POLITECNICO DI TORINO

Master of Science in Electronic Engineering

Master degree Thesis

Exploration and Implementation of Model for Testing Inductive Cooking Systems

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Abstract

This project aims at testing the good functioning of inductive cooking systems innovated within Whirlpool company through checking the behavior of these inductive cook-tops put under several tests.

The features and characteristics of the different devices such as the AC power supply SPS300VAC12000W and PYNQ-Z2 used in this project have been elaborated. Based on that, an evaluation of the various communication protocols supported by the components has been performed and the most adequate one has been chosen in order to ensure the communication between devices as well as the drive of data. Comparing the different interfaces, the serial communication USB/RS232 is counted the best protocol to be used in this project. A first version has been presented as a starting point for the work in which the board PYNQ-Z2 is set-up and the configuration of the AC power supply is operated using by that a bunch of specific commands. The addition of the device under test which is the inductive cooking system has been carried-out in order to start the testing and to observe the behaviour of the cooktop under these settings. Eight tests have been performed with regular and irregular shapes and with a range of voltages according to the European standard. The output data has been extracted through applications developed based on the i100 protocol which is specific for the DUT. Several parameters have been selected for the output data such as current generated to the cooktop, Vbus, power and Vce in order to best evaluate the response of the DUT which has behaved greatly and properly thanks to its robust internal construction.

Contents

Acronyms

Abbreviation	Meaning
IH	Inductive Heating
HB	Half-Bridge
QR	Quasi-Resonant
IGBT	Insulated Gate Bipolar Transistor
GPIB	General Purpose Interface Bus
AC	Alternating Current
EMF	Electromotive Force
DUT	Device Under Test
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
DSP	Digital Signal Processor
CPLD	Complex Programmable Logic Device
PFC	Power Factor Correction
FPGA	Field Programmable Gate Array
CLB	Configurable Logic Blocks
DTE	Data Transmission Equipment
DCE	Data Communication Equipment
TXD	Transmitter
RXD	Receiver
RTS	Request To Send
CTS	Clear To Send

Symbol	Measurement
H	The magnetic field intensity
ϕ	The magnetic flux
i	The current flowing in the conductor
B	The flux density
μ	Permeability
μ_0	Permeability in free space
μ_r	The relative permeability
e	The electromotive force in volts
N	The number of turns of wire

1 Introduction

1.1 Company introduction

As an industry-leading company with a 110-year heritage of accomplishment and a strong focus on improving life at home, Whirlpool Corporation is dedicated to deliver a long-term customer value. Whirlpool Corporation (NYSE: WHR) is engaged in its commitment as the world's best kitchen and laundry company, in an ongoing journey to enhance home life. In an intensely digital world, the company leads focused product innovation to fulfill evolving needs of consumers through its portfolio of award-winning brands, which include Whirlpool, KitchenAid, Maytag, Hotpoint, Consul, Brastemp, Amana, Bauknecht, JennAir, Indesit and Yummly, same as for the induction cooking systems. In 2021, the corporation claimed annual sales of around $22 billion, 69,000 employees and 54 manufacturing and technology RD centers. The sales category is divided into four sections; 16% dedicated to dishwasher, 30% to refrigeration, 28% to laundry Appliances and 26% for cooking Appliances which include of course the induction cooking systems. In other hand, all sales are distributed around the whole world for 14% to Latin America, 6% for Asia,23% dedicated in Europe, middle east and Africa and 57% in north America.

The Whirlpool vision and mission
The main vision of the company is to be the leading company of kitchen and laundry equipment, by keeping a permanent workforce of enhancing the life at home. While the mission is to build confidence and develop market demand for the brands in a digital world. Five values define this company which are Integrity, Respect, Inclusion Diversity, One Whirlpool and Spirit of Winning.

The company's purpose
Making life at home better and easier has been the global purpose for 110 years. The company is dedicated to continually develop and introduce innovative products that allow consumers to reduce their time and effort. Beginning with the first electric washer-extractor and stand mixer back in the early 1900s, extending to an entire line of both energy and

water saving products, besides the leadership in today's smart connected appliances and maintaining a continuous reinventing to bring purposeful homes customer innovation whatever is the socio-economic levels around the world constitute the pathway of this corporation. Along the road of development and growth, no change in the way of commitment to a culture has been made. A firm determination to do the right things in the right way, is the most important purpose made by the company.

The company's values are the driving force behind the commitment even to the employees and the communities by offering a cooperative, secure and welcoming atmosphere so that Whirlpool is the best place to work and exchange innovative ideas and creations. In addition, and as already mentioned, the boost of life quality in the communities is the main reason of the establishment of this corporation by relying on different vision grounded in improving life at home, dedicating all the focus on incorporating valuable innovations into the products and seeking new ways to reduce the environmental impact while also providing significant long-term value to the consumers and investors.

All the Whirlpool products have created a rich experience for all customers as the lines between life and work blend and because of the devotion in spending more time at home, the consumer has maintained a focus on many brands. To respond to a steadily growing need for quiet, peaceful home surroundings, Whirlpool has found an optimal balance between function and form through its " Supreme Silence" laundry products, providing consumers with the quietest washing machines and dryers. KitchenAid introduced also the induction cooking systems which make the cooking process faster by offering a Quick Cleanup. When cooking with special cookware, additional cooking features are introduced to help making more efficient use of time when preparing other dishes.

Some of the additional Features for the inductive cooking systems developed by Whirlpool are the following:

- Assisted boil and Pan Frying: with the help of a flashing light or a tone, a notification to the user of this equipment would indicate the requested temperature.

- Maintain a steady temperature: by providing low heat, food would be ready to serve which will save time spent on heating up food.

- Pan Detection: Cookware detection provides an easy way to identify which item is active. A blinking indicator warns whenever a pan is removed or returned to an active element.

Safety and Occupational Health

EHS is the abbreviation for the Environment, Health, and Safety which are the main commitment that Whirlpool keeps improving and maintaining. All these values are reflected on every program and results. By formalizing "We Care" engagement, Whirlpool has created a safe atmosphere for all the employees and that by protecting the environment and making all the employees as active members in order to share responsibility to ensure the EHS Policy and Standards.

As already mentioned, the "We Care" manual takes in consideration the improvement of the EHS features and of course by promoting its principals within the Whirlpool corporation to build a safe and dedicated atmosphere in the company. It has the ability to ensure the company with the requirement of control related to the EHS risks in all the sites which is updated according to the Global EHS Policy commitment. To protect the employees, visitors and contractors, the preservation of the environment is a mandatory issue in order to enable the business to act sustainably.

Statistically speaking, the number of injury and illness cases that has been recorded in 2019, is 528 cases, while 518 cases have been declared in 2020, this number has been significantly reduced in 2021 with only 480 cases which make the illness rate 0.72 that year and which is better than the years 2019 and 2020 that have 0.76 as illness rate.

Global Machine Safety Evaluation and Remediation

Depending on the incidents' analytics, Whirlpool corporation has developed a machine remediation program involving the Thermoforms since 2018. Including globally machinery evaluation tools and controls, the effort was expanded globally. The term the multi-year Machine Safety has been initiated by Whirlpool in 2020. The sequence of equipment to be intervened was identified and prioritized by the Asset Ranking Process. For each piece of equipment, three specific processes are performed following this prioritization:

- To ensure minimum machine safety requirements accuracy Machine Safety Threshold Questionnaire Evaluation form was established.

- For each single safety device inspection routines must be done to ensure its safety by applying the Functional Safety Check Procedure.

- As part of the Machine's Remediation Process and in order to identify gaps and implement countermeasures the Machine Risk Assessment Deep analysis of machine's, is implemented

1.2 Motivation

Recently, technology has reached a crucial improvement in various fields namely power electronics and more precisely cooking systems. Engineers are working harder in order to make life easier and more efficient in terms of environment, time, power and specially safety. It's noticeable that innovations are tending to be more electrical and automated without the requirement of external parts for its functioning.

Nowadays, inductive cooking applications are becoming more and more demanded and are gaining a good popularity widely. In fact this innovation presents an excellent efficiency conversion factor in relation to standard solutions (the gas and electric stoves). In addition, the Induction heating for cooking applications has various advantages from the efficiency, cost and safety point of view: quick heating, localized spot heating, direct heating, high power density, high reliability, reduced operating costs and it also presents no acoustic noise. Statistically speaking and based on the U.S. Department of Energy, the energy transfer efficiency factor for the induction heating for the cooking applications is more important compared to the smooth-top non-induction electric unit evaluated as 84% against 74% and by that the energy savings can reach up to 10% for the same amount of heat transfer.

Since this innovation will be used worldwide, its good functioning has to be ensured. Provided that, due to different electric standards of each country, the alimenting for electronic devices at home can vary. For that reason, the testing is required to be performed in order to assure that this device can function properly under these conditions, which is the goal of this thesis. This project aims to perform the testing of inductive cooking systems designed at Whirlpool Company and which can be alimented by different standards, using by that a hardware-software board PYNQ-Z2 in order to ensure the proper functioning of the cooktop.

1.3 Goal statement

As mentioned in the previous section, this thesis expects to perform the testing of the inductive cooking systems, using several components such as AC power supply and the PYNQ-Z2 board, for the aim to provide the good functioning of the cook-top in terms of voltages and frequencies.The process is described in figure 1.1.

The figure 1.1 presents the different parts that are required for achieving the purpose work. The project comes in the form of a closed loop, where the PYNQ-Z2 will configure the AC
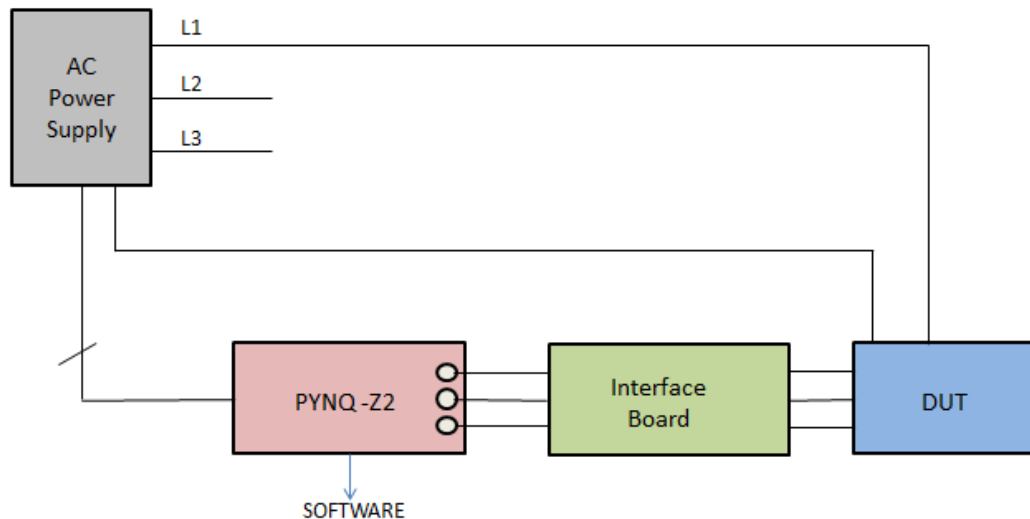
Figure 1.1: Schematic description for the purpose work

power supply through a bunch of setting commands developed in a python code and will be elaborated more in details shortly.

Then, the settings that have been done and which consist of voltages, frequencies in regular or irregular waveforms will be sent to the DUT and the data (the response of the inductive cook-top) will be displayed later through the interface linked to the board.

The interface block is supposed to be an Electronic board that has to be designed specifically for our purpose in which the circuitry aims at reading the values received and sent by the DUT directly on the PYNQ Z-2 board to have a high performance in terms of time (real-time operation).

The DUT block is an inverter, specifically, a power inverter which is the cook-top. It receives AC values, converts them to DC then converts them again to AC values. The purpose of such conversion, is to adjust the frequency. In fact, the input frequency is too low, so this conversion is needed in order to boost the frequency and have the adequate one at the output.

In order to connect these blocks together and have a working loop, first an evaluation of each of the power supply, board and the supported interfaces will be done. Based on that evaluation that will allow the appropriate choice of the communication interface between components, the testing will be put into practice. The tests will be performed using different type of shapes and voltages in order to observe the behavior of the cook-top.

1.4 Structure of the thesis

In this thesis, the different types of interfaces will play an important role for driving data between blocks. For that purpose, it has to be chosen adequately for achieving the good communication. In chapter two, the features of the AC power supply as well as the characteristics of the PYNQ-Z2 board will be presented. In addition, all the supported interfaces by the previously mentioned components will be described. Chapter three aims to focus on the project constitutions. It will cover all the steps that have been performed: from the evaluation of the communication protocols and the comparison of them to the testing part. The results and the evaluation of the different testing will be demonstrated in chapter four. An outlook for future work and a summary are given in the last Chapter.

2 Fundamentals

This chapter aims to clarify and explain the basic principles and concepts from a theoretical point of view of the different components that have been employed in order to achieve the project. Section 2.1 describes the principle behind the induction cooking system as well as its different topologies. Section 2.2 and 2.3 includes the characteristics of the AC power supply and PYNQ-Z2 board used in this project respectively. Section 2.4 elaborates the different communication protocols supported by the two devices mentioned previously, the purpose of using them, their features, advantages and disadvantages.

2.1 Inductive cooking systems
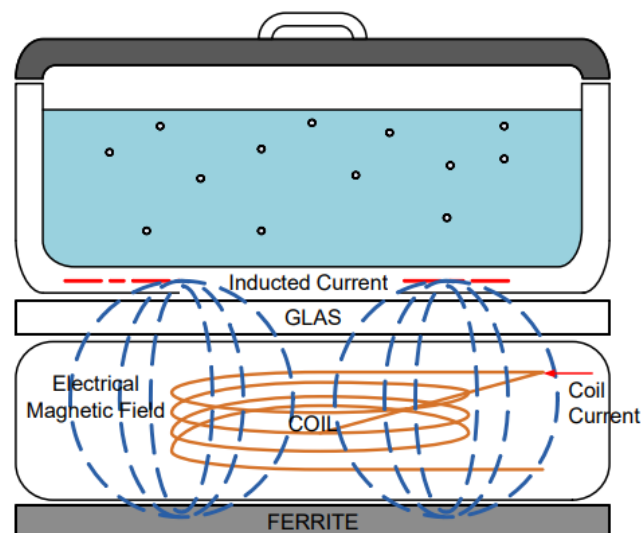
2.1.1 Introduction

Figure 2.1: Scheme of an inductive cooking system (Onsemi 2014)

As mentioned in Motivation section, the induction heating concept for cooking applications is gaining a huge and good reputation as it provides many advantages such as an excellent

efficiency conversion factor in relation to standard solutions(the gas and electric stoves). The figure 2.1 depicts the scheme of an inductive cooking system whose principle will be detailed shortly. The concept of an induction stove (Onsemi 2014) is based on exciting a coil of wire and applying a current into a high magnetic permeability material which will be located in the near surroundings of the previous coil. The heat produced is caused by eddy currents created in the base layer of the cooking pot, in combination with the hysteresis losses of the container's magnetic material. The cooking containers must be made of a ferromagnetic metal which is the same case for almost all induction cooktop model. It may be placed also on an adapter panel that supports the use of non-induction cooking equipment on induction cooking surfaces. A coil of copper wire is located under the pot for the induction cookers applications. An oscillating magnetic field is created and resulted when applying an alternating electric current in which will flow through the coil. This field produces an electric current in the cooking pot. The current flowing through the metal pot generates resistive heating that will create a heating energy and warm the food up. Even though the current is high, this whole procedure is produced by low voltage.

Heating a metal by electromagnetic induction is the process that creates induction heating. In fact, Eddy currents are created by the electromagnetic induction throughout the material and therefore its resistance leads to Joule heating, besides the magnetic material's hysteresis in the pan can also produce losses.

Electromagnetic Induction

According to Faraday's law, in a closed circuit the induced electromotive force (emf) is given by the negative of the time rate of change of the magnetic flux in the same circuit, this law can be demonstrated by the upcoming rule: Electromagnetic Induction takes place when an alternating current flowing through a circuit which will generate a current in a second circuit that is placed in an alternating flux field. In general knowledge, in a conductor, when an alternating current flows into it, a magnetic field would be generated which lead to these equations:

$$\oint H.dl = \sum i \tag{2.1}$$

$$\phi = \iint_A B.dA \tag{2.2}$$

$$B = \mu.H \tag{2.3}$$

$$\mu = \mu_0.\mu_r \tag{2.4}$$

$$e = N.\frac{d\phi}{dt} \tag{2.5}$$

where:

- H [A/m] is the magnetic field intensity.

- $d\phi$ is an infinitesimal arc length along the wire, and the line integral is evaluated along it.

- i is the current that flows in the conductor.

- B is the magnetic field.

- μ is the permeability and μ_0 is the permeability in free space while μ_r is the relative permeability.

- e is the electromotive force (EMF) in volts.

- ϕ[Wb] is the magnetic flux.

- N is the number of turns of wire.

- dA is an area of surface's element related to A, in other word dA is the infinitesimal amount of magnetic flux.

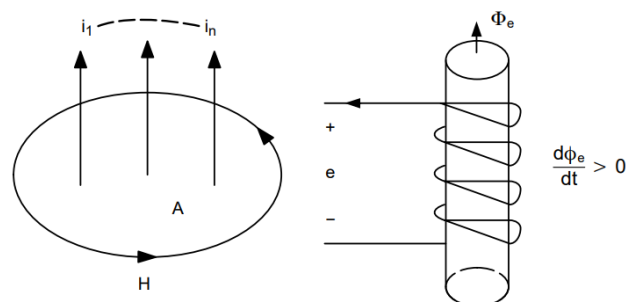- ϕB is the magnetic flux flows through a loop.

Figure 2.2: An Illustration of Lenz's Law and Ampere's Law (Onsemi 2014)

The figure 2.2 presents an illustration of each of the Lenz and Amper Law. As mentioned above, in a simple loop the number of magnetic flux lines that surround it, is proportional to the related magnetic flux. The electromotive force direction is determined according to Lenz's law. As the flow of the loop changes, it develops an electromotive force e [V], known as the energy available from charge's unit once passing around the loop. As illustrated in the circuit of the figure 2.2, e is the amount of voltage that would be determined by cutting the wire to generate an open circuit and connecting a voltmeter.

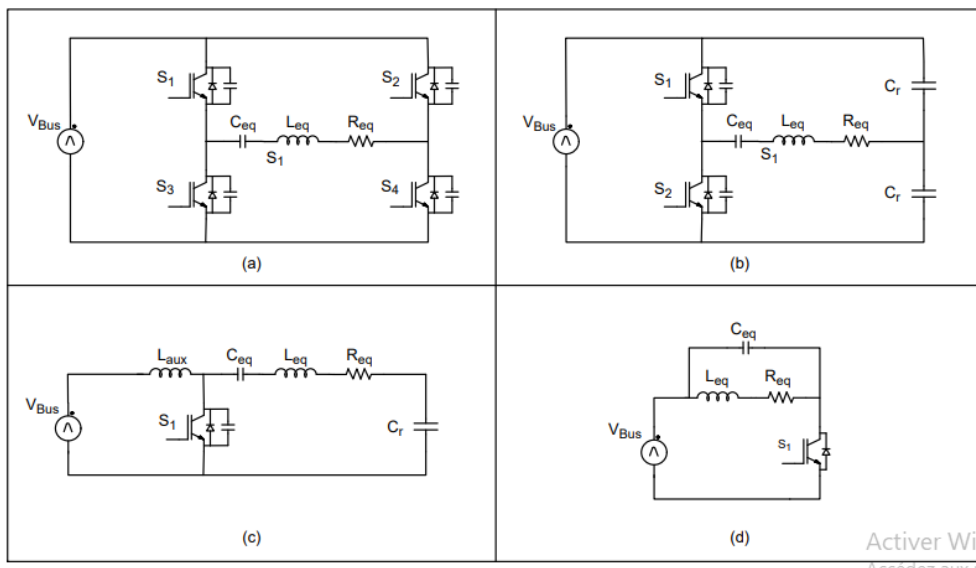### 2.1.2 Topologies of Induction heating

Figure 2.3: Samples of topologies of inductive cooking systems (Onsemi 2014)

The figure 2.3 shows the samples of the topologies of induction heating presented in the last decades (Onsemi 2014) (Infineon 2021). The figure is devided into four different topologies. In fact the figure (a) is for the full bridge, figure (b) is destinated to half-bridge, figures (c) and (d) represents the single switch inverter topologies with the Zero Voltage Switching (ZVS) (c) and Zero Current Switching (ZCS) operation (d) consequently and which are the main topologies for Quasi-Resonant inverters.

As mentioned above, essentially, there are three types of topologies employed in the construction of an induction cooker:

- Single-ended parallel resonant converter which are the Quasi-resonant converter, very popular and well known in the Asian market used especially in the single-hob stoves

and rice cookers.

- Half-bridge series resonant converter, practically these converters are most used to build high-end multi-hob cookers and microwave ovens.

- Full-bridge series resonant converter: the Full-bridge series is limited to the commercial cooker market because of the higher power capability.

There are different performance characteristics in each power converter topology with specific requirements in regards to cost, hardware and control complexity. These systems are very familiar in the literature, same as the design criteria for all their main parameters. The half-bridge serial to resonant converter (HB) and the single switch Quasi Resonant (QR) or QR flyback converter are the most used topologies for IH. The resonant half-bridge is very popular for four-burner cooktops especially in the European market. Unlike the Quasi-Resonant or QR flyback, which is very common for the single burner, and is the most famous in the Asian market.

Resonant Half-Bridge

As mentioned above, the resonant half bridge converter 2.3(b) is the most used topology in induction stoves for multiple burners because of its simplicity, cost savings and electrical components specifications which are commonly found in European markets. The resonant tank consists of the inductive coil, the resonant capacitors and the equivalent resistance of the pan which will present the equivalent load. The inductor-coil coupling itself can be represented as a series of an inductor and a resistor, based on the transformer analogy, and it is specified by the parameters of Lr and Rload. Such factors are mostly related to the switching frequency, the pan construction material, the temperature, and the inductor-panel coupling. And by that the resonant converter family include the resonant half-bridge. It is analogous to a standard half-bridge, where the bus capacitance, in other term the resonance capacitors is defined depending on the resonance coil at a specific frequency and this is where the name of resonance frequency has came from. A coil, two capacitors, anti-parallel diodes in association with two switches are the main composition of the power stage.
The circuit may also be optimized for calculation purposes, as shown in figure 2.4, where both capacitors are connected in parallel.
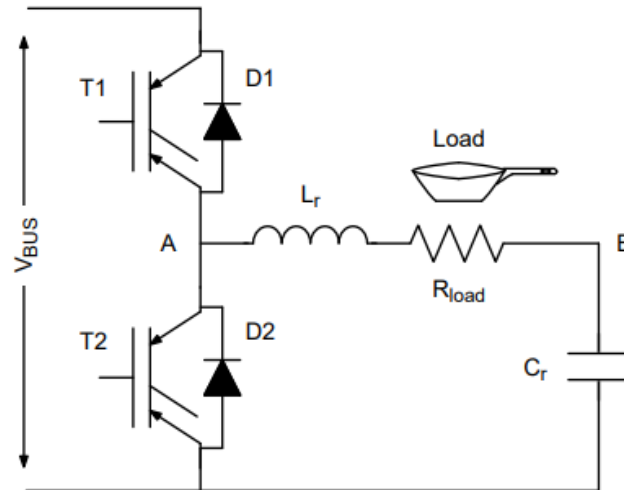
Figure 2.4: Equivalent Circuit for a Resonant Half-Bridge (Onsemi 2014)

Quasi-Resonant

Quasi-resonant (QR) converters are commonly utilized as AC power supplies, for instance in induction cooktop applications or microwave inverters to power the magnetron. Such converters are highly appealing for domestic applications as they require just a single switch, normally an IGBT, and a resonant capacitor. QR converters can be regarded as a great combination of cost and energy conversion efficiency. They are very common for single burner countertop appliances in the Asian market.
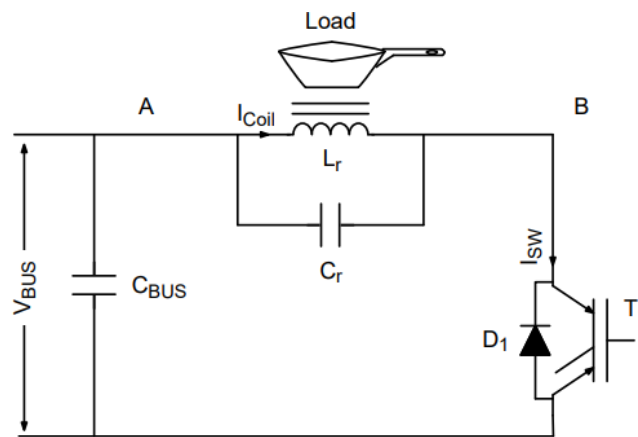

Figure 2.5: Equivalent Circuit for a Quasi-Resonant converter (Onsemi 2014)

Advantages and disadvantages of the quasi-resonant converter for induction cooking applications

The QR converter is extremely well accepted in the induction cooking marketplace (Infineon 2021). Here are a few of the benefits for choosing this topology:

- Thanks to the soft-switching operation of the power switch, an excellent power conversion is obtained.

- With a single power switch a whole process can be done which make it not only simple but effective.

- Budget friendly in relation to alternative converter configurations seen in induction cooking.

Some of the inconveniences of this topology are:

- Resonant voltage functioning making the input voltage lower than VCE of the IGBT.

- Because the voltage resonance amplifies the input voltage, more sensitivity to grid voltage variations is observed.

- Difficulty monitoring, as the load is not always reliable, and this can considerably affect the converter's operation (e.g., damping factor, resonance frequency, etc.).

The QR converter is mostly used in induction cookers which have just a single cooking area. In this situation, the QR converter has the best balance of cost and efficiency. Typically, the converter's power rating is restricted around 2.2 kW, since higher power ratings would raise the voltage class of the IGBT, that leads to higher device losses. Because of cost concerns in the consumer sector, this topology is increasingly becoming the preferred choice, even in the multifunctional device market, particularly in the lower end of the market.

2.2 AC Power Supply

As depicted in the figure 1.1 in the goal statement section, an Ac power supply is needed in order to be configured and generate the adequate voltages and frequencies. For that purpose, the testing will be performed by the Coupled 3-phase AC power supply SPS300VAC12000W (APM Technologies). This device shown in figure 2.6 is a programmable AC power supply having 3-phase output which offers a high power density. This generator is able to realize AC/DC stable output and also 3-phase/1-phase output. This is possible thanks to the several characteristics that the device has:

- High-speed DSP and CPLD control

- High-frequency PWM technology

- Active PFC design

Figure 2.6: Picture of the AC power supply SPS300VAC12000W (APM Technologies)

The terms that have been used previously, are defined as follows:
DSP stands for "Digital Signal Processor". It contributes in completing all the real-time signal sampling, processing, transformation and computation.
CPLD stands for "Complex Programmable Logic Device". It is used as a complement to DSP in order to address the functionality of logic signal processing such as signal conditioning and

fault detection.

PFC stands for "Power Factor Correction". It's also known as power factor controller. It's a feature that is implemented in some computer and power supply boxes for the aim to reduce the amount of reactive power generated. Note that this feature is required for power supplies shipped to Europe.

High reliability, high precision and high power density are the characteristics of this device. Actually, it's a good fit for production testing in several fields such as electrical, lighting, aerospace... In fact, it has the ability to produce an analogue output with power consumption for electrical equipment for the purpose to meet test requirements. In addition, it has a user interface. It can be configured either through this interface with a touchscreen and manual buttons (full-featured and easy to operate) or through a bunch of specific commands developed in a python code, which is the case in this project. This point will described more in details in the next section. The AC power supply SPS300VAC12000W has various features:

- It has several types of coupling, AC+DC mixed or independent output mode for voltage DC offset simulation.

- The output slope of voltage and frequency is adjustable. It's same for the phase angle also $(0 \sim 359.9°)$

- The output frequency is in the range $(15 \sim 1000)$Hz.

- Requirements of surge testing could be met by a high output crest factor.

- It has a wide selection of various current measurement levels which leads to the increase of the accuracy.

- An implemented power meter which can measure up to 15 electrical parameters per phase: voltage, current, power, etc.

- In order to avoid reverse current, reverse current protection is present.

- The possibility of setting the limits of voltage and current output.

2.3 PYNQ-Z2 Board

In order to achieve this project, a board has been used. This board is called PYNQ-Z2. It's shown in figure 2.7. More details about it, will be elaborated shortly.

As it's known, Xilinx is a semiconductor company and its tremendous electronic products have contributed widely in the development of the technology. Among its achievement, it has created an architecture called Zynq. This creation consists in a combination of an FPGA with ARM and I/O into one product. The FPGA part is called Programmable Logic (PL) while the ARM part presents the Processing System. In order to be used more widely, Xilinx has created PYNQ (PYNQ 2021) .

PYNQ is a hardware-software stack allowing the use of FPGA via Python and Jupyter
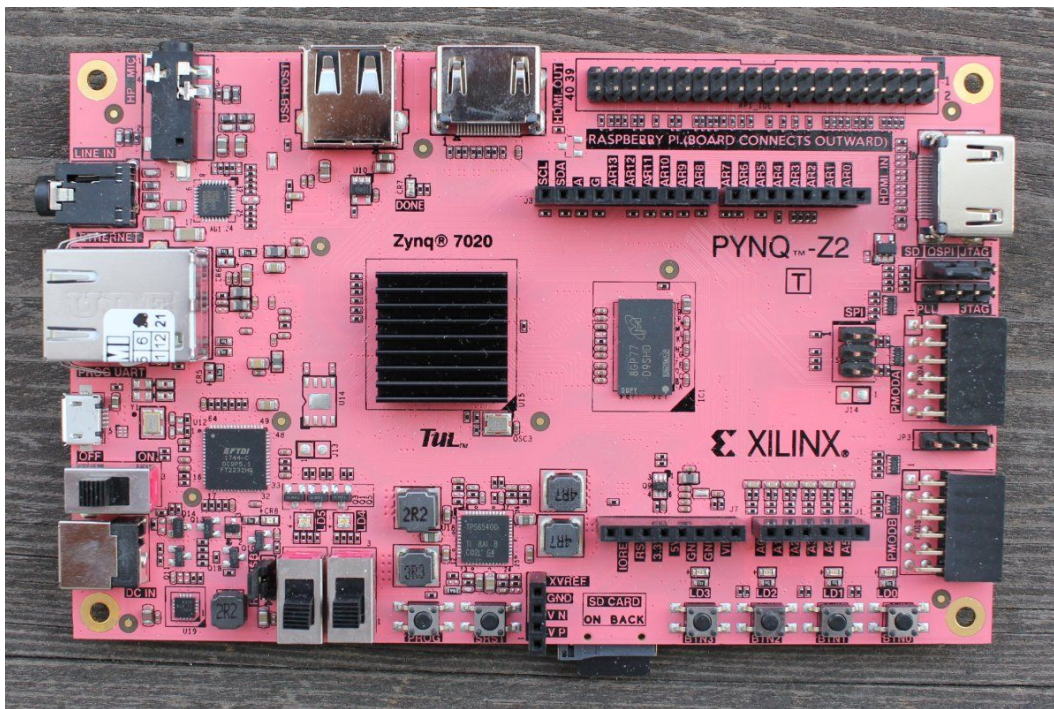

Figure 2.7: PYNQ-Z2 board (PYNQ 2021)

notebooks that run on the chip itself. This one is not for creating designs for the FPGA, but it is used for interfacing and employing designs made by hardware engineers. The innovation of PYNQ aims to be widely used by a bunch of designers and developers. Some types are stated as follows:

- `Software developers`: They have the ability to take advantage of Zynq and programmable hardware without the need to use ASIC-style design tools for designing hardware.

- `System architects`: wanting an easy software interface and framework in order to rapidly prototype and develop their Zynq design.

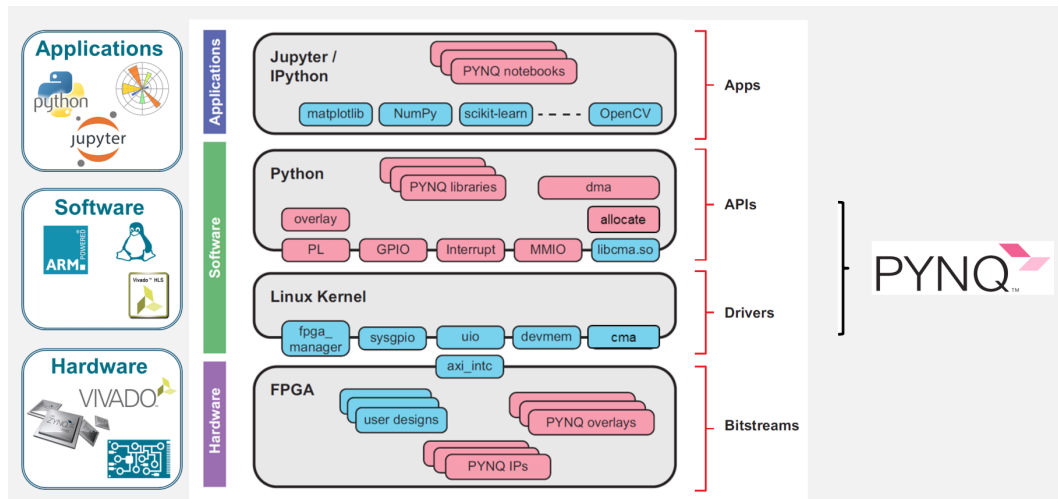- `Hardware designers`: wanting their designs to be used by the largest possible audience.

Figure 2.8: PYNQ software stack (PYNQ 2021)

The figure 2.8 depicts the overview of PYNQ. It presents the connection between layers, from low level hardware to Python applications.

The FPGA term has been used in the description above, so let's define it briefly. Actually, this word stands for "Field Programmable Gate Array". The idea is, that designers or customers can configure and program the internal logic after manufacturing in order to obtain desired applications or functionality requirements. The figure 2.9 presents the architecture of this semiconductor device which is based around a matrix of configurable logic blocks (CLBs) and connected via programmable interconnects. Various features can be found in this special board such as:

- USB and Ethernet

    - Gigabit Ethernet PHY

    - Micro USB-JTAG Programming circuitry

    - Micro USB-UART bridge

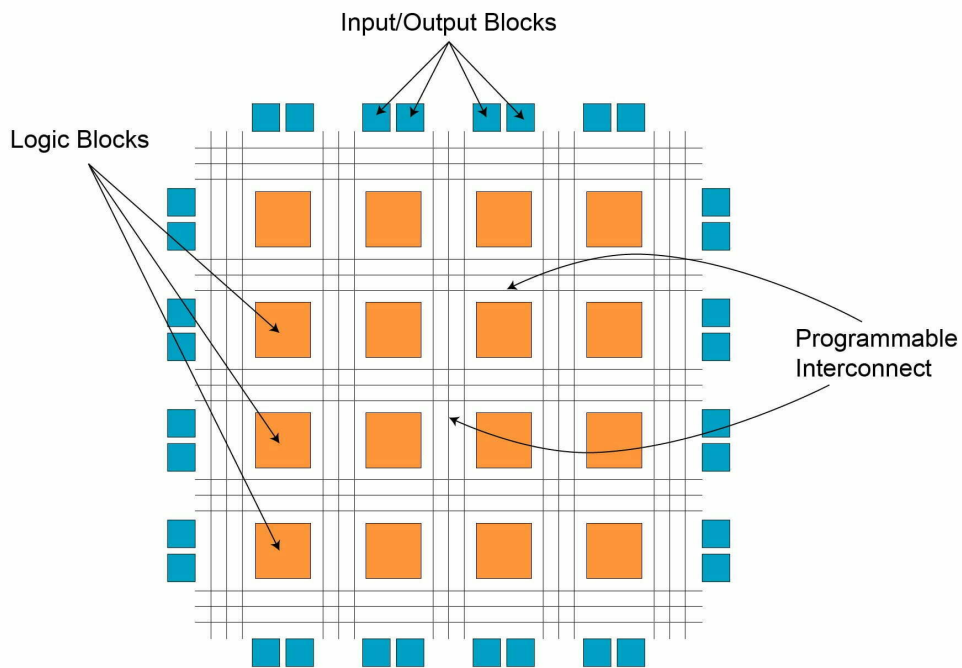   - USB 2.0 OTG PHY (only host supported)

Figure 2.9: FPGA architecture (Dheeraj Punia 2021)

- Memory

    - 512MB DDR3 with 16-bit bus 1050Mbps

    - MicroSD slot

- Powered from USB or 7V-15V external power source

- High-bandwidth peripheral controllers: 1G Ethernet, USB 2.0, SDIO

- Low-bandwidth peripheral controller SPI, UART, CAN, I2

These are some of its features and there are various others related to other interfaces(see ref).

2.4 Communication Protocols

As mentioned in the goal statement section, the aim is to connect several components with each other in order to perform the testing. For that purpose, an evaluation on the different communication protocols has been performed in order to choose adequately the one that will assure the link between devices.

Since the device SPS300VAC12000W AC power supply and the PYNQ-Z2 board are employed in this project, only interfaces that are supported by the two devices will be evaluated. Before starting with the description of these protocols, let's have a brief introduction on the communication in general (Abhimanyu Pandit 2019). Actually, it consists in the exchange of information between two or more mediums. In embedded systems, the communication stand for the data that is exchanged between two microcontrollers in the form of bits. A set of rules is defined in order to ensure that exchange of data bits. These defined rules are known as communication protocols. There are two types of communication protocols: Serial communication and Parallel communication. The first type is described as follows.

2.4.1 Serial communication

In serial communication, the data is sent sequentially. In fact, the data is transmitted bit by bit over a computer bus. Serial communication approach is largely used for transferring information between data processing peripherals (Abhimanyu Pandit 2019).

Three modes of transmission can be found:

- `Simplex mode`: As it can be seen in figure 2.10, the transfer is performed between a transmitter (sender) and a receiver. In this mode, only one-direction communication can be ensured. It means that either the transmitter can be active or the receiver. In other words, if the transmitter is sending the data then receiver can only accept and vice versa, such as the case of Television and Radio.

- `Half Duplex mode`: On the contrary of the previous mode, both the transmitter and the receiver can be active, however it can't be at the same time. In fact, if the transmitter is sending then receiver can accept data but can't transmit and vice versa. The internet is an example of this mode.

- `Full Duplex mode`: In this mode, both receiver and sender can transmit data to each other at the same time. The mobile phone is the best example for this mode.
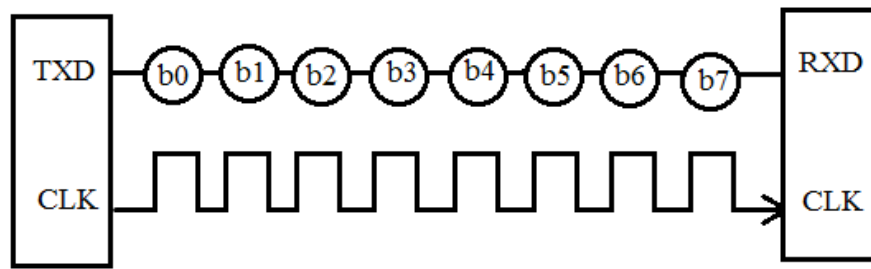
Figure 2.10: Illustration of Serial communication Protocol (Tamanna Sharma 2018)

In figure 2.10, CLK which stands for clock is present. Actually, it's very important in the processing of data transmission and it counts one of the principal source. The malfunction of this primary element can lead to unexpected data transmission and sometimes to data loss. For that, the clock synchronisation is becoming more and more crucial when using serial communication.

The clock synchronisation can be classified in two types, Synchronous and Asynchronous Serial Interface. A clock pulse is a signal which is employed for synchronisation.

These two modes of data transfer are defined as follows:

- **Synchronous Data Transfer**: In this mode, the bits are synchronised by a clock pulse. A single CPU bus is used by all the devices in order to share data and clock, which results in a good performance in terms of time as the data transmission becomes faster.

- **Asynchronous Data Transfer**: On the contrary of the previous mode, the bits are not synchronised by a clock pulse. Long distance applications are the good example for this mode as it ensures the stable communication. Actually, in asynchronous mode the external clock source is absent, which makes it rely on various parameters that will be elaborated in the next paragraph

The serial communication is characterised by several terms such as:

- **Baud rate**: is a parameter that is used in order to measure the speed of transmission. It's defined as bits per second (bps). In other word, the amount of bits passing in one second. It can be 9600, 2400, 57600, 115200. Note that the sender and receiver should have the same baud rate.

- **Stop Bits**: are used for a single packet in order to stop the transmission. They can take one of these threee values: 1, 1.5 and 2 bits.

- **Parity Bit**: has the aim of checking the errors. It can be one of these four types: even, odd, marked and spaced.

- **Error Control**: Since in serial communication, there are several factors that may lead to noise or affect the performance, the error control is then crucial to track the transmission. In order to get rid of the error, Parity bit described previously are used.

Now, the different serial communication protocols will be described. First an example of a synchronous serial protocols is presented.

2.4.1.1 USB

USB (Universal Serial Bus) is a widely standard establishing features for cables, connectors and protocols for connection, interfacing between power supply, computers and peripherals (Abhimanyu Pandit 2019). It has different versions and speeds. A single USB host controller can be connected to a maximum of 127 peripherals. It's also largely used among various devices such as keyboards, cameras, printers...USB has been designed for several motivations which are easy installation, faster data rated, less cabling and hot swapping. As it's known always in communication, there's the problem of interference (the fact that anything can disrupt or modify the message). So, in order to reduce interference and allow high-speed transmission over a long distance, USB tends to use differential signalling. Actually, a diffeential bus has two wires. One is representing the transmitted data and the other one is its complement. The idea behind this is that, the voltage (average) on the wires doesn't carry any information which leads to less interference.

There are different speeds that are supported by USB versions such as 1.5Mbps (USB 1.0), 480 Mbps (USB 2.0) and 5Gbps (USB 3.0). As it has been stated, USB was designed for simplifying and improving the interface between computer and peripheral devices. This interface has several advantages. Some of them are mentioned as follows:

- It's self-configuring, there's no need for the user to adjust the device's settings or configure it in terms of speed, data format or input/output addresses.

- USB interface is hot-swappable which means that devices can be exchanged without the need to reboot the host computer.

- It can be used as a source for powering small devices.

- Its protocols can be as a recovery from common errors which leads to the improvement of the reliability over previous interfaces.

But as all technologies, USB interface has some limitations such as

- The length of USB cables is limited, as the interface was intended for connecting peripherals on the same table-top. But, on the other side, a gateway (networking hardware or software) can be connected to a USB port to access distant devices.

- Its data transfer rates are slow comparing to other interfaces.

- Signals cannot be diffused by a host to all peripherals at once,each have to be addressed individually.

Let's move now with the asynchronous serial protocols. As mentioned above, for a reliable long distance data transfer, the asynchronous protocols are very important. It doesn't need a timing clock. In fact, in an independent manner, each device listens and sends digital pulses representing data bits at an agreed-upon rate.

2.4.1.2 RS232

RS232 stands for Recommended Standard 232. This standard protocol is used for serial communication (Tamanna Sharma 2018). It aims at connecting computer and its peripheral devices in order to ensure the data transfer. The RS232 connection is performed between two main parts: *Data Transmission Equipment (DTE)* which represents the transmitter and *Data Communication Equipment (DCE)* that represents the receiver as shown in figure 2.11 . Universal Asynchronous Data Receiver Transmitter (UART) is associated with RS232 in order to transfer data between printer and computer.

There are several electrical specifications. They're described in the following paragraph:

- **Voltage Levels**: There are two voltage levels, HIGH and LOW. The HIGH voltage level is represented by the binary "0", which works with voltages up to +5V to +15Vdc. The latter is called as "ON" or spacing. On the other hand, the LOW voltage level is represented by the binary "1". This level works with voltages up to -5V to -15Vdc and it's called as "OFF" or marking.

- **Received signal voltage level**: On the received signal, the binary "0" works up to +3V to +13Vdc. Regarding the binary "1", this one works up to -3V to -13Vdc.

- **Line Impedances**: The impedance of wires is in the range [3,7]ohms and 15 meters is the maximum cable length.

- **Operation Voltage**: The operation voltage can reach 250V AC maximum.

- **Current Rating**: The rating of the current has the value of 3Amps maximum.

- **Dielectric withstanding voltage**: The minimum value is 1000 Vac.

- **Slew Rate**: This term represents the rate at which the signal levels change. It can reach up to 30V per microsecond. Regarding the bit-rate, this one can reach 20kbps.
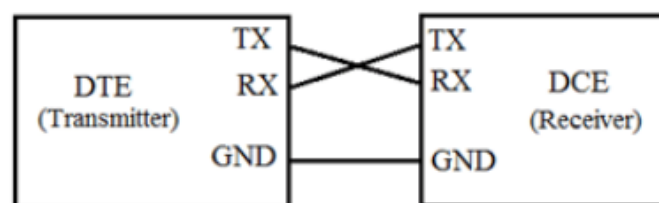

Figure 2.11: RS232 Standard (Tamanna Sharma 2018)

Note that these parameters stated above change with equipment model. As mentioned above, there are three different data transfer modes. RS232 adopts for the second model which is the two-way communication. As depicted in figure, the two parts DTE and DCE are connected together and have the pins: *TXD* (Transmitter), *RXD* (Receiver), *RTS* (Request To Send) and *CTS* (Clear To Send). The process of transferring data is as follows.

Starting from DTE side, RTS creates the request to send data. On the other hand, from DCE side, CTS prepares the path to receive the data. After cleaning the path, a signal will be given to RTS of the DTE side for sending it. By that, the bits are transmitted from DTE to DCE. Now, heading out from DCE source, the request to send data is produced by RTS, then the CTS of DTE clears the path in order to receive data and a signal will be given.

In the process described previously, a signal which is transferred from DTE to DCE have been mentioned. But, how the transfer is ensured successfully? For this reason, the term of " Handshaking" is introduced (Tamanna Sharma 2018).

Handshaking

It ensures the messaging between transmitter and receiver.In fact, it's the process that is employed for transferring the signal from DTE to DCE in order to make the connection before the actual transfer of data. If there's no handshaking, then it can result to data loss. In fact, in serial communication, the transfer is done bit by bit. On the receiver side, there's a buffer. It's a memory location where received data is stored.But, only one bit can be stored in this buffer. For that, the receiver has to read the memory buffer before the next bit is sent from DTE and arrives. As a consequence, if the receiver is unable to read the bit that is stored in the buffer, then this bit will be lost. Two other processes are described:

Hardware Handshaking

In this process, specific serial ports RTS and CTS are used for controlling data flow. On the contrary of the case where there's no handshaking, the transmitter checks with the receiver if it's ready to receive data. On his turn, the receiver checks the buffer if it's empty, then a signal will be given to the transmitter to send the data i.e receiver is ready to receive data. If it's not the case i.e the receiver cannot read the received data, this latter will generate a signal to transmitter for not sending any bit.

Software Handshaking

In this process, two signals are introduced: X-ON and X-OFF. "X" can be the transmitter or the receiver. "X-ON" is the moment in which the data transmission resumes and "X-OFF" is when the data transmission pauses. As a result, the control of data flow and the loss prevention are guaranteed.

2.4.1.3 Ethernet

Ethernet is the standard connection technology used to connect devices in both local network (LAN) or a wider network (WAN) (TechTarget 2022). It enables communication between devices through a protocol, defined as a rule base or a shared network language. In order to identify, receive and process the information or the data inside the devices located in same LAN, the Ethernet explain how the network equipment are formatted.

The use of Ethernet is expressed when especially a cable is utilized in the connected devices in order to get access into localized network which is not the case for the wireless connection devices. Providing a great benefit such as reliability and security, many users related to business and gamers really depend on Ethernet connectivity. Ethernet connectivity presents a huge benefit that is really important for all users which is network security, that is not the

case for the wireless LAN (WLAN) technology and that's what make Ethernet less vulnerable to disruption. Due to the ability of control by providing a greater level of network security, it's impractical for outsiders to obtain access to network data or to hack the bandwidth for unauthorized devices.

Ethernet is widely used communication method which is destinated to device connection in a specific network. This popular method is really required for many organizations like hospitals schools, universities, and of course company offices. Because it offers high speed factor and ensures security, Ethernet has became so reliable.

Because of the low price compared to competing technologies, and in relation to network connectivity at that time (for example IBM's token ring), Ethernet has obtained its popularity and its great reputation among other technologies. During the time network technologies has evolved and so the Ethernet offering the best levels of performance. As it evolved, Ethernet also retained backward compatibility.

In the mid-1990s, Ethernet's has a 10 megabits per second speed which has expanded tenfold to 100 Mbps. Many improvements in performance through successive upgrades has been done thanks to the Institute of Electrical and Electronics Engineers (IEEE). Due to its high enhancement, Today's versions of Ethernet can handle operations up to 400 gigabits per second (Gbps).

Ethernet protocol affects both layer 1 which represent the physical layer and layer 2 related to the data link of the OSI (Open Systems Interconnection) model, and this is according to the family of standards IEEE 802.3. The packet and the frame are the Ethernet's two units of transmission. The frame consists of the transmitted data payload including the follows elements:

- Addresses of the sender and receiver known as MAC which is the physical Media Access Control.

- Information's quality of service (QoS) and virtual LAN (VLAN) tagging.

- In order to identify all types of the transmission problems an error correction information factor is introduced.

To set up the connection and mark the beginning of the frame, multiple bytes of information are included in a packet which is wrapped in every frame. As ethernet evolved, Ethernet hubs were widely replaced to network switches. Since a hub cannot distinguish between points on a network segment, it cannot send data directly from point A to point B. Instead, whenever a network device transmits data through an input port, the hub will duplicate the data and

dispatch it to all the output ports that are available. In other hand, a switch intelligently sends only the traffics destined for its devices to a specific port instead of copying all transmissions on the network segment, improving by that both security and efficiency.

Advantages of Ethernet

- Budget friendly

- Compatible to previous version

- Noiseless

- Excellent Data transfer quality

- Fast

- Reliable

- Data protection

Disadvantages of Ethernet

- Designed for smaller and local networks

- Reduced level of mobility

- Long cable may lead to crosstalk

- In real-time applications, Ethernet has a restricted performance

- Depending on the traffic amount, the speed decrease

- Data packets are not being confirmed by the receivers

- In order to identify which particular cable or node is the source of the issue, troubleshooting is quite a complicated task.

2.4.2 Parallel Communication

As mentioned above, there are two types of data transmission: serial communication and parallel communication. The parallel one consists of transmitting multiple bits simultaneously as shown in figure 2.12, on the contrary of the serial communication which transmits only one bit per time. Among these parallel interfaces, there's the GPIB protocol.
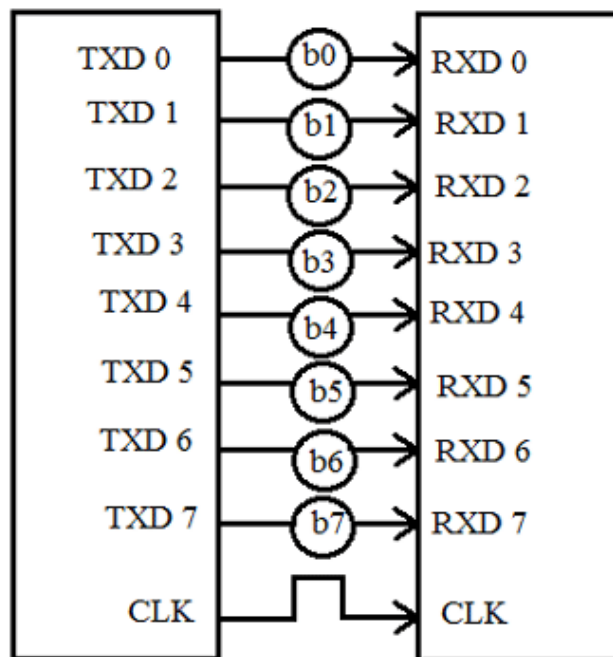

Figure 2.12: Illustration of Parallel Communication (Abhimanyu Pandit 2019)

2.4.2.1 GPIB

An interface between computers and measuring instruments was developed known as GPIB which stands for General Purpose Interface Bus. This interface is responsible for connecting PCs and measuring instruments to each other. Originally, GPIB was created as HP-IB which is an internal standard approved by the IEEE (Institute of Electrical and Electronics Engineers) and designed by Hewlett Packard. GPIB is now an international standard which is implemented in many measuring instruments, and by that it is used extensively in measuring systems using PCs and measuring instruments (CONTEC Technology).

Like already mentioned, GPIB is used extensively in many fields. This standard includes both IEEE-488 and the higher-level IEEE-488.2 protocol. The IEEE-488.2 does not only provide syntax for text data, numeric terms, commands and queries used by all instruments, but also it can make the transfer methods which is specified in IEEE-488. And by that, these compliant instruments can interact between each others and which are using the same protocol (IEEE-488.2) or even devices with IEEE-488, which is indicated in the framework by the IEEE-488 standard.
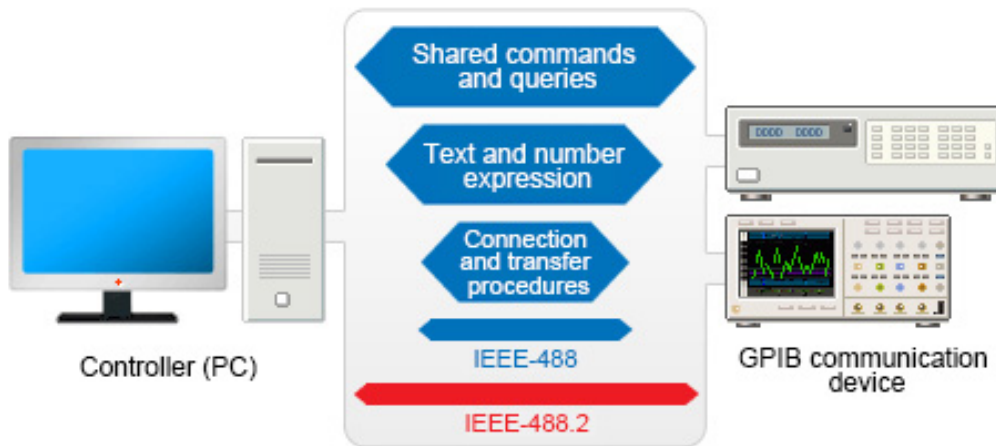
Figure 2.13: Overview of the GPIB Protocol (CONTEC Technology)

Regarding the number of connections, in a single system only 15 devices can be connected which is the GPIB standard limits for device connection, including the controller. The whole system will collapse when using a superior number of devices. The methods of connecting the devices offer a high degree of freedom. A daisy-chained, star-connected or a combination of both are the different types of connection that device can be connected. Devices should not be connected in a loop.

In order to transfer 1 byte of data at a time at a speed of up to 1 MB/s the GPIB standards uses 8 data lines. In other hand, the devices communication speed connected on the same bus is in fact limited to that of the slowest device and this is due to the slow communication speed of many instruments. There are two types of devices which are connected to a bus: the "listeners" these devices are responsible of receiving the data, and the second type is the "talker" which is responsible of sending the data. These two devices are determined by the controller which runs the whole system. Normally a controller is the PC itself.

As the name indicates, the master is the device that has the ability to make GPIB communication decisions (transmitting commands, etc.), whereas the slave is required to follow the master's instructions (receiving commands, etc.) In configuring a system, one master and at least one slave must be present. In the case of controlling a measuring instrument, the PC which acts as the controller is the master.

When an operation of data sending or data receiving is made, a handshake communication method is applied. In fact, when the sender and the receiver are interfering between each other and by repeating this procedure, the sender and receiver transfer data while checking that it is being sent and received and by that and thanks to the handshake communication, the GPIB standard can achieve highly reliable data transmission.

Controller roles

At any point in time the recommended number of devices related to the GPIB bus that can send data is only one device. This is in order to prevent from data collapsing. Of course, the mentioned device is the controller. it is also recommended to make a GPIB system that has a computer as a controller in case of having a program to execute. It is also responsible of the different operations mentioned below:

- Both talker and listener identification (the listener must be specified in regards with the talker) in this case many devices can be used.

- System initialization using the reset.

- Remotely, control each device.

- Responding to service requests from each device.

- Each device must take commands from the controller.

GPIB advantages

- In order to connect and setup peripheral devices, the piggyback connector which is shown in figure 2.14,is highly recommended to be used. This is thanks to the GPIB bus interface employment. Even though other devices are related to the system afterwards, it is conceivable to use a single PC interface.

- To provide data transfer reliability, a handshake communication is implemented.

- By managing a single protocol, users can control a different kind of measuring instruments of course due to the GPIB interface employment on these instruments related to the standard bus of the measuring instrument industry.

- Even with different level of communication speed, devices can be connected on which the system would be limited to the slowest device.

- Data and measurements already extracted automatically can be easily displayed and represented under a measurement system such as graphs and significant measurement data files which employ the pc's capabilities.

Figure 2.14: Piggy back connector (CONTEC Technology)

3 Approach

This chapter gives an overview about the preliminary steps of the project that must be constructed in order to make the testing process succeed. First of all, in the section 3.1 an evaluation of communication protocols will be performed. Considering various factors, the most adequate interface will be chosen in order to link the blocks together. In section 3.2, a simple version of the project will be presented. As stated in goal statement, the project is composed of several blocks that has specific features each. For that purpose, as a first step, the project has been simplified. During this section, first the configuration of the AC power supply will be done. Then, the board will be introduced, booted and set-up. Finally, the testing of some irregular wave-forms will be carried-out. After being sure that the communication is working successfully and having the wanted settings, the addition of the cooktop is done. The testing of its particular protocol will be made. This will be described in details in section 3.3.

The software used during this work is Python, since it's the software supported by PYNQ-Z2 board. With its large variety of packages and libraries, this language allows a good range of applications.

Different kind of commands used in this approach

Before starting to elaborate the several steps and explain the approach adopted in this project, a brief description of the various commands used during in the setting of the AC power supply and the testing of the device will be presented.
Since the communication will be carry out between instruments and external devices, SCPI commands will be used. SCPI is a programmable language standard which is designed especially for programmable instruments and it defines how to communicate with the instruments from an external computer.
In the section "Evaluation of communication protocols", the main command used to test the different protocols is "*IDN". In fact, "*IDN" is a command that requests a download of information about the AC power source such as manufacturer, model number, series number

and software version number. "*" can be found before some commands indicating that these are common commands and may be including common functions of IEEE-488.2 regardless of hierarchy. The table 3.1 shows some of the relevant commands used in this approach in

Command	Function
OUTPUT:VDC:_<NR2>	set AC output voltage in volts
OUTPUT:VDC?	query the DC output voltage in volts
OUTPUT:FREQ:_<NR2>	set output frequency in Hertz (Hz)
OUTPUT:COUPLE:_<NR2>	set output coupling setting
OUTPUT:WAVEFORMA:_<NR2>,<NR3>	set the parameters of waveform

Table 3.1: Some setting commands

order to set the AC power supply for the purpose to send the appropriate tests to the inductive cooking systems. Note that for the two last commands, numbers indicating specific states should be used. In fact, for the waveform command, <NR2> can be one of these values: 0 (SINE), 1 (SQUA), 2 (CSINE), 3(FIXED), 4 (USER). Regarding the couple command, it should has as parameter: 0(AC), 1(DC) or 2(AC+DC).

When sending these kind of commands, usually it takes 5 to 10 seconds, on the contrary of "*IDN" command which is quite fast (one second), for that reason, it's used at the beginning to test the different protocols in order to choose later which one is more adequate to work with.

3.1 Evaluation of communication protocols

As mentioned in Fundamentals chapter, each of the AC power supply and the PYNQ-Z2 board has specific features. In order to be able to connect the two devices, it's required to choose the adequate interface. For that aim, an evaluation of all the supported communication protocols has to be done.So, based on the description of each interface elaborated in the Fundamentals chapter, a comparison will be performed, taking into account various factors such as complexity, bandwidth, latency, cost etc.

Specifications	ETHERNET	GPIB
Maximum Bandwidth	100Mb/s up to 1Gb/s	1.8Mb/s or 14.4Mb/s
Latency	1,000μs range	100μs

Table 3.2: Comparison between Ethernet and GPIB

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The table 3.2 depicts some specifications of Ethernet and GBIP (McCarthy 2005). Overall, it's noticeable that the two interfaces are fast. Speaking of the bandwidth factor, this gives Ethernet a 7 times bandwidth advantage over GPIB. Regarding the latency, GPIB has a shorter latency than Ethernet which gives GPIB a 10 times latency advantage over Ethernet. Considering these parameters, it's remarkable that GPIB should be better fitted for short data transfers and Ethernet is better suited for large data transfers. Taking into account another factors which are the queries tasks and transfer sizes, GPIB is almost 6 times faster than Ethernet for setting tasks and for very small transfers providing the statistics shown in histogram 3.1 revealing that GPIB is 578% faster than Ethernet for Set State and 390% faster for very small transfers. Let's say that for the query task "*IDN?" they're almost the same because it's widely implemented and there are no delays from the front-end interactions of the instrument. As dedicated previously also, Ethernet is better for large transfers which can be seen in histogram 3.2.
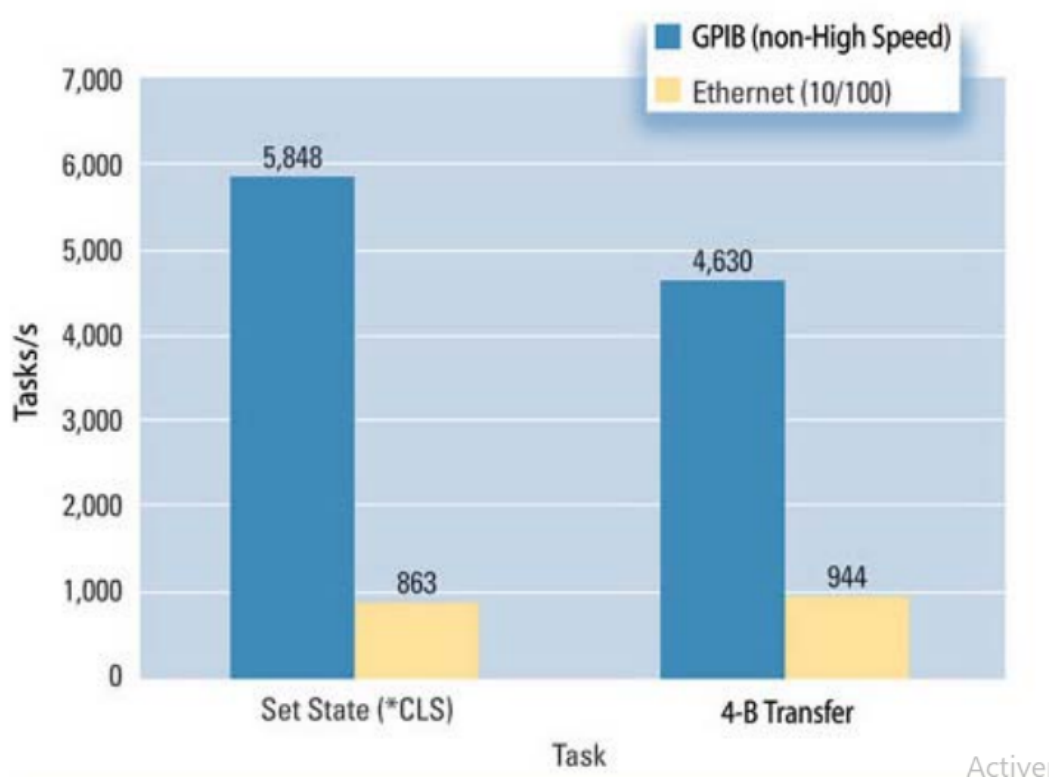
Figure 3.1: Histogram of set state tasks and transfers for GPIB and Ethernet (McCarthy 2005)
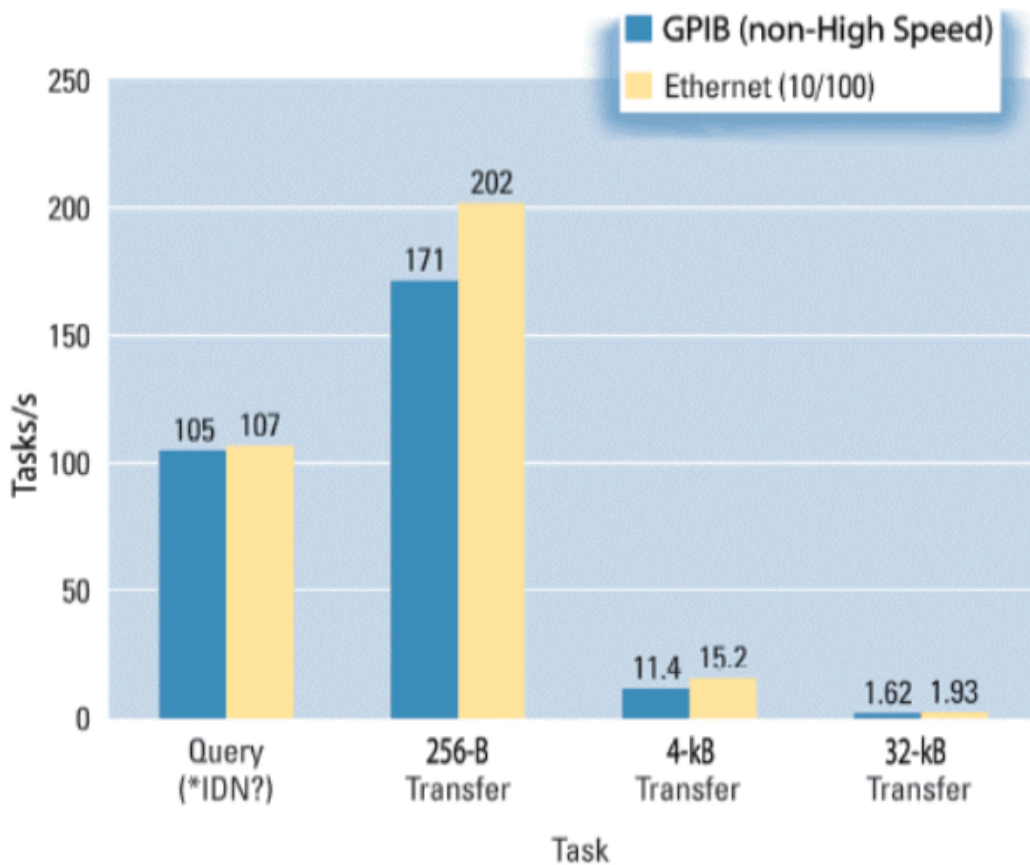
*Figure 3.2: Histogram of "*IDN" query task and large transfers for GPIB and Ethernet (Mc-Carthy 2005)*

Specifications	GPIB	RS232
Maximum distance	2 meter	50 meter
Maximum speed samples/second	1 MHz	700
Number of devices	14 per cable	1 per cable
Computer Adaptor Card	Needed	Not needed

Table 3.3: Comparison between GPIB and Serial interface RS232 (RF Wireless World)

The table 3.3 presents the different spacifications of the two interfaces GPIB and RS232. The GPIB is faster but it requires a special Computer Adopter Card and further configuration steps.

For summarising, GPIB is fast and robust but it needs a special card. It can be the best option for several instruments having only GPIB connectors. Regarding the Ethernet, it's a fast interface also and it uses inexpensive cables and connectors. It's a recommended technique for connecting distant devices. Finally, USB is a quick and easy method to perform

the connection between instruments and computers. When using this protocol, there's the possibility to use an Interface Converter to establish the connectivity easily and inexpensively in order to have Serial Port RS232. This famous interface is cheap and widely available, but comparing to the other interfaces, it's a bit slower.

As per now, the most important factors to consider when determining which is the best bus to choose are:

- Bus Bandwidth

- Latency

- Instrument side: control hardware and software implementation point of view

- The software on the host side

Furthermore, for the sake of performance mainly in terms of time, the host PC and the instrument hardware and software could be kept constant by the test setup (Use-case, set state, query, data transfer etc). As a consequence, the impact of the bus performance on transfer time and the tasks per second, is the key metric.

Now, the testing of the protocols compared above will be performed and the choice will be made.

Testing the protocols on the AC power supply

In order to carry out the evaluation of the different protocols, a simple test on query task "*IDN" is performed. This will help more in choosing practically the most adequate interface. In fact, "*IDN" is a command that requests a download of information about the AC power source such as manufacturer, model number, series number and software version number. "*" can be found before some commands indicating that these are common commands and may be including common functions of IEEE-488.2 regardless of hierarchy.
As it's mentioned above, for testing the GPIB interface, a Computer Card is required. Unfortunately, this card is not provided so the test couldn't be operated for the GPIB interface.

Moving to the next protocol Ethernet, sockets are provided in Python and can be used in order to send SCPI commands to a power supply connected via Ethernet. In fact, they are kind of a form of `inter-process-communication` (a mechanism that allows processes sharing data). In follows, the lines of the code are shown:

```
import socket
s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
s.connect(('192.168.1.100',20))
s.send('*IDN?_n')
print (s.recv())
```

SCPI is a programmable language standard which is designed especially for programmable instruments and it defines how to communicate with the instruments from an external computer.

These lines presents the IP Ethernet connection settings using address IP of power supply which can be found in the settings of the device and its port. The creation of a socket object is done with type socket.SOCK_STREAM. This is the default protocol that's used is the Transmission Control Protocol (TCP) since it prevents from packet loss. Regrading AF_INET, it is the Internet address family for IPv4. The declaration of `Socket` object and the use of the default protocol (TCP) are employed for their several advantages such as:

- **Reliability**: The detection of packets that are dropped in the network and the re-transmission of it by the sender.

- **In-order data delivery**: The application reads the data in the order the sender has written it.

`.CONNECT()`, `.SEND()` and `.RECS()` belong to the primary socket API (Application Programming Interface) functions.

From the PC side, several commands have been performed to ensure the connectivity with the AC power supply. For that, the IP address of the instrument is needed. This parameter can be found on the device. These commands have been used while adopting the Ethernet protocol, providing that IP_Add_Instr stands for the IP of the addressed instrument.

- **PING** IP_Add_Instr: to assure the connectivity with the instrument.

- **netstat -a** in order to display all ports with their IP address.

- **Telnet** IP_addr_Instr Port: in order to verify the connectivity with that port.

Note that the instrument side software and the PC hardware and software are factors also and since the testing will be performed using the PYNQ-Z2 board so the communication will be linked to the FPGA part. Going deep with the Ethernet frames in the FPGA design, this combination is quite complex. In fact, there's a lack of flexibility.

Ethernet is limited by the difficulty of the design of state machines and logic in order to handle complex IP protocols. In addition, with pure hardware designs, handling updates and maintenance is much more difficult and costly. Furthermore, `User Datagram Protocol` (UDP) sockets are not reliable and the receiver can read the data sent by the sender in an out-of-order manner. Overall, in such use-case, Ethernet may be a best-way delivery system but the data is not guaranteed for reaching its destination or receiving what it has been sent.

The final test will be done employing the serial connection and using by that the pySerial package in Python.

```python
import serial
conn = serial.Serial(port='COM14',baudrate=115200,bytesize=serial.EIGHTBITS,
parity=serial.PARITY_NONE,stopbits=serial.STOPBITS_ONE)
cmd="*IDN?_n"
conn.write(cmd.encode())
print (conn.readline())
```

This piece of code presents the serial communication. While creating it, various parameters are required to ensure that connection:

- **Baud-rate**: used to measure the speed of transmission. It is described as the number of bits passing in one second.

- **Stop Bit**: used for a single packet to stop the transmission.

- **Parity Bit**: used to check errors. Four types are found: even, odd, marked and spaced.

These information are provided in settings on the front panel of the Ac power supply device. Regarding the port, it can be found on the device manager.
The result of this code is the information about the AC power supply as displayed as follows:
b'APM,SP300VAC4000W,ADVANCED,0134581950000042,
V100R003C54,V100R003C36,V100R002C29_n'
After evaluating all the aspects of the different protocols and running some simple testing, the serial communication protocol USB converted to RS232 will be chosen for realizing the work. When studying the requirements of this project and the blocks used, serial protocol is the best adoption as it's widely used, inexpensive, simple and can guarantee a good transfer of data.

3.2 Simple version of the project
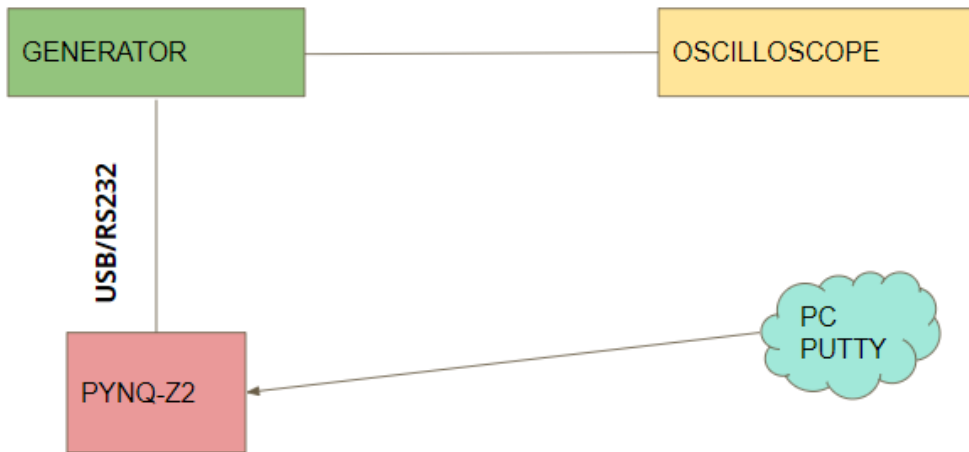
Figure 3.3: Diagram of a simple version of the purpose work

After performing the evaluation of the different communication protocols and choosing the most adequate interface in order to ensure the communication of the several blocks and the drive of data, the next steps can be performed properly. In the follow, several steps will be detailed and elaborated in order to lead to the final stage which consists of putting the inductive cooking system under the testand observe its response.

The figure 3.3 depicts a simplified version of the purpose work. During this section, first the PYNQ-Z2 board will be set-up and booted. Some testing will be done on that board for its various functionality. Then, an introduction on the wave-forms with distortion that will be tested also will be presented. The following step will be the configuration of the AC power supply. An oscilloscope is employed in order to display the configuration and be sure of the good settings. Finally, the connectivity of the board will be tested through PuTTY which will be replaced later with the cook-top (further information will be elaborated in the next section).

3.2.1 Set-up of PYNQ-Z2 board

In this section, the setup of the PYNQ-Z2 board will be described (PYNQ 2021). For performing that, several components are required such as:

- Ethernet cable

- Micro USB cable

- Micro-SD card with the pre-loaded image

As a first step, the MicroSD card should be setup. An appropriate PYNQ image has to be downloaded from *PYNQ* site. Then the image is unzipped in order to be written to the blank MicroSD card which is of the size 32GB (minimum 16GB).
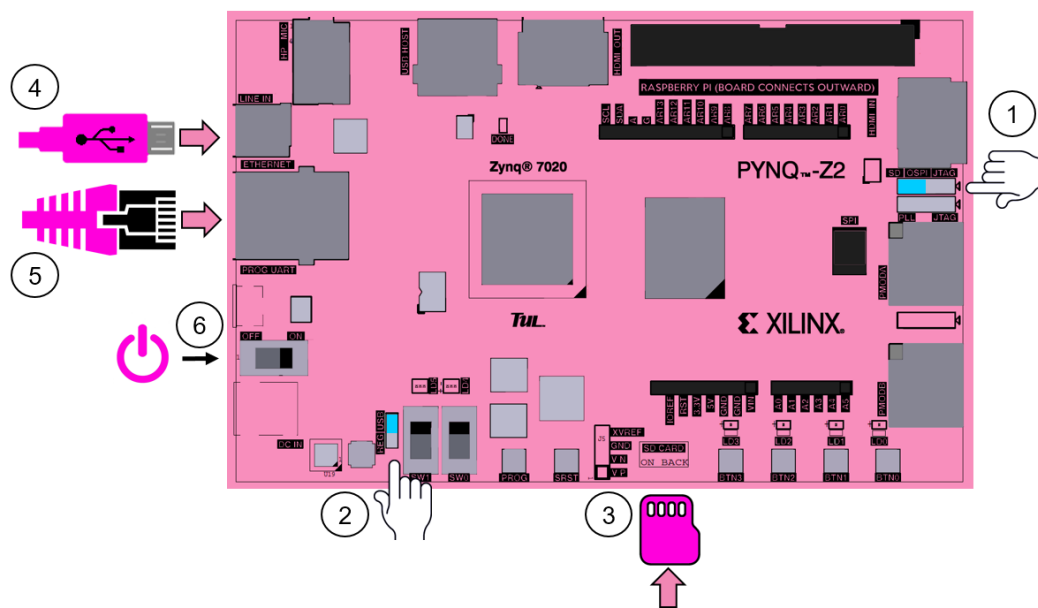
Figure 3.4: Diagram of a simple version of the purpose work (PYNQ 2021)

The figure 3.4 shows an overview on the board setup. Numbers on the figure present the steps to make the board functional.

1. The jumper is set to the SD position. This will allow to set the board to boot from the MicroSD card.

2. To power the board, there are two possibilitis. Either from the micro USB cable by setting the Power jumper to *USB* position or from an external 12V power regulator by setting the jumper to *REG*. In this project, the jumper will be set to *REG* since the two USB ports are used for communicating with the other blocks.

3. The MicroSD card that has been loaded with the PYNQ-Z2 image is inserted into the MicroSD slot in the board.

4. Link the USB port of the computer and the PROG-UART MicroUSB port on the board together using a USB cable.

5. Connect the Ethernet cable. Further details will be elaborated shortly.

6. Switch on the PYNQ-Z2 board.

After turning on the board, the boot has to be checked. In fact, the Red LED will be on immediately confirming by that the board is powered. After few seconds, Green Done LED will come on showing that the ZYNQ device is functional.

After approximately a minute, two Blue LEDs and four Green LEDs will flash simultaneously, then only the Green LEDs will remain on. The figure 3.5 shows the board after the setup. The board now is ready to be used.

PYNQ uses the Jupyter Notebook environment in order to afford some examples and docu-
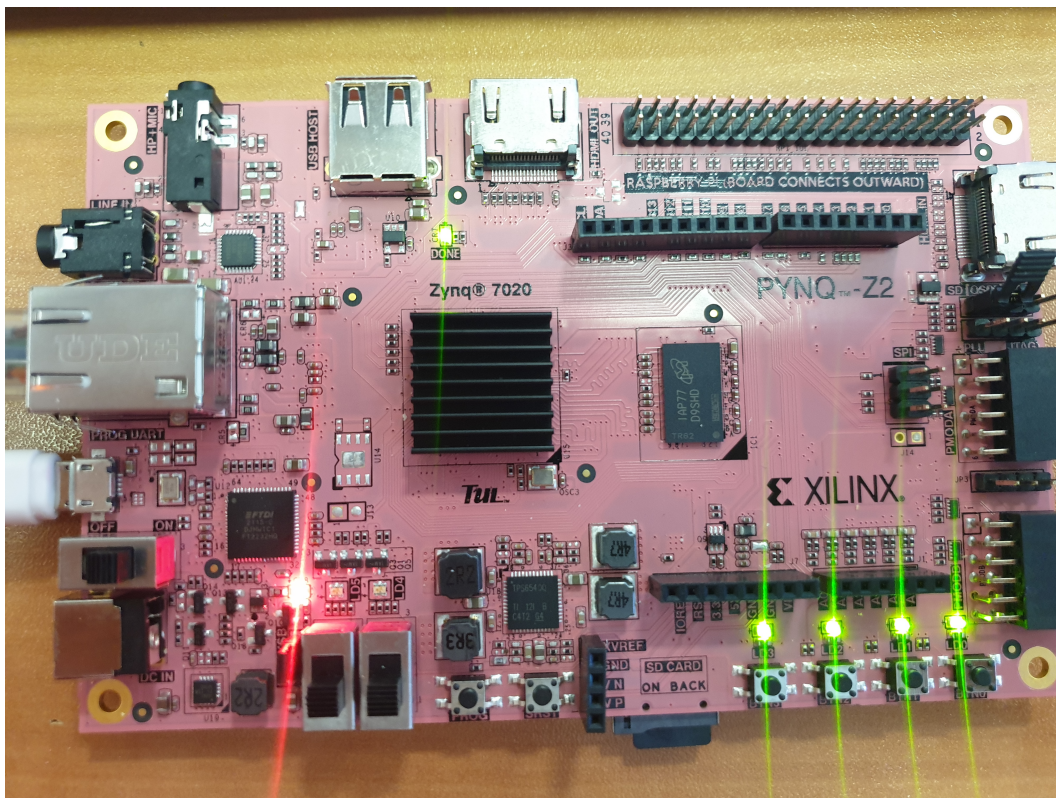
Figure 3.5: Aspect of the board after the setup

mentation about the board. After performing all the steps described above, in order to connect to this environment, it's sufficient to open a web browser and navigate to http://192.168.2.99. After logging in, all the documentation and examples of Python files on the various functionalities of the board.

PuTTY Test

As elaborated above, The board will be connected via USB to the AC power supply in order to configure it with the wanted settings which will be mentioned in the next paragraph. Then, the cooktop will be connected also on the other USB port of the board. For that purpose, a first test will be performed using PuTTY to verify the serial connectivity. After connecting the board to the computer via a USB cable, the port can be found in the Device Manager to use it later in the settings. Once PuTTY is open, the serial option is selected as well as the COM port number and the baudrate. These parameters and their description are detailed in the previous sections. Figures 3.6 and 3.7 present the PuTTY settings with the adequate parameters and the terminal showing the serial connectivity respectively.
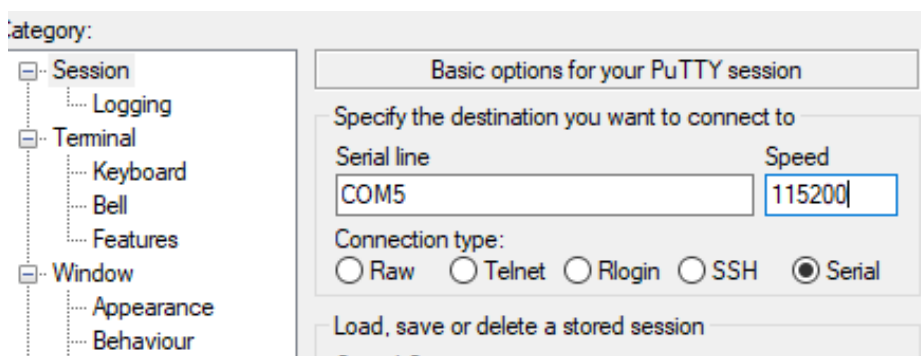
Figure 3.6: The PuTTY settings

Figure 3.7: Serial connectivity with IP details

3.2.2 Configuration of AC power supply

Going through the documentation of the AC power supply SPS300VAC12000W provided by the manufacturer, there are SCPI commands with a specific syntax that have to be used in order to be able to set and configure the power supply. Voltages and frequencies will be set according to the Italian standard and according to the American standard. For that purpose, a Python code has been develop using specific commands. The voltages that will be set are 180V, 230V and 265V in Rms values, where 230V is the ideal voltage for a functioning cook-top, 180V and 265V are the minimum and maximum values respectively. For each voltage, a test will be run with the different frequencies according to the aforementioned standards, where the Italian values are 47, 50 and 53 and the American one are 57, 60 and 63. The waveforms of these settings are displayed in the next chapter where they're put in position for the testings. Some commands are displayed as follows:

- "OUTPUT:WAVEFORMA: 0 ": This the command used to set the needed shape. 0 presents the sinusoidal shape.

- "OUTPUT:VAC: 180 ": For setting the AC voltage

- "OUTPUT:FREQ: 50 ": For setting the frequency.

Note that these commands have to be written with this syntax respecting by that all spaces and notations, otherwise it won't work.

Waveforms with distortion

The purpose of the work, is to test the functioning of the cook-top alimented by different values of voltages and frequencies. The aim is to test the behavior of the inductive cooking system on several irregular shapes which means by that shapes with distortion. As described in the Fundamentals section, the AC power supply can be configured and set through specific SCPI commands that are large in terms of functionality. But, since the version implemented in the device that is used does not support harmonics, it's not possible to design a specific waveform configuring the amplitude of its different harmonics and setting the phases. Alternatively, The are self-implemented waveforms, a range of 29 shapes, each with different harmonics, amplitude and phase. They're defined as fixed. These waveforms are documented by the AC power supply manufacturer and provided by them. The tests then will be run on these kind of

shapes with the configuration elaborated previously. The oscilloscope is installed in order to display the final shapes that have been set. A differential Prob has been used for that. In fact, it's very important to use this kind of Prob because of several motivations. First, it allows the protection of the devices since with a normal one a simple mistake of powering on the device in a non-correct manner may destroy everything. In addition, the differential Prob has wider range of voltage up to 6.5KV on the contrary of the normal one which is 300V.

3.3 The addition of the cook-top
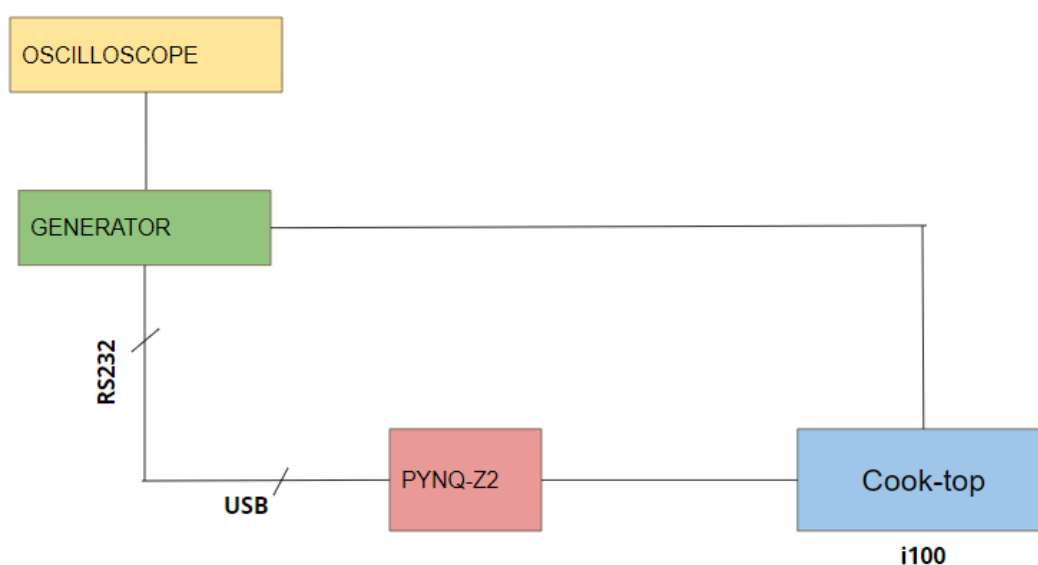
Figure 3.8: Schematic of the purpose work with the addition of the cooktop

The final step consists of adding the cooktop that will be tested through the loop that has been designed and described in the goal statement section. Every system has its own protocol. The one dedicated to the proposed cook-top is i100. It's a protocol developed by Whirlpool employees and which ensure the communication between it and the board. In fact, the configuration that has been elaborated above, will be sent to the cooktop then the output data will be read by means of that specific protocol. Thanks to the application based on that protocol, retrieving the output data is done with two steps. First, all the data will be retrieved in .bin files. Then, the wanted data will be extracted in .csv files in order to be evaluated.

4 Results and Evaluation

In this chapter, the results of the different testing that have been performed on the cook-top will be presented as well as an evaluation will be provided in order to understand better the outcome of these testing and how far the project is successful. Several tests have been performed on the cook-top. It consists of changing the voltages and the waveforms(regular and irregular) for the purpose to evaluate the functioning of the cooktop and its behavior toward a wide range of settings. Eight tests have been performed with the European standard fixing by that the frequency to 50Hz and the level of heating on 13.

4.1 Tests with sinusoidal shape

Tests	Voltage
Test 1	230V
Test 2	265V
Test 3	180V

Table 4.1: Voltage setting for Tests with sinusoidal shape

The table 4.1 presents the voltage that has to be set for every test with the frequency fixed on 50Hz. The purpose is to see the behavior of the cooktop under these tests as well as the output values that are shown in table 4.2. The waveforms of the three tests are displayed in figure 4.1, 4.2 and 4.3 with V_peak 310V, 370V and 250V respectively.

Tests	Iline_Rms	Vbus_Rms	Current_Rms	Vce_Max_Absolute	Power_Rms
Test 1	3.96	225	3.97	922.179	894
Test 2	3.45	260	3.43	957.099	892
Test 3	5.05	176	5.04	868.344	888

Table 4.2: Results of the different Tests

The table 4.2 presents the results of the different tests that have been performed. As mentioned in the Approach part, there is a specific protocol i100 that has been developed in order to retrieve data from the cooktop on two steps. First, all possible data will be retrieved in .bin files. Then, another tool allows to extract the wanted data in .csv files.

For only 2 seconds after launching the communication, a bunch of data is retrieved. Every second, the output is saved and measured from the cooktop. For that purpose, only one line from each extracted file will be evaluated in this section. Note that all values in one file are quite the same.

Iline_Rms presents the current generated to the cooktop which is quite the same as the value of *Current_Rms_Line*. This can be explained by the fact that the testing is done by switching on only one pot. Otherwise, it will be the sum of the lines turned on.

Regarding the *Vce_Max_Absolute*, it's a parameter for checking the good functioning of the cooktop. In fact, as detailed in the Fundamentals part about the principle of the inductive cooking systems, the cooktop is based on the Quasi-resonant circuits. The maximum value is 1.3KV. For all tests performed, this value is under the limit and this reveals that the cooktop is robust and working properly under the variation of voltages for a sinusoidal shape.

Moving to *Vbus_Rms*, this parameter presents the real output value of the cooktop. Note that there's a long cable linking the AC power supply and the cooktop, so according to ohm's law, the cable has some non-negligeable resistance as well as the measurement performed in the internal circuitry of the cooktop which lead to the slight drop of voltage at the output.
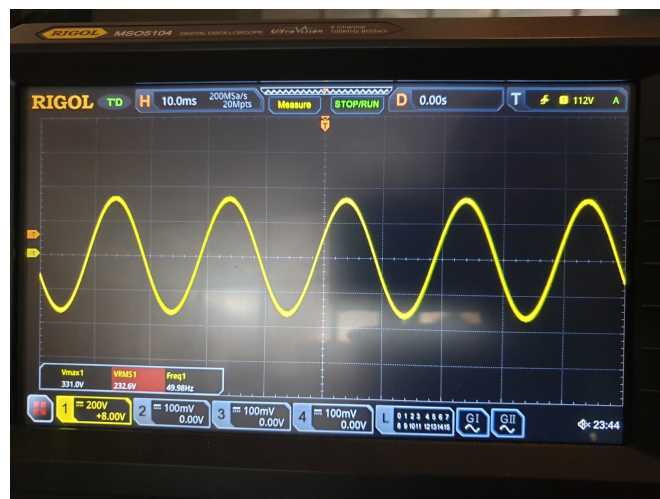
Figure 4.1: Waveform of Test 1

After performing the testing on a regular shape, another tests are run using a different shape that's irregular. As detailed in previous section about the configuration of the AC power supply
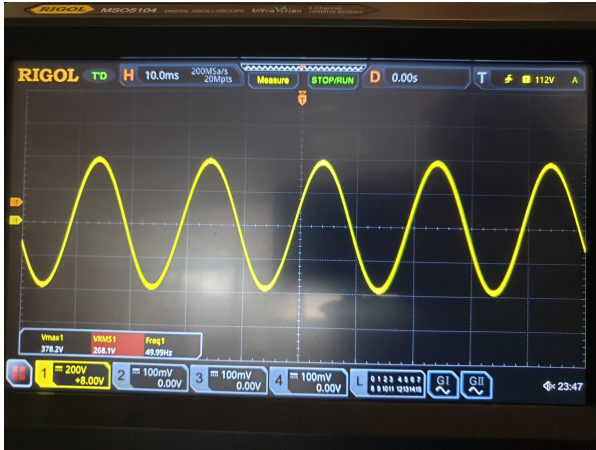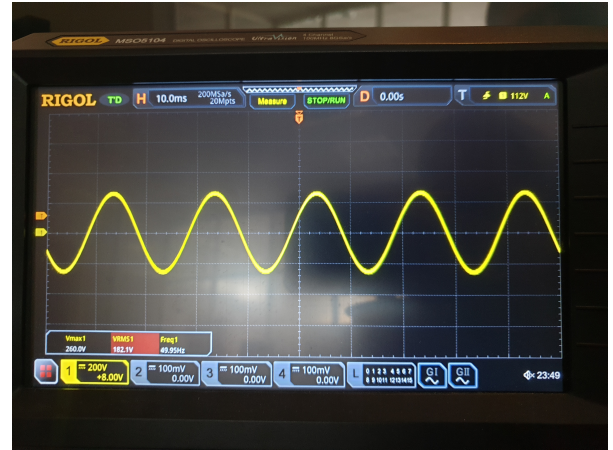
Figure 4.2: Waveform of Test 2

Figure 4.3: Waveform of Test 3

with some irregular shapes: waveforms with distortion, one of these shapes is chosen in order to observe the behavior of the cooktop working under this it. Remember that these shapes are provided by the Ac power supply manufacturer and can be set as fixed waveforms and by using a specific commands.

4.2 Tests with irregular shape

It consists of a waveform with distortion. The one that has been chosen for the test is the *Fixed, NO.19*. It's a shape that has four harmonics 3, 5, 9 and 13 whose amplitude in % is 9.38, 3.44, 1.12 and 0.5 respectively. Regarding the phases, it's 0 for the third and ninth and 180 for the others. The tests will be performed according to the European standard also and the frequency is fixed on 50Hz. The table 4.3 presents the different voltages that have been to be set for every test. A larger range of voltage is employed in this case for a good reason which will be elaborated shortly.

Tests	Voltage
Test 4	230V
Test 5	265V
Test 6	180V
Test 7	190V
Test 8	200V

Table 4.3: Voltage setting for Tests with irregular shape

Tests	Voltage	Vpeak	Response
Test 9	230V	360V	OK
Test 10	265V	413V	NO
Test 11	255V	396V	NO
Test 12	250V	387V	Protection mode
Test 13	245V	383V	OK

Table 4.4: Voltage setting for Tests with irregular shape 2

The waveforms of these five tests are displayed in figures 4.4, 4.5, 4.6, 4.7 and 4.8 respectively. The maximum Vpeak that has been reached is 323V in test 5 shown in figure 4.5. Regarding the minimum value, it is 220V for test 6 displayed in figure 4.6 and in which the cooktop couldn't start.

Tests	Iline_Rms	Vbus_Rms	Current_Rms	Vce_Max_Absolute	Power_Rms
Test 4	3.94	225	3.92	818.583	882
Test 5	3.47	259	3.41	856.413	885
Test 8	4.51	196	4.53	792.975	889

Table 4.5: Results of the Tests with irregular shape

It can be noticeable that 5 tests have been performed but only three of them are reported in the results table 4.5. Actually, when launching the test 6, the cooktop hadn't switched on and couldn't start the heating and same for test 7. The voltages for these tests are 180V and 190V respectively and are the minimum values for the voltage. The cooktop when reading the voltage alimented by, couldn't start the heating as these values are too low for the good functioning of it.

In fact, as this is a test with an irregular shape with distortion, it's clamped compared to the sinusoidal one and hence when working with the minimum value, the cooktop can't have a normal functioning as it's too low to start the process and power the coil.

As mentioned previously, the output files extracted by the specific tools mentioned above, contains a lot of data which is quite the same. So, one line from this file is sufficient to evaluate the behavior of the cooktop. The tests reported in table 4.5 show that the inductive cooking system put under test is working well with the adequate voltages reported in *Vbus_Rms* column. Same for this testing, there's a slight drop in the voltages reported in the table 4.5 as they're the real values measured. This drop is due to the resistance of the cables linking the devices. For this case also , the current value generated to the cooktop and the current of the line are the same, since only one line is used for the testing.For checking more on the

good functioning of the cooktop, the value of *Vce_Max_Absolute* can be a reference since it's under the maximum value which is 1.3KV.

The values of power in tables 4.2 and 4.5 are quite the same and are in the range of 880 W. This can be explained as follows: the level of heating was fixed on 13 for all tests. The stability of the power at the output of the cooktop is due to the control algorithm that is implemented in the inductive cooking system. Whatever the input voltage, the PWM changes the switching frequency according to that value and fix it. This phenomenon can be proved by observing the increase of the current value in tests working under minimum values of voltage.
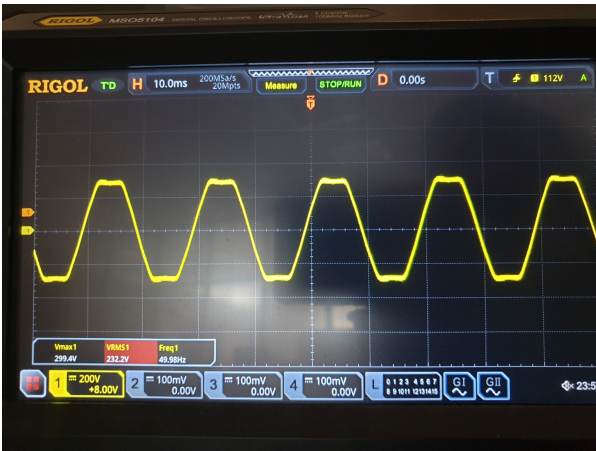
Figure 4.4: Waveform of Test 4
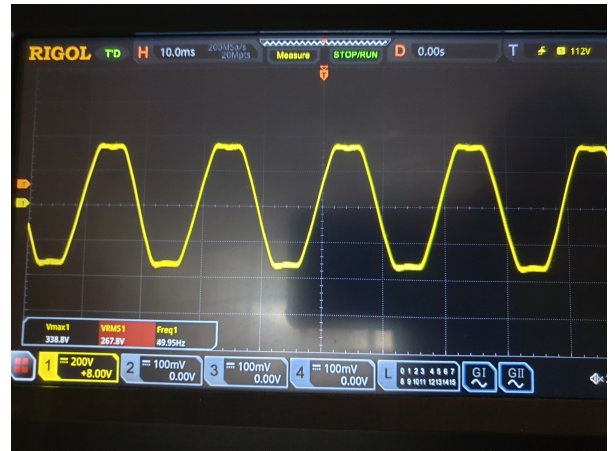
Figure 4.5: Waveform of Test 5

Figure 4.6: Waveform of Test 6
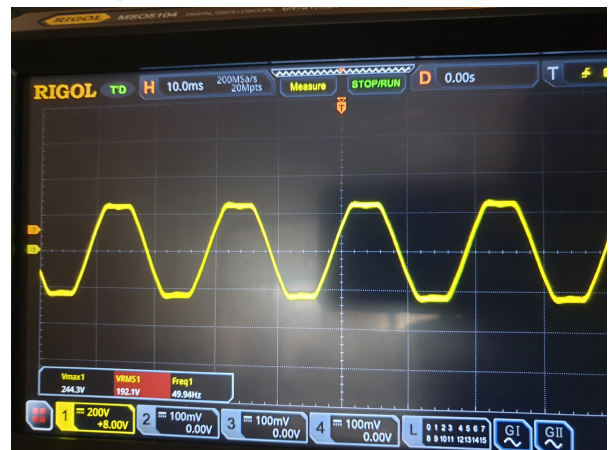
Figure 4.7: Waveform of Test 7
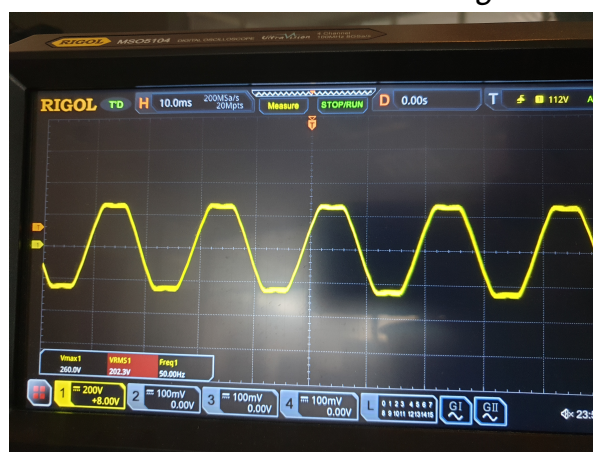
Figure 4.8: Waveform of Test 8

5 Conclusion and Future Work

5.1 Conclusion

Inductive cooking applications are becoming more and more demanded and are gaining a good popularity widely. So, for ensuring the good functioning of these cooktops, they should be tested properly since they can be alimented by different standards European as well as American.

During this internship, a project has been introduced in order to perform these testing using by that a specific board which is PYNQ-Z2. A documentation has been provided on the different devices such as the AC power supply and PYNQ board that were employed for performing this testing. Based on the features extracted of the different blocks described above, an evaluation of the various communication protocols which are supported by the components, is performed and the most adequate interface which is the serial communication USB/RS232 has been chosen in order to be used to operate the communication and the drive of data. In order to test the cooktop with different settings, the configuration of the AC power supply has been done through a bunch of setting commands to be sent lately to the device under test. Finally, the output data has been extracted via i100 protocol which is the specific interface of the cooktop and which is developed in order to display all the parameters. Based on these values, the behaviour of the DUT is checked.

It has revealed that putting the DUT under several settings of voltages and frequencies, the cooktop behaves greatly and properly thanks to its internal control system and its robust construction.

5.2 Future Work

During this project, several conditions were imposed. The most crucial one is the time constraint. The testing has been performed successfully but it can be ameliorated in order to achieve a better performance mainly in terms of time. There are two possibilities for improving it.

First, the project has been performed using the serial communication protocