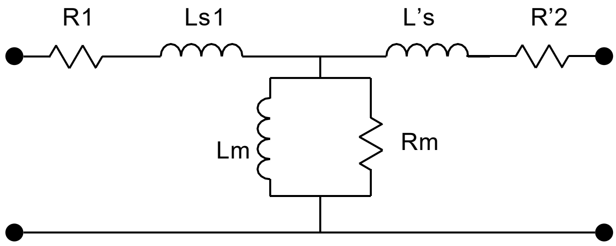

Figure 2.13 - T Model.

The T model does not completely describe the equivalent circuit of the transformer even though it is a good estimate. This is so because leakage induction in the T model is described as belonging to two different coils, and thus, the leakage inductance can only be defined for a pair of windings. Therefore, this approximation should only be applied when the elements do not have any physical relation with the transformer's building elements, like the core or the windings. In real transformers, this approximation might be too coarse when applied to some cases and so a different model is presented.

For most cases, the T model is a correct approximation and the simpler approach to modeling. Yet, studies have been conducted that reveal that the T model is incapable of properly representing the transformer under heavy saturation, see [9]. Errors up to 73% in inrush currents have been measured when the transformer presents a large leakage inductance and under heavy saturation.

The π model surfaces as an alternative. It has only one leakage inductance branch in series and two shunt magnetizing branches, see **Figure 2.15**.

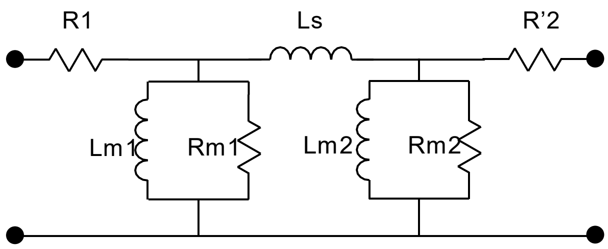

Figure 2.15 - π Model.

2.6 - Resonant Effect

An object free to vibrate tends to do so at a specific rate, this rate is his natural, or resonant frequency [10].

Resonance is the amplification effect resulting from submitting a system to its natural frequency. This type of phenomenon is observed in different types of systems. Among them the magnification effect of resonating an item with sound at its natural frequency, like a glass breaking when is immersed in sound at the right frequency [11]. Orbital resonance which occurs when two orbiting bodies exert periodic influence in each other, either destabilizing or helping to maintain an orbit. There is also optical and atomic resonance and more relevant in context, electrical resonance. Most of these systems are ruled by the same set of rules.

2.6.1 - Electrical Resonance

A phenomenon that occurs when an electric circuit is subjected to a frequency in which it resonates. In such circumstances, the impedance (Z) and admittances (Y) of the circuit elements cancel each other. Resonant circuits can generate higher voltages and, currents because of it, are of great importance for wireless systems.

2.6.1.1 Resonant circuits

An LC or resonant circuit is an electric circuit consisting of an inductor and a capacitor, **Figure 2.17**. Such a circuit can function as a resonator, oscillating at the resonant frequency.

The operation of an LC tank consists of a charged capacitor, stored electric field (E), discharging to an inductor. The inductor in its turn stores the energy as a magnetic field (B). When the capacitor's voltage across its terminals drops to zero the current stops and a voltage at the inductor's terminals begins increasing because inductors oppose changes in current. This induced voltage recharges the capacitor.

With a perfect LC circuit, there would be no dissipation of energy due to resistance and the system would remain perpetually switching energy from the capacitor to the inductor. Such a scenario is not possible due to the inevitable reality of resistance.

Electrical LC circuits can be assembled as a series or a parallel configuration.

In a series configuration, **Figure 2.16**, the voltage to the system's terminals is the sum of the voltage of the inductor and the capacitor and the current is the same in both components. The impedance is the sum of the impedances of both the capacitor and inductor.

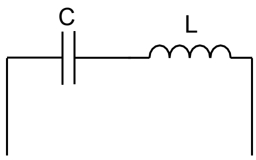

Figure 2.16 - Series LC Circuit.

In the parallel configuration the same voltage is applied to every component and the current it is divided among the capacitor and the inductor. The impedance of the system is achieved by calculating the parallel of both device impedances.

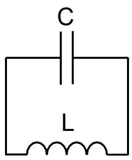

Figure 2.17 - Parallel LC Tank Circuit.

$$Z = \frac{Z_L Z_C}{Z_L + Z_C} \tag{2.5}$$

The natural frequency, f_0, of both configurations it is calculated with the capacitance and inductance values of the devices.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{2.6}$$

In practical terms, a series resonant circuit provides voltage magnification and a parallel circuit provides current magnification.

2.7 - Printed Electronics

Printed electronics refers to electronic circuits created through the deposition of electrical configurations over multiples possible substrates. The substrates can be flexible or rigid and the applied material can be of organic or inorganic nature [12].

With the increase in the number of devices per person and its tendency to increase even further, an opportunity appears to create IoT applications and innovative edge devices [13].

Edge devices are the endpoints of IoT networks. They are the components of the network capable of interacting with the physical world. This means having some type of sensing, actuation or gateway establishment [14].

These types of devices, in many situations, are meant to be used in scenarios where volume must be kept as small as possible, the budget is limited or even if there is a need for a flexible result. Printed electronics opens the possibilities of what can be done within a project.

The design of this type of circuits is comparable in its principle with the standard additive printing. Standard printing consists of deposition of ink over a piece of paper, while in circuit printing the process deposits conductive material over a substrate with the desired physical characteristics.

Additive printing has some advantages over the creation of Integrated Circuits (IC). IC usually demand a long and complex design process while circuit printing it is a very simple process [15]. Printed electronics can also be much less expensive depending on the amount of deposition material used [16].

Circuit printing is especially relevant in the industries where size is of great importance: flat screens, smartphones and in more recent years wearables, like smartwatches and clothing [15].

2.8 - Circuit Printing Techniques

Depending on the type of function expected from the circuit different types of deposition are possible, and each one has its advantages and disadvantages. Among them are Screen Printing, Vinyl masking, Inkjet printing, stamping/nanoimprinting and gravure printing [16]. Besides the former, there is also jet printing [17] and laser direct writing [18]. For the project only screen printing and vinyl masking were considered and so only those will be explored, nevertheless, other methods are available. With them, other possibilities can be explored in printed electronics

2.8.1 - Screen Printing

Screen printing it is the oldest circuit printing method and the most versatile. It can print more than electrical configurations, and is, also used by other different industries like textiles and decals.

The method requires only four items: the printing means, the film with the desired pattern to be printed, a surface in which the printing will be performed and a press that will push the printing mean through the film.

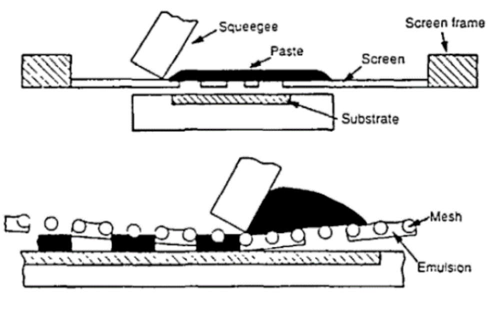

Figure 2.18 - Screen Printing, reprinted from [19].

The film is usually composed of three sections: a stencil that defines the pattern to be printed, a mesh supporting the stencil and a frame supporting the mesh. When printing circuits the most common film to be used is metallic and frequently an aluminum alloy [19].

2.8.2 - Vinyl Masking

This technique is not specially created to be applied to electronics. Vinyl Masking is a simple method of molding conductor material into the desired shape and thickness. The vinyl is used due to the swiftness by which it can be cut, either by machine or by hand. The created shape can then be filled with the desired conductor and taken to cure.

The process allows for quick prototyping and great versatility in design. This method is further analyzed in 3.4 - .

2.9 - Planar Inductor

As referred previously an inductor is a passive element that stores energy as a magnetic field. Here, a specific type of inductor will be discussed, which is the planar inductor.

A planar inductor, or PCB inductor, as it could be referred, consists of an inductor which only possesses two significant dimensions. This could be an advantage for systems like the one presented in this document in which size is a concern.

From a performance point of view, there are three important parameters [20]: the inductance (L), the resonant frequency (f_R) and the quality factor (Q).

The more relevant types of geometry are square (a), hexagonal (b), octagonal (c) and circular (d), as referenced in **Figure 2.19**. The geometrical parameters for each geometry are the number of turns (N), track width (W), the spacing between turns (S), the thickness of the track (t), outer diameter (D_{out}) and inner diameter (D_{in}).

In [20] a comparative study between the different geometries was performed. The results tend to favor the square design by showing favorable results both in resistance and inductance, concluding than the inductance of the coil is mainly dependent on the form.

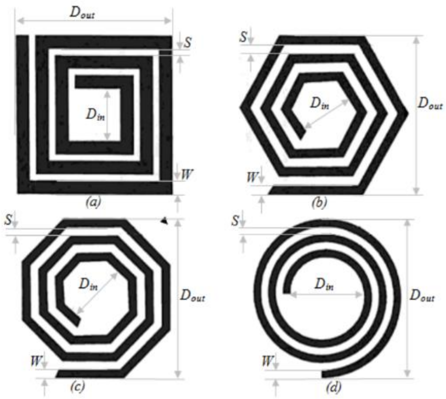

Figure 2.19 - Printed Inductors Geometry, reprinted from [20].

These results are confirmed in [21], revealing that the mutual inductance of the circular inductors drops faster than the squares. However, the work also shows that a perfectly aligned circular coil can transfer more power.

The inductance (L) of these inductors can be calculated based on the Wheeler formula [22]. In the original paper the formula was designed to be used in single-layered helical coils i.e. circular coils, but over time adaptations to the formulas were made to adapt to different coils. In [23] an adaptation to the formula can be found and meant for IC coils.

Wheeler's Formula:

$$L = \frac{a^2 n^2}{9a + 10c} \tag{2.7}$$

a = coil radius in inches
c = coil length in inches
n = number of turns

The resonant frequency (f_R) of the inductor consists of the frequency of oscillating current imposed on the coil which causes the system to start resonating. It is created between the parasitic capacitance of the coil and its inductance. The tank creates a magnifying effect that intensifies the magnetic field created.

The quality factor (Q), is a dimensionless parameter that describes the relation between stored energy and energy dissipation.

In the case of the coil, which is a resonator, the quality factor is given by the following formula:

$$Q = \frac{wL}{R} \tag{2.8}$$

w = angular frequency
R = resistance
L = inductance

$$w = 2\pi f \tag{2.9}$$

f = frequency applied to inductor

2.10 - Planar Transformer

The planar transformer or PCB transformer is a type of converter built with planar inductors. It uses the same principles of the standard, non-planar transformer but the inductors used are one dimensional.

The use of planar inductors to create this type of transformers makes it possible to create smaller circuits, low cost and faster implementation. This type of transformers can be printed into a circuit board or even microcircuits.

The major difficulties found in designing planar transformer derive from the need for high frequency to achieve acceptable efficiency. In [24] such a system was developed and tested for a range of frequencies and loads. The test was conducted with a 100pF and a 1000pF resonator capacitor.

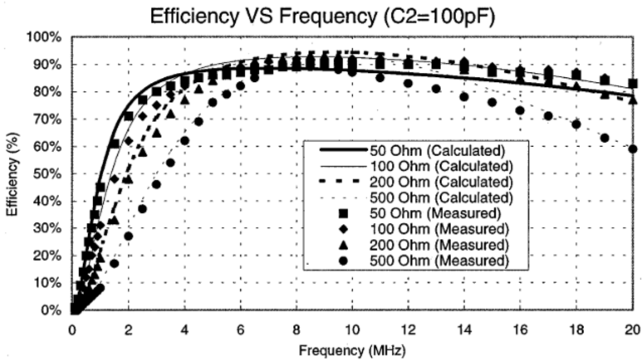

Figure 2.20 - Planar transformer, 100pF Resonator Capacitor, reprinted from [24].

In **Figure 2.20** and **Figure 2.21** the results of the experimentation are displayed. The inductors used in said experimentation have 19 turns and were printed into both sides of a PCB.

The results demonstrate that printed inductors could be used to achieve high-frequency energy transfer. It should be noted that the transformer only reaches high efficiency for frequencies around 2Mhz. In the case of the 100pF resonator capacitor, it reaches close 70% and the 1000pF capacitor closer to 78%. Such high frequency creates a challenge to design switching circuits.

2.11 - Circuit Switching

When aiming to achieve magnetic induction, circuit switching is necessary to create the needed current variation. In conventional transformers, the 50Hz, commonly found in grid electricity, is enough to transmit energy between the two sides of the component. If the

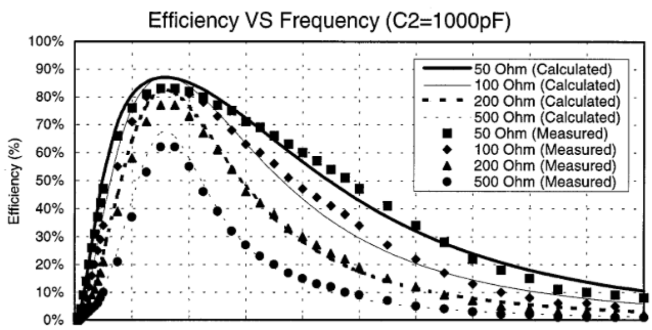

Figure 2.21 - Planar transformer, 1000pF Resonator Capacitor, reprinted from [24].

system requires a higher frequency, it is necessary to first convert to DC and then use a switching circuit.

A circuit switch receives a DC signal and converts it to an AC signal. The frequency can be chosen according to the needs of the project.

As presented in 2.10 - , it is shown that to achieve an efficient energy transfer between primary and secondary sides high frequencies are needed. The frequencies range between some hundreds of kHz to Mhz.

To convert a signal to a higher frequency, first, that signal must be converted to DC using rectification and filtering. The DC signal then is reconverted to an AC signal using transistors. The principle of switching consists of turning off and on the conduction across a transistor, the transistor can be either bipolar or MOSFET. The conduction control is performed by a PWM signal generator or gate driver. The PWM generator creates a bipolar wave switching between positive and null values enabling or disabling, for example, a MOSFET conduction across its source and drain.

In this section, a presentation of the main switching methods will be performed. The ones discussed will are the full-bridge switch, the half-bridge switch and the Flyback. The full and half-bridge switches will be presented due to the importance that these topologies have in power supply designs.

2.11.1 -– Full-Bridge Switching

With a Full bridge, or H bridge, configuration, it is possible to output voltage levels ranging from negative to positive [25]. The circuit inverts the current at the output by switching between two different current paths. The topology allows for a greater current variation on the inductor and could increase the system's efficiency.

The configuration uses two PWM signals with a phase variation of 180°. This difference in phase means that when one signal turns off, the other is turning on. In **Figure 2.22** a simple representation of a full bridge switch. The plots a) and b) represent the input DC current and the switched current output, respectively.

This type of circuit is often used to perform high frequency switching for multiple applications [26].

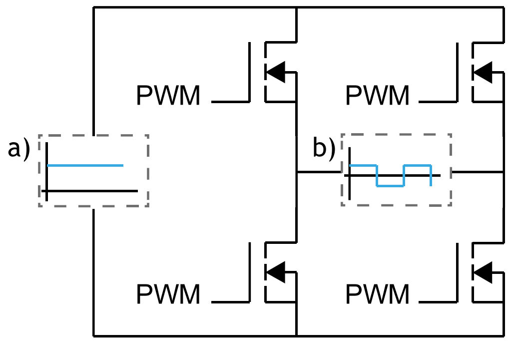

Figure 2.22 - Full Wave Switching Circuit. Plot a) input current, plot b) switched current.

2.11.2 - Half-Bridge Switching

A half-bridge converter is a variation of the H bridge switch that possesses only two transistors on the side of the load. Like the full bridge, it also uses two PWM signals out of phase by 180° and the output signal also oscillates between negative and positive values. The mains difference resides on the maximum value of the output voltage. In the half-bridge inverter, the peak voltage is half of the DC supply voltage. The configuration is exemplified in **Figure 2.23**.

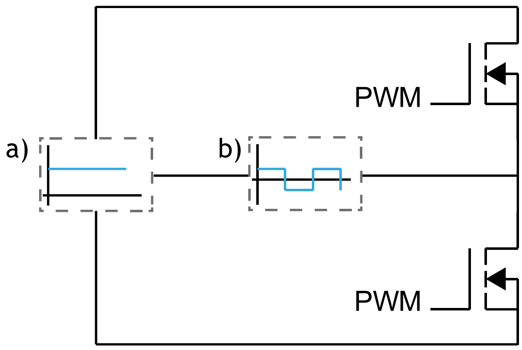

Figure 2.23 - Half-Bridge Switching. Plot a) input current, plot b) switched current.

2.11.3 - Flyback

The Flyback is the inverter circuit configuration in which the transistor activates or deactivates conduction across a load. Unlike the full-bridge or half-bridge, when the PWM is in off mode the current does not possess any other path, so the circuit is simply cutoff. This method is the simplest form of signal inversion that only requires one PWM signal generator and one transistor.

The main concern when using this type of circuit should be voltage transients. Because the current is abruptly cut off every time the MOSFET switches off transient voltages may occur. Such effect depending on its intensity may damage or destroy the transistor due to high voltage peaks. To avoid this problem a snubber circuit should be implemented

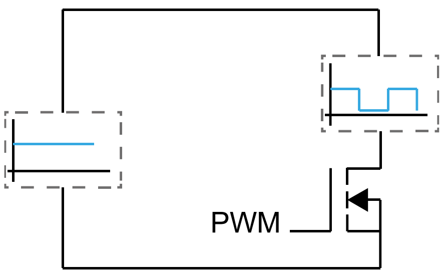

Figure 2.24 - Flyback Switching.

2.12 - Snubber Circuits

As discussed, voltage transients in switching devices may cause irreparable damage to transistors.

Voltage transients are a phenomenon that occurs when there is a sudden interruption in current flow. This leads to a sharp rise in voltage across the transistor's terminals, also known as the inductive kick. This effect may also be a source of electromagnetic interference in other circuits.

Snubber circuits provide a short-term alternative path around the current switching device. This way when the current is interrupted the transient will not damage the transistor. Such circuits are mainly divided into three methods [27], the RCD rate of voltage rise snubber, the RCD clamping snubber, and the non-dissipative snubber.

The RCD rate of voltage rise snubber circuit limits the voltage rise when the transistor switches off.

The RCD clamping snubber is essentially a peak detector mostly used in AM demodulation and consists of an RC filter.

The most relevant snubber mechanism in the context of this dissertation is the non-dissipative snubber [28]. Due to the efficiency requirements, losses in the switching should be minimized and so a non-dissipative approach should be considered.

A non-dissipative snubber uses a capacitor to avoid the transient voltage peak. However, to avoid energy expenditure the capacitor does not discharge to a resistor, instead to of an inductor. This configuration creates an LC tank that minimizes losses by returning the stored current when the conduction in the transistor is restored.

The circuit's configuration is displayed in **Figure 2.25**. The capacitor C1 and the inductor L1 are resonant with each other.

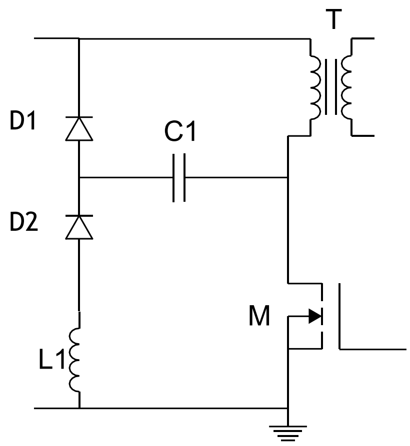

Figure 2.25 - Non-dissipative snubber.

2.13 - Wireless Power Transfer

Wireless Power Transfer (WPT), or electromagnetic power transfer consists of the transmission of electricity without the need for cables, wires, or a kind of physical link. A wireless energy transmission system in its purest form requires that a power source of any type be used to create a time-varying electromagnetic field. That magnetic excitation is then accepted by the receiver and used to power an electrical load.

In the future WPT may be of great importance to society and individuals in general because has the potential to replace the need for wires and batteries. Wireless Power Transfer system also adds a layer of security to an electrical system because it creates a physical separation between the users and the power source.

Systems transferring energy through free space are already in use in many different industries. Some examples are medical implants, like the cochlear implant, electric toothbrushes [29], electrical car charging [30], cell phones, robots, and home electronics appliances.

WPT can be divided into three types, near-field, non-radiative, or far-field. When addressing far-field techniques, also called power beaming the main transfer is achieved through a beam of radiation like microwave, or laser. The biggest concern relates to the beam exposition to living beings. The beam carrying high power levels may cause harm.

In the near-field power transfer, the receiving system must be within one wavelength (λ) of the transmitter. This type is the most used wireless power transfer system because it is safer. The electrical power transmission could be achieved through capacitive coupling (electrostatic induction) or inductive coupling (electromagnetic induction).

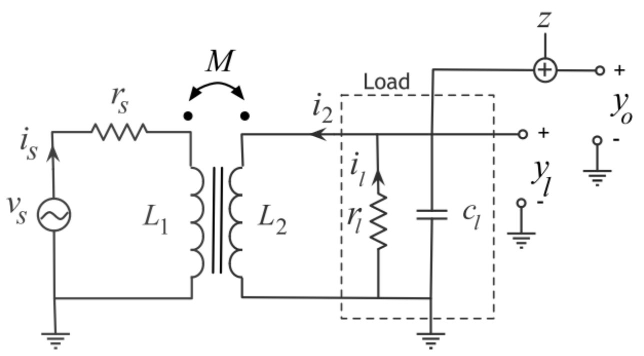

Figure 2.26 - Simplest implementation of a WPT System, reprinted from [29].

Capacitive coupling or electrical coupling makes use of electrical fields to transmit power between an anode and a cathode. The electrical field creates a capacitance in the space in-between. In electrostatic induction, power transfer happens between to electrodes separated by a dielectric. The use of capacitive coupling for power transfer is limited to low power applications as the high voltages required to obtain power transfer across the dielectric can be dangerous. Capacitive power transfer is also problematic as it uses electric fields instead of magnetic, an electric field can interact with most materials while magnetic only with magnetic ones. In some cases, capacitive coupling has been reported to be used to charge portable devices [26] as well as feed energy in real time to biomedical implants. As previously discussed, capacitive coupling can be used as an isolator for signal transfer.

Resonance can also be used with capacitive coupling to extend the system's range.

Inductive coupling works on the formerly considered topic of electromagnetic induction. An inductor is submitted to an AC current which induces a magnetic field around it, the opposite side is magnetized by influence and generates a current on the load. When both transmitter and receiver are tuned to the same resonating frequency, the system also increases in range as well as received power.

In [31], Wheeler described the influence that Nikola Tesla had on the high-frequency domain, Tesla discovered resonant coupling during its experiments on Wireless Power Transfer. More recently the technology has been gaining more attention and uses. Inductor coupling systems possess a higher k factor which enables energy transfer at a more efficient rate. Inductive coupling is a growing field with different applications being discovered. In [32] a solution has been developed for rehabilitation patients during physiotherapy.

High power inductive power transfer might become an area of great development in the future. The development and massification of electrical vehicles might hold great promise in the ways people charge their vehicles. Some systems in advancement, [33] aim to create charging systems that enable power transfer between the main and the car by simply parking over it, in [34] a tourist city tour tram uses such a system. Other more difficult systems even consider dynamic charging of electric vehicles that can be charged on the road while in movement, [35].

2.14 - Proposed System Architecture

For this dissertation, a switched mode power supply is proposed. The requirements of the project are to obtain a low power, high-efficiency supply to deliver up to 0.5W of power, 5V and 100mA to a load as high as 50Ω.

The system must be scalable to reduced size and to be able to be partially printed in a flexible substrate, also to reduce the volume. Due to that condition, the primary objective becomes to drop the mains voltage (230VAC/325VDC) to a value closer to the requirement. The second, to rectify the output to make it usable by low power DC circuits. The solution found is a Transformerless Power supply.

A TPS configuration can be used to drop the voltage and then rectify it in order to be used by DC components. Because of the efficiency requirements, the power supply can't directly drop the voltage with a pair of resistors due to the energy consumption associated with resistive components.

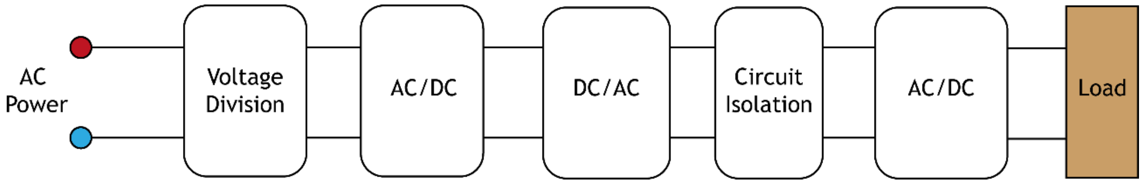

Figure 2.27 - System Configuration Block Diagram.

Capacitive elements do not possess resistance, but its reactance can be used in the same manner as resistors, which makes them adequate for the system.

An important aspect to consider is the dangerous nature of transformerless power supplies. These devices do not contain proper isolation to protect users and connected circuit from possible electrical discharges. To make it secure the approach must be isolated. For this project electromagnetic isolation was evaluated to be the most efficient and secure, providing complete separation from the hazardous parts of the system. To accomplish it the system places a 1:1 transformer ahead of the TPS.

Standard transformers can function with low frequency but also add size to the system. The investigation presented in the previous chapter is here utilized to reduce system's volume. Such inductors, as presented, possess smaller inductance than the available in traditional transformer coils. Because of this, greater frequencies are needed to achieve efficient energy transfer, so, the rate of the alternating current must be increased. The block diagram of the proposed system is represented in **Figure 2.27**.

The mains power is converted from 325VDC to 15VDC, which then is converted into a high-frequency AC voltage. The 1:1 transformer transfers the power from the primary to the secondary side, feeding the load.

The system proposed is designed according to a Flyback topology with an optocoupler feedback mechanism. The flyback uses one MOSFET transistor and a gate driver connected thought the feedback to an amplifier on the output side. The amplifier is the negative feedback controller that manages the output to the desired voltage output.

As previously investigated in this thesis the printed inductors require frequencies in the order of 2MHz and up, to achieve a high enough power output. This creates a challenge in the design of the DC to AC converter. Switched Mode Power Supplies do not usually operate at frequencies so elevated.

To use frequencies as high the system must possess components fast enough to keep up. The transistors able to have that level of switching time must be GaN or SiC. For the presented design, a SiC MOSFET was used. To drive the transistor a gate driver or PWM generator must also be used. In Flyback circuit configurations that use frequencies under 1Mhz, an integrated solution could be used [36]. To reach higher frequencies, the most common solution found involves using high-frequency gate drivers with an also high rate PWM generator or microcontroller.

Chapter 3

Printed Inductors

3.1 - Introduction

In this chapter, the investigation conducted into printed inductors will be presented.

The desired output of the thesis is a power supply capable of delivering power to small devices for instance sensors, network gateways or small actuators. If, as is the case of this project, the grid power is chosen to be the main power source, security becomes a concern. As previously discussed in 2.3 - , isolation is of great importance both to human handling as to devices interfacing with the power supply.

The approach taken to accomplish safety is electromagnetic isolation as is commonly found in traditional transformers. This is due to the greater efficiency achievable through this method versus the alternatives.

Taking into consideration the objective to utilize the system in devices of reduced dimensions, common transformers require too great a volume in relation to the appliance size. To circumvent this limitation, planar transformers are investigated. The converters studied are composed of planar inductors stacked and separated by the substrate or substrates in which they are deposed.

The desired system is experimented with first through electromagnetic simulation, then, the coils are manufactured using printed electronics methods. These processes are also explored within this chapter to evaluate adequacy in this type of project. After fabrication, the printed inductors are experimented with as close-range wireless power transfer emitter and receiver the results are cross-examined with the electromagnetic simulation's results.

In the context of the project, these inductors serve the purpose of providing galvanic isolation for the project which enables secure handling of the projected device.

3.2 - Inductor Model

To design a power supply of reduced volume, the transformer part of the circuit becomes the bottleneck. Transformers, as previously discussed 2.5.1 -, are usually components of great volume in relation to the desired circuit and represent a great cut of the device budget. When considering the isolation function of the transformer, there are alternatives in Surface Mount Technology (SMD), capable of delivering up to 3W of power. These transformers usually have dimensions around 10x10x10mm and can be used to provide isolation to switched mode power supplies. Despite the advantages of such components it is relevant to investigate alternatives as the one in this chapter. Printed coils have the potential to facilitate prototyping and reduce production time for a final product and to offer a different approach by which to find project solutions. In this manner, the study of these coils is justified.

The considered inductors are planar as presented in 2.10 - with spiral geometry of various dimensions and electrical characteristics.

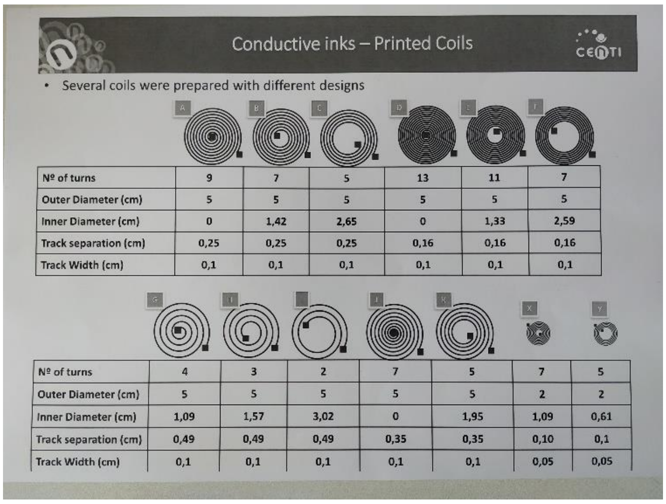

Figure 3.1 - Printed Coil Models.

The choice of the most adequate coil geometry was based on multiple aspects. Firstly, an investigation was performed to determine which basic geometry would be best and it was evaluated to be the spiral coil. Based on other work performed in the field such as [37] and [24] it was concluded that the greater the line density and number of turns the greater the potential for high efficiency power transfer. But given the methods used for prototyping the coils, which will be further discussed, as the traces become smaller and the gap between turns reduces, the fabrication quality decreases. The results may possess cuts in the trace and bridges between turns which can lead to open circuits, high resistance, and lower inductance.

The pre-characterized models available at CeNTI, **Figure 3.1**, had screens fabricated, which would open the possibility for screen printing. Among the possibilities the coil E, **Figure 3.2**, had the better balance between quality factor and geometric characteristics. Its shape with wider inner diameter allowed for easiest crimping for connector attachment and so was the chosen coil.

Table 1 - Printed Coil Characteristics

Printed Coils Characteristics						
Coil	Resistance (Ω)	Number of Turns	Inductance - 100kHz (µH)	Quality Factor	Inductance - 3MHz (µH)	Quality Factor
A	7.4	9	1.73	0.15	1.73	4.41
B	7.2	7	1.68	0.15	1.69	4.42
C	6.1	5	1.99	0.20	2.03	6.27
D	12.4	13	3.72	0.19	3.58	5.44
E	12.3	11	3.57	0.18	2.66	4.08
F	9.8	7	2.65	0.17	0.54	1.04
G	3.7	4	0.54	0.09	0.54	2.75
H	4	3	0.53	0.08	0.54	2.54
I	2.8	2	0.4	0.09	0.41	2.76
J	6.3	7	1.11	0.11	1.11	3.32
K	5.5	5	0.93	0.11	0.92	3.15
X	6.7	7	0.61	0.06	0.63	1.77
Y	5.2	5	0.49	0.06	0.49	1.78

In **Table 1 -** Printed Coil Characteristics the electrical characteristics of the coils modeled at CeNTI are presented. The table is cross-referenced in **Figure 3.1**. The inductor E geometric and electrical characteristics are presented in **Table 2**.

Table 2 - Inductor Characteristics

Inductor E	
Physical Characteristics	
Number of Turns	11
Outter Diameter(mm)	50
Inner Diameter(mm)	13.3
Track Separation (mm)	1.6
Track Width (mm)	1
Expected Electrical Characteristics	
Resistance (Ω)	12.3
Inductance - 100kHz (µH)	3.57
Inductance - 3MHz (µH)	3.58

These inductors are made at CeNTI by two possible printing methods: Screen Printing and Vinyl Masking. Both will be further explored in this chapter.

According to Wheeler's formula, the expected inductance for the inductor E based on its geometric dimensions is 2.8µH which is close to the measured value.

The material used to print the inductors is DuPont 5025 silver. The conductor is a general-purpose silver ink used to produce low voltage circuitry especially in flexible substrates. The material can be used both for manual printing, as in vinyl masking, as well as screen printing.

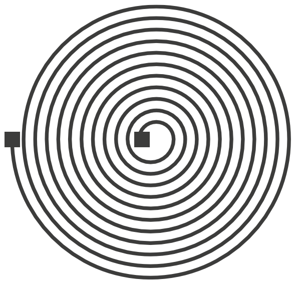

Figure 3.2 - Inductor E Geometry.

DuPont 5025 possesses the characteristics observed in **Table 3 -** DuPont 5025 Properties. The most relevant characteristic is the sheet resistivity which determines the resistance of the printed coil.

The substrate employed in experimentation is Polyethylene terephthalate (PET). PET was chosen for the reference substrate versus Polymide, or Kapton as is usually referred to, due to the availability of the material in CeNTI laboratories. The characteristics of the PET substrate can be observed in **Table 4**. From this information, it is especially important the relative permittivity and thickness. This data provides information to the model by which to simulate the system.

Table 3 - DuPont 5025 Properties

Test	Properties
Sheet Resistivity (mΩ/sq/mil)	[12, 15]
Resisitivity after Flex (mΩ/sq/mil)	≤50
Adhesion/Tape Pull ()	No Ag Transfer
Abrasion Resistance, Pencil Hardness	≥1
Operating Use Temperature (°C)	≤110
Solderability	Not recomended
Change in Physical Properties after Test	Insignificant
Change in Physical Properties after Test (%)	<10

Table 4 - PET Characteristics

PET	
Density (g/cm3)	1.37
Tensile Strength (MPa)	55
Flexural Strength (%)	>50
Elasticity (Mpa)	2500
Relative Permitivity	3.2
Dielectric Strength (Kv/mm)	60
Working Temperature Short Term (°C)	180
Working Temperature Long Term (°C)	80
Tickness (µm)	75

3.3 - Electromagnetic Simulation

3.3.1 - Inductor Modeling

To have a greater level of security in the results presented, simulating the electromagnetic aspects of the coils is important. After choosing the most adequate inductor (The E model) among the templates available at CeNTI, it was then 3D modeled in Altair FEKO for experimentation.

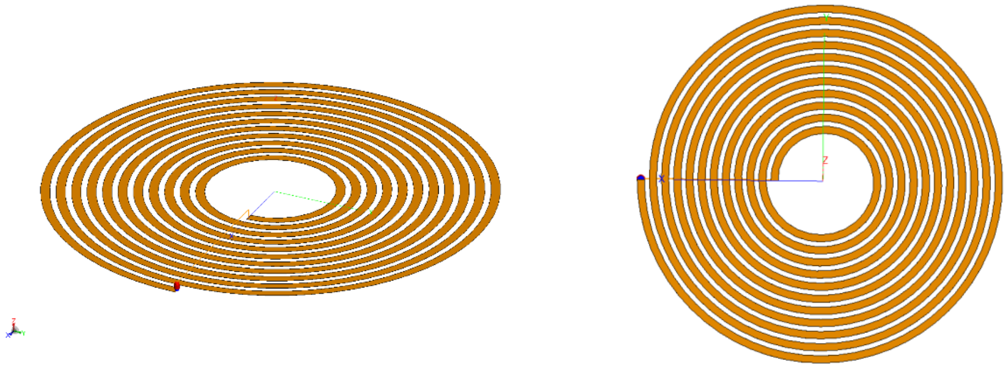

Figure 3.3 - From left to right. The Coil Model 3/4 perspective and top perspective.

The model for the inductor was defined according to the specifications of the inductor E, **Table 2** - Inductor Characteristic.

It was applied to the inductor a series resistance at its port to simulate its resistance. For this model, such resistance is 12.3Ω. The value chosen is based on the resistance value measured on the real inductor. While the printing ink utilized has a very high level of purity by default, the continued use of the same ink container results in deterioration of the ink by contact with the air. Which leads to greater resistivity and consequently greater resistance of the coil.

Table 5 - Coil Model Dimensions

Coil Electromagnetic model dimensions	
Number of Turns	11
Outter Radius (mm)	25
Inner Radius (mm)	6.65
Path Width (mm)	1
Path Tickness (mm)	0.01
* Tickness was chosen according to recomended value by ink manufactorer	

3.3.2 - Transformer Model Simulation

With the built inductor model a 1:1 transformer was built and simulated in FEKO [38]. The designed component is composed of two similar coils overlapping each other with only the substrate between them and a separation distance of 7μm The result is represented in **Figure 3.4** and **Figure 3.5**.

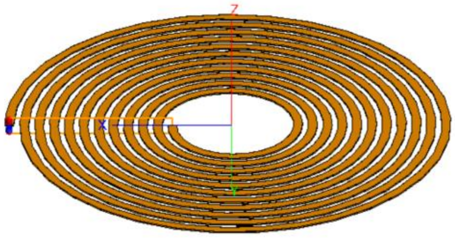

Figure 3.4 - Transformer Model 3/4 perspective.

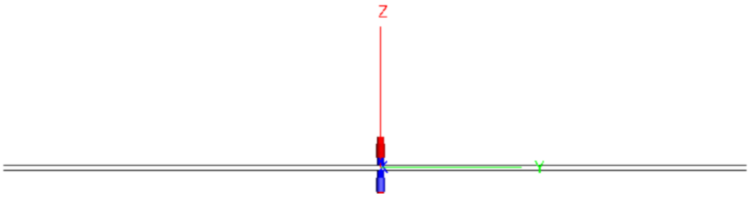

Figure 3.5 - Transformer Model Front perspective.

The system was connected on the primary side to a 15V AC voltage source and a 0.5W power request was configurated, to ensure that the power delivery to the primary was constant, which allows for easier calculation of the efficiency.

In **Figure 3.6** is represented the magnetic field measured on the xy plane.

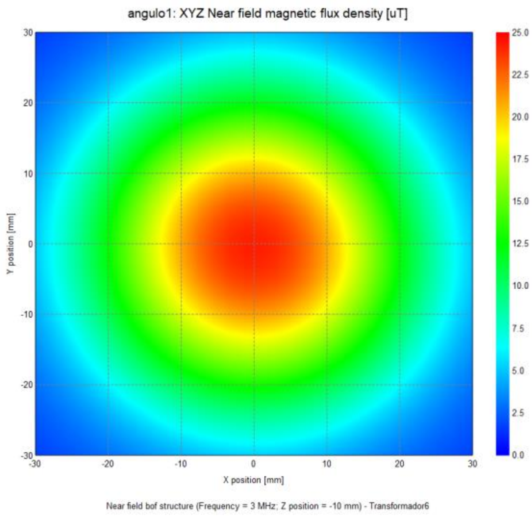

Figure 3.6 - Transformer Magnetic Field

3.3.2.1 Simulation with 50Ω load

A load of 50Ω was inserted on the receiver. As expected, with the rise in frequency the system gravitated towards greater power transfer and which represents greater efficiency. In **Figure 3.7** the progression of power received on the load is presented. It can be observed that the power converges to approximately 65% efficiency when greater frequencies are applied.

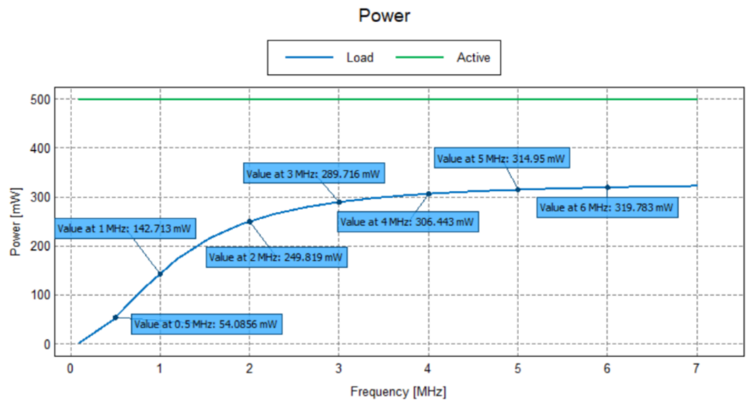

Figure 3.7 - Received Power on 50 Ω load.

At this point some potential for wireless power transfer can be inferred. At frequencies high enough the transformer reaches acceptable energy transfer levels.

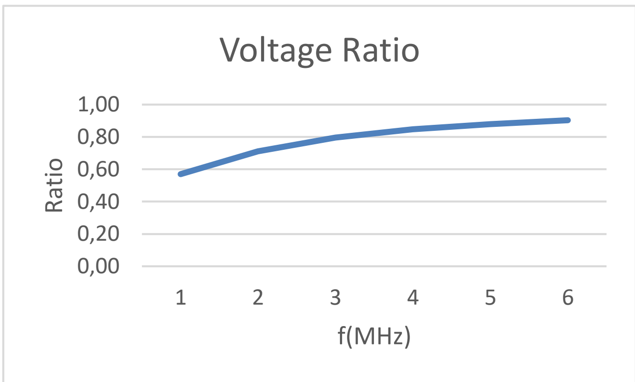

Figure 3.8 - Simulated Voltage Ratio with frequency increase.

3.3.2.2 Resonant Effect transformer Simulation

The simulation results at this point show a need for very high frequency to achieve considerable efficiency. To drop the needed frequency to lower values investigation was conducted into the use of the resonant effect. The resonant effect would increase efficiency around a frequency value programmed around with the LC Tank. Such experimentation also allows calculating the inductance of the simulated coils.

Parallel Capacitor on the primary and secondary side

A tuning capacitor was placed on the primary and secondary sides in parallel with each respective coil. The capacitor's value was calculated based on the expected inductance for the printed coils with the LC tank formula, (2.6), the frequency considered was 1Mhz.

For such frequency with the inductance of 2.6µH expected of the coil the needed

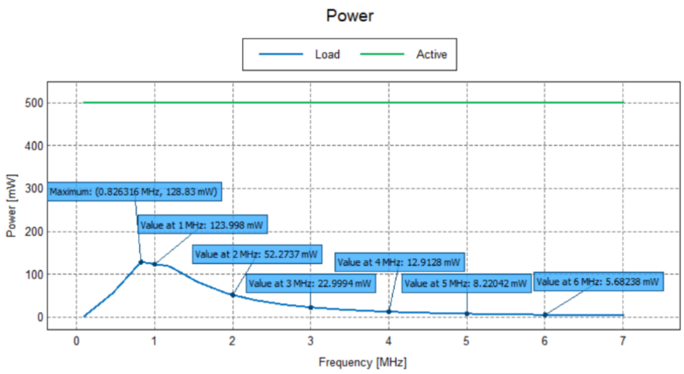

Figure 3.9 - Resonant Effect 7nF Capacitor.

capacitor was evaluated to be 7nF.

The results presented in **Figure 3.9** shows, in fact, a filtering effect caused by the resonant effect. The maximum power transfer is accomplished for f= 826.32kHz.

Parallel Capacitor on the secondary side

As previously explained in section 2.13 - , according to the circuit by [29], the capacitor could be placed only on the secondary side. Such configuration was simulated, and the results show the same energy transfer and frequency filtration as with a capacitor on both sides. So, the system may not require the capacitor on both sides, relying that the secondary side is tuned to the frequency of the primary.

At maximum transfer frequency, 826.32kHz, the system transmits 128.83mW which represents 25.67% of the input power. For the same frequency, the system without a resonant capacitor on either side transmits 114.676mW for an output efficiency of 22.94%. The increase of efficiency is about 3% which may not justify the use of the resonator capacitor tuned for a frequency so low.

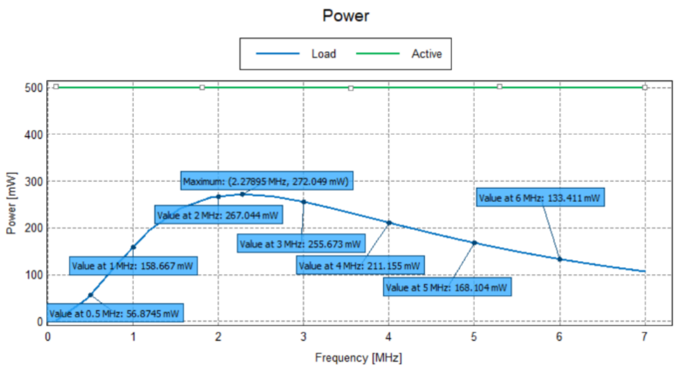

Figure 3.10 - Resonator Effect 1.2nF Capacitor.

The system was then simulated with a resonating capacitor of 1.2nF on the secondary which tunes the system to resonate at 2Mhz. The results are represented in **Figure 3.10**.

The simulated system reaches maximum output power at 2.28MHz reaching 272.049mW. This represents 54% efficiency, an increase in 1% versus the previously calculated system without resonator capacitors.

3.4 - Inductor Fabrication Process

After the selection of the best-suited inductor to conduct experiments, the next step necessary was to construct the coils.

The method employed to produce the inductors was vinyl masking. The process starts with the cutting of the inductor's shape into a large sheet of vinyl.

After cutting, the coil mold is removed from the cutting machine, the inner side of the vinyl mold of the coil is removed and manually passed to the transfer material. This step is optional, but the use of transfer plastic enables easier removal of the vinyl protective plastic.

The transfer material, now with the vinyl adhered to it, is, in its turn, adhered to the substrate. By this point the coil vinyl frame is complete.

With the scaffold of the inductor, it is now possible to progress to the printing.

The silver ink material, DuPont 5025, is applied over the mold with care and the resulting product is then taken to the oven to cure. The process takes around 5-6 minutes at 120°C.

When the ink is dry, it is then possible to end the fabrication by removing the mold from the substrate, leaving just the printed coil. This part constitutes a critical point in the process. As the entire procedure is manual there is a risk for human fault, which becomes aggravated in this step. Removing the mold is a precision task, especially if the tracks are too thin. Improper removal will result in errors in the design like gaps or connections between turn in the coil. The creation of gaps in the inductor will affect the desired inductance.

When the coils are printed, the endpoints are crimped to create electrical connections. The crimps used are easy to apply but result in very sensitive connections that cannot sustain much movement. Such a method of connection should only be used for prototyping.

Screen Printing was also available but would be less agile in terms of project development.

After completion, the inductors can finally be assembled as a transformer. The initial projected structure was to print the inductors into each side of the substrate in order to reduce the distance between the coils. Due to the constraints caused by manually printing such a system the solution found was to print each coil into a different substrate and overlap them. This method duplicates the thickness of the substrate, **Table 4 -** PET Characteristics, but has a small impact on the results of the system.

The conclusion reached after the fabrication process was that vinyl masking is a very versatile method for printing electronics especially when applied to Radio Frequency antennas or low power conductors. Yet, the method does not guarantee the quality of the product when precision is necessary. The technique does not allow for proper control of the thickness and homogeneity of the conductor. Because the printing is manual there is also a chance for human error that may cause a waste of materials and time. The way to ensure some degree of quality consists in printing multiple pieces and evaluating post-print if they meet the requirements.

3.5 - Real Environment Coil Experimentation

To test the designed transformer, an experience was designed. The component previously built, now with connections on the primary and secondary side is assembled into the circuit represented in **Figure 3.11**.

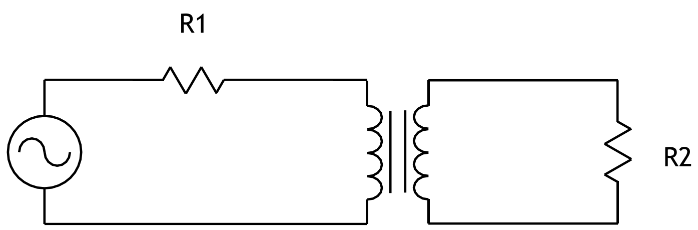

Figure 3.11 - Coil Testing Circuit.

The inductor chosen is the same as the Electromagnetic simulation to compare results.

On the primary side a resistance, R_1, is connected in series with the coil and on the secondary, a resistance, R_2, is connected in parallel. A function generator is connected to generate the signal to transmit to the transformer.

The value of R_1 regulates the amount of current drawn from the function generator. The greater the resistance the smaller the current delivered to the coil with the generator incapable of generating high currents, a 267Ω resistor was chosen. The resistance R1 is of value to the test because it will be the reference by which to measure the current delivered to the inductor.

The function generator is set 15V peak-to-peak.

The R_2 element is set to the maximum load (minimum resistance) the system is supposed to sustain, i.e. 50Ω, to approximate to the standard E series a 47Ω resistance is picked.

The experiment consists of a frequency sweep from f_0=100kHz to f_0=7MHz and for each frequency measure the amount of transferred power from primary to the secondary.

Such measuring is taken by probing R_1 terminal's voltage and calculate the current, then measure the maximum voltage on the coil's terminals and with the previously calculated current, gauge the power delivered to the primary side.

$$P = v_{L1} i_{R1} \tag{3.1}$$

The delivered power is calculated by analyzing the peak voltage at the terminals of the output resistance R_2 and the value of the resistance.

$$P = \frac{{v_{R2}}^2}{\mathrm{R2}} \tag{3.2}$$

During experimentation, some interference from the probe was noted when connecting it to the R_1 component. This was evaluated as the effect of the internal capacity of the oscilloscope. Such interference would boost the voltage at the input of the coil and consequently, the voltage at the output. The influence was deemed negligible.

The results of the experimentation on the built transformer are presented in **Figure 3.12**. The plot shows the efficiency in terms of the frequency (kHz).

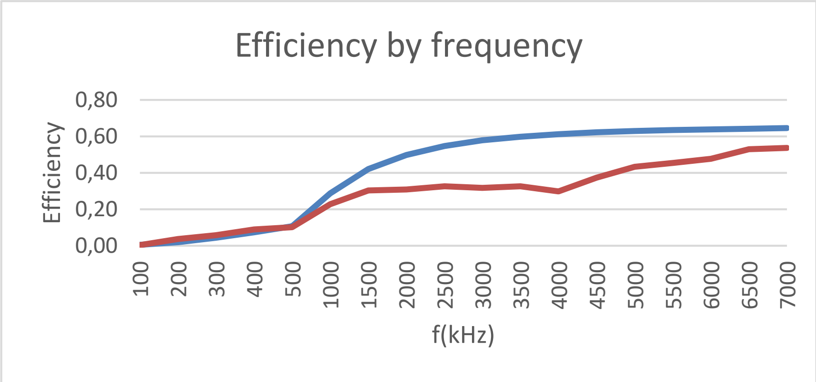

Figure 3.12 - Efficiency Vs Frequency Measured and Simulated. Red line: measured; Blue line: simulated.

From the results can be inferRed some validity to the electromagnetic simulations and becomes apparent that the coils tend to transmit greater power for frequencies above 1Mhz. From the results of both simulation and experimentation the efficiency only starts to reach interesting values above 5Mhz, 50% and up.

To justify the use of these coils the designed circuit must be able to also reach such frequencies.

The voltage ratio observed during experimentation was below 1.0 in all measurements and reached its peak at 1Mhz, see **Figure 3.13**. The results of the experimentation are further detailed in **Table 6**.

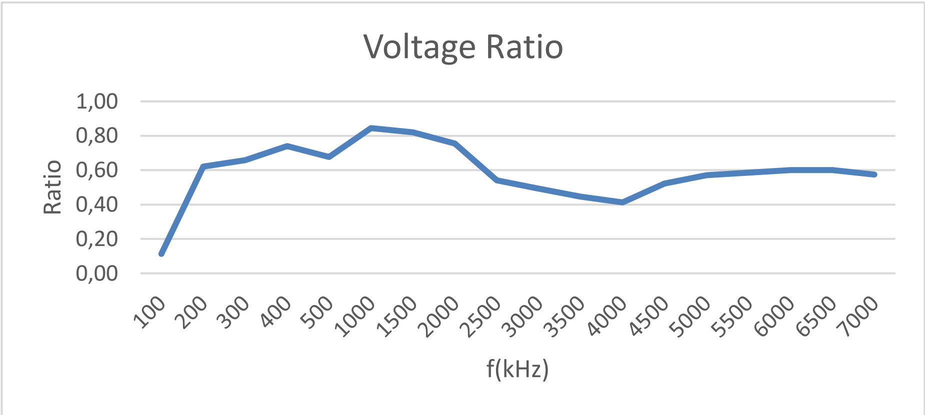

Figure 3.13 - Voltage Ratio.

Table 6 - Experiment Measurements

Vin_pp	VR1 (V)	VR2(V)	VL1 (V)	f (kHz)	IR1 (A)	PL1 (W)	PR2 (W)	Eficiencia	Voltage Ratio	N
15	6.4	0.035	0.310	100	0.0240	0.0074	0.0000	0.004	0.11	1
15	6.4	0.067	0.108	200	0.0240	0.0026	0.0001	0.037	0.62	2
15	6.4	0.100	0.152	300	0.0240	0.0036	0.0002	0.058	0.66	3
15	6.4	0.136	0.184	400	0.0240	0.0044	0.0004	0.089	0.74	4
15	6.4	0.168	0.248	500	0.0240	0.0059	0.0006	0.101	0.68	5
15	6.4	0.304	0.360	1000	0.0240	0.0086	0.0020	0.228	0.84	6
15	6.3	0.410	0.500	1500	0.0236	0.0118	0.0036	0.303	0.82	7
15	6.4	0.460	0.610	2000	0.0240	0.0146	0.0045	0.308	0.75	8
15	5.0	0.530	0.980	2500	0.0187	0.0184	0.0060	0.326	0.54	9
15	5.2	0.590	1.200	3000	0.0195	0.0234	0.0074	0.317	0.49	10
15	5.2	0.670	1.500	3500	0.0195	0.0292	0.0096	0.327	0.45	11
15	5.2	0.660	1.600	4000	0.0195	0.0312	0.0093	0.297	0.41	12
15	5.8	0.730	1.400	4500	0.0217	0.0304	0.0113	0.373	0.52	13
15	6.0	0.800	1.400	5000	0.0225	0.0315	0.0136	0.433	0.57	14
15	6.0	0.820	1.400	5500	0.0225	0.0315	0.0143	0.455	0.59	15
15	6.0	0.840	1.400	6000	0.0225	0.0315	0.0150	0.477	0.60	16
15	5.8	0.900	1.500	6500	0.0217	0.0326	0.0172	0.529	0.60	17
15	5.6	0.920	1.600	7000	0.0210	0.0336	0.0180	0.537	0.58	18

Chapter 4

Project Development

In this chapter, the proposed architecture will be further explored and implemented in a simulation environment. The simulated circuit is divided into two major sections, the mains electricity management, and DC/AC conversion.

4.1 - Mains Electricity Management

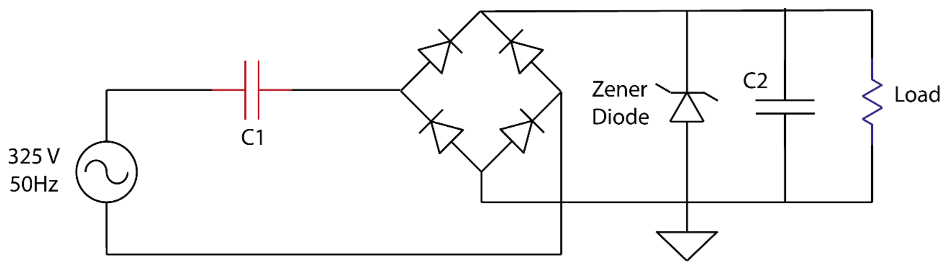

Figure 4.1 - Capacitive Transformerless Power Supply.

The first part of the power supply is the voltage division from the 325V, peak AC voltage of the grid to 15V DC using a capacitive TPS topology.

First, the current that the Capacitive TPS must deliver is chosen. The requirements of the project ask that the system may deliver 100mA. Taking into consideration the losses that are expected to occur in the transfer from the primary to the secondary side of the transformer, 400mA is decided, maintaining a 1:1 transformation factor.

Using Ohm's law, for the 325V of input voltage to achieve 400mA then the impedance (Z) must be 812.5Ω.

$$V = ZI \tag{4.1}$$

Considering Z as the capacitor's reactance, X, it is now possible to calculate the capacitor value that will deliver that amount of current. In this scenario f=50Hz.

$$X = \frac{1}{2\pi f C} \tag{4.2}$$

The calculated value for the capacitor is 4μF. A problem surges when using capacitors to drop power in a real circuit environment which is the amount of voltage the capacitor will have to handle to its terminals. In the previously calculated case, the capacitor must deal, at the peak, with 310V.

Such high voltage requires that the capacitor possess a very high voltage rating. The most adequate capacitors for such function are X rated. Despite being the most capable of dealing with such voltage X rated capacitors also require a great deal of volume which makes them inadequate for the project.

The solution found is to connect multiple capacitors of equal value in series, instead of one when implementing the circuit. This way the amount of voltage at the terminals of each capacitor is distributed. To ensure that the voltage across each capacitor is equal a resistance is placed in parallel with each one, see **Figure 4.2**.

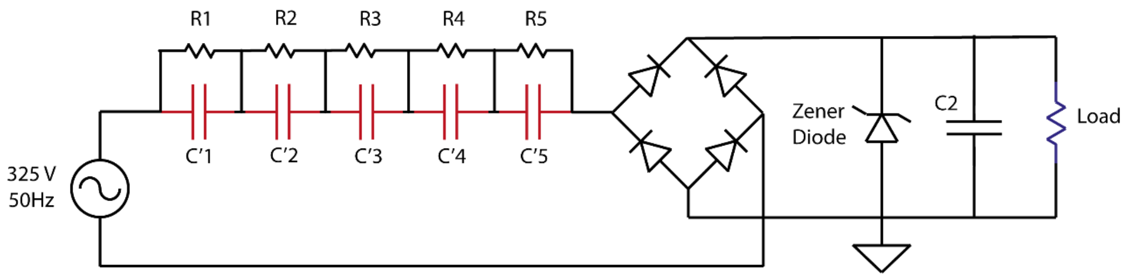

Figure 4.2 - Capacitive TPS, five capacitors voltage divider.

Adding more resistors increases power consumption, but, high valued resistive components pull less current through, so a 1.6MΩ resistor is added to each capacitor. In simulations with a 50Ω load, it is observed, through simulation, that the power consumption in each resistor averages at 1.28mW. A total wasted amount of 6.4mW is used to ensure equal division of voltage across each capacitor. In this configuration, each capacitor only must deal with up to 62V across its terminals.

To ensure the results are as expected the system was simulated. The components used for the simulation are the following:

$C'_1 = C'_2 = C'_3 = C'_4 = C'_5 = 20\mu F$;

$R_1 = R_2 = R_3 = R_4 = R_5 = 1.6M\Omega$;

The Zener diode was chosen to have a breakdown voltage of 15V, the load is 50Ω and the capacitor $C_2 = 300\mu F$. The output voltage is presented in **Figure 4.3**. The supply delivers 13V with a 14% ripple.

With an increase in the load's resistance, the capacitive power supply tends to be more stable in terms of output. The increase to the load resistance also increases the discharge time of the capacitor leading to more effective smoothing.

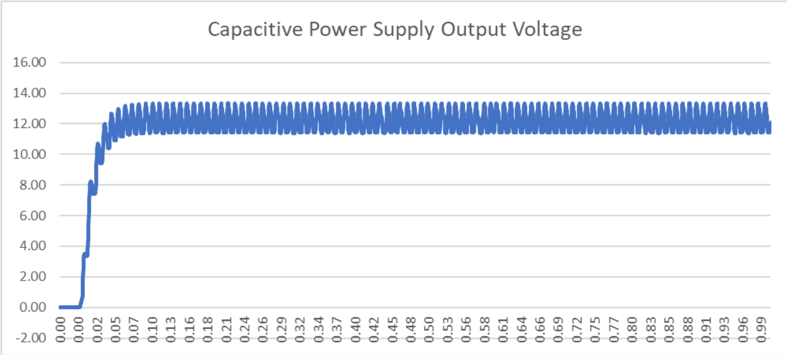

Figure 4.3 - Capacitive Power Supply Output Voltage.

4.2 - Flyback System

The system here presented is a flyback system designed for the conversion of the DC output of the capacitive power supply to a high-frequency AC signal. This switching method was chosen due to its simplicity and time constraints, in a future iteration of the circuit a better method should be employed like full wave switching to ensure greater efficiency.

To simulate the driver, the system uses the PWM component from Multisim's library. The device is composed of a comparator and programable saw tooth wave. In a real circuit implementation, the system would either use a completely integrated gate driver or a gate driver with a PWM signal generator. Such a system could be a microcontroller or a high-frequency PWM generator.

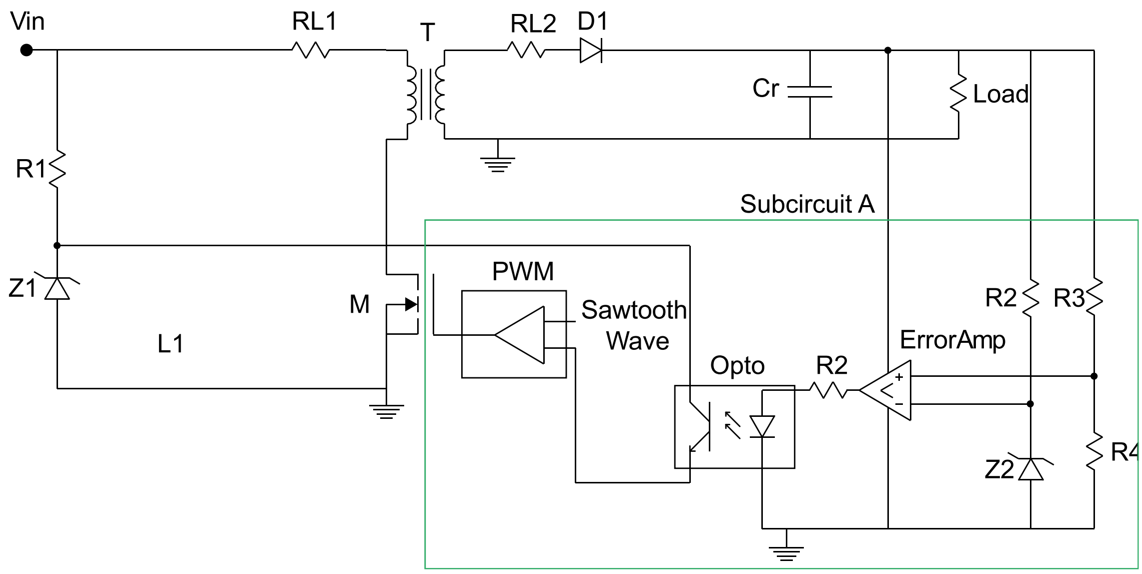

Figure 4.4 - Simulated Flyback.

The circuit represented in **Figure 4.4** receives the input as a ≈14V DC signal which is switched with the transistor M, an NMOS SiC MOSFET which activates and deactivates the input to the transformer. The converter is modeled according to the simulated coils, developed in section 4.3 - .

The frequency is chosen according to the experimentation and simulation results with the planar inductors and set to 4Mhz.

A concern when working with this type of Flyback configuration is transient voltages on the transistor's terminals.

On the receiver side, a simple half-bridge rectification is performed allied with a rectifier capacitor, the rectifier was chosen to be 100nF.

Voltage regulation on the secondary is provided by a negative feedback circuit, the Subcircuit A, represented in **Figure 4.4.** It uses an analog comparator to detect the difference between the output voltage that the system is providing to the load and the programmed reference voltage. In the case of the expected power supply the output should be 5V, so, the comparator is connected to a reference Zener through its negative terminal with 3V breakdown voltage forcing the voltage on that terminal to 3V. The positive terminal is connected to the middle point of a voltage divider. If the voltage goes above the programed 5V then the difference to the expected will be amplified and passed to optocoupler. The device transmits the error signal disabling the gate driver and turning off the transistor. The circuit will then start to decrease the output in the load disabling the feedback, this method is often referred to as pulse skipping. In **Figure 4.5** the regulation mechanism is presented. With it the system can provide voltage regulation.

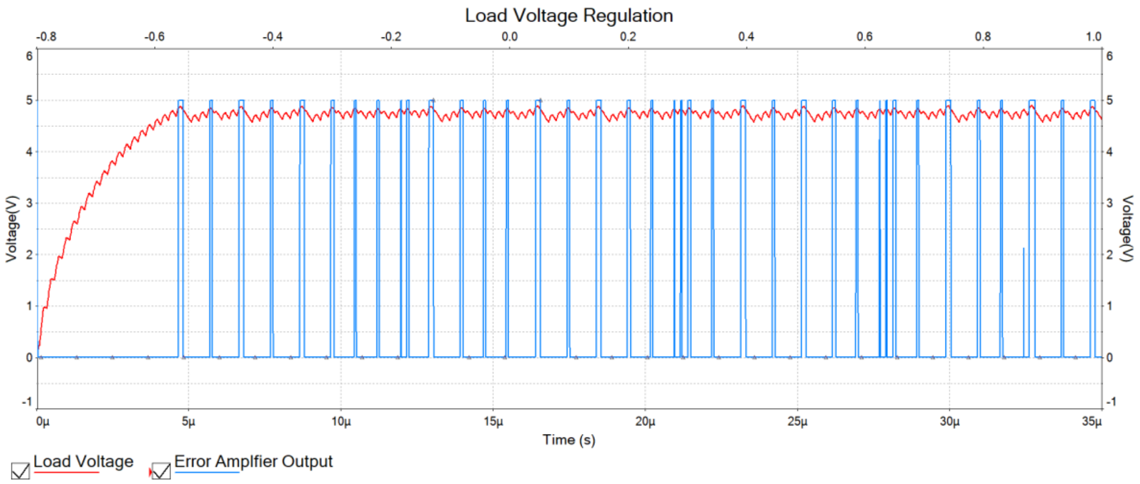

Figure 4.5 - Voltage Regulation

4.3 - Modeled Transformer

To simulate the electrical characteristics of the transformer a coupled transformer model was used. The model allows configuring the desired coupling coefficient and the inductance of each coil. To simulate the resistance of each, a resistance was added in series with each side.

The resistance and inductance of the coils were measured directly on the real transformer.

To attain the coupling coefficient a separate electromagnetic simulation was performed in Ansys Maxwell electromagnetic simulation software.

The modeled transformed is presented in **Table 7**.

In **Figure 4.4** the simulated resistances R_{L1} and R_{L2} are respectively set to their measured value.

Table 7 - Modeled Transformer Characteristics

	Primary	Secondary
Resistance (Ω)	12.5	10.7
Inductance (μH)	3.60	3.60
Coupling Coefficient	0.834	

4.4 - Simulation Results

The simulation of the system was performed first with the designed capacitive power supply to ensure the viability of its use. The supply proves that it can manage the DC voltage value and supply enough current to keep the system stable.

To simulate with greater detail the flyback stability and load regulation, the capacitive power supply Is replaced by a 15V DC power supply.

The system is then tested for a range of loads to evaluate the load capacity. The results are presented in **Table 8Table 7** and the relation between the Load's value and the power consumption is plotted in **Figure 4.6**.

Table 8 - Simulation results

Load (Ω)	Average Voltage (V)	Power Consumed by the load (mW)
5	1	200
10	1.75	334
20	3.2	496
30	4.2	579
40	4.7	549
50	4.7	446
80	4.8	288
100	4.8	232
150	4.9	154
200	4.9	117
500	4.9	47
1000	4.9	24
10000	4.9	2.3
Open Circuit	4.9	0

The voltage output of the circuit becomes stable at 40Ω, setting it as the maximum load.

When the voltage at the output reaches stability at 4.9V the feedback system starts activating and deactivating the MOSFET's conduction.

The power consumption of the flyback circuit was tested with the wattmeter of the simulation program and load of 50Ω. The results are presented in **Table 9** and show an efficiency of 27.88%, calculated between the power consumed by the load and the supplied by the power supply.

An estimation of the wasted power per component was also performed with a 50Ω load, the results are presented in **Table 10.** The power consumption is greatly influenced by the inductors resistance which combined consume over 0.5W. Without that influence the power consumed by the system would drop to 0.73W with an efficiency of 61%. A much more acceptable efficiency level.

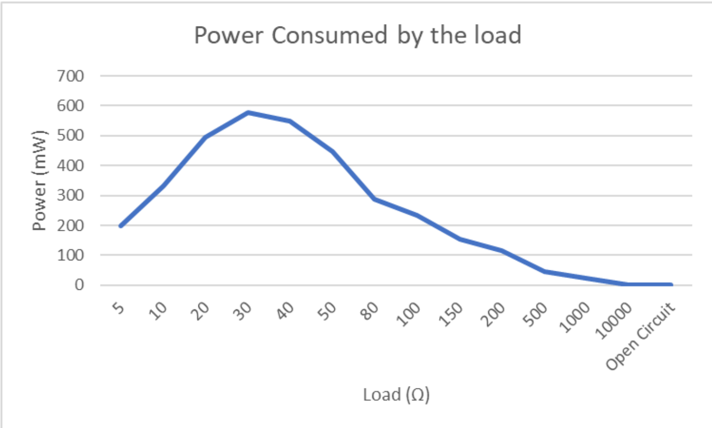

Figure 4.6 - Power Consumed by the Load.

Table 9 - Efficiency According to the Load.

Efficiency(%)	Load (Ω)
6.97	5
12.83	10
20.67	20
26.32	30
29.36	40
31.86	50
35.12	80
34.63	100
34.22	150
36.56	200
32.41	500
30.00	1000
15.33	10000
	Open Circuit

Table 10 - Power Consumption

Primary	
	Power (W)
DC Power Supply	-1.6
MOSFET	0.3
Coil with resistance	1.12
Coil Resistance	*0.34*
Secondary	
Coil supply*	-0.78
Coil Resistance	*0.24*
Diode	0.075
Load	0.446

** The coils's supply power was calculated by subtracting the power consumed by the resistance of the the coil on the primary side. The result is aproximatly the power supplied to the secondary side.*

Chapter 5

Conclusion and Future Work

This dissertation focused on the design of a power supply using printed electronics technology to minimize the final volume of the system. Through experimentation and simulation, it was evaluated the possibility of using planar printed inductors as transformers. After such work is was assessed that the use of the printed inductors would require high frequencies to achieve results interesting enough to justify the use.

To validate the findings a circuit was designed that would make use of the printed coils to feed a load reaching values as low as 50Ω. The configuration should use a high-frequency SiC transistor or similar, to switch the input voltage to the primary coil and to create a magnetic field capable of delivering power to the secondary side.

The resulting circuit has the potential to be constructed as a printed solution combined with surface mount components (SMD). Such a solution would use less space, height-wise, and would be able to distribute that volume in terms of area.

In terms of usability, the supply provides an alternative that may be used in projects where the power requirements are low. One possibility would be IoT sensors attached to walls for sensing purposes. The supply could be mounted against the wall, distributing the used space for the coils on a surface where it does not interfere with the system's available area.

The main disadvantage of the use of printed coils as transformers is the amount of resistance introduced in the system. Among the coils available most have resistance values over 6Ω which causes major power losses to the system.

In terms of future work, there are aspects of the thesis that could be further explored and optimized.

The coils can be optimized by printing with a material with lower resistance such as pure silver, instead of the considered silver that possesses organic elements that increase the resistance of the final component.

Another alternative would be to fabricate the coils by cutting a copper sheet using the same method as the one used for vinyl masking. With this technique, the manufacturing process would have the same level of versatility while having a much higher conductivity as well as efficiency. It would also mean that the coils would require a much lower frequency, facilitating the switching by removing the need for high-speed MOSFET and Gate Drivers

In the circuit design, a solution more stable could be investigated using different methods of switching. The flyback method used can provide an oscillating current to the coil but cannot provide inverting current. The inverted current as the one produced by a full wave switching method would provide a higher current variation and with it a more efficient magnetic field.

Another way to improve the overall system efficiency would be to substitute the current differential amplifier for one with better efficiency as well as the power MOSFET used, which in the present circuit is consuming a great deal of energy. Also, the rectifier diode on the secondary side could be optimized for better switching if swapped for a ZVDS (Zero Voltage Diode). Such circuit would allow for faster switching on the diode leading to less power consumption.

A method for driving the Gate of the MOSFET may also be investigated. The considered MOSFET is of SiC composition. The presented solution leaves open the method of generating the pulse to feed the PWM generator. While investigating the components available for high frequencies, some were found capable of driving at a very high speed.

Overall, the configuration could be further improved and investigated. With higher quality factor coils, reducing the necessary frequency, the working conditions of the remaining components would be less demanding and require simpler and less expensive components. Teamed with the optimization of switching methods the circuit could reach higher efficiency levels that would allow it to compete with existing power supply solutions. Such power supply could be especially useful for home automation and industrial settings for IoT applications.

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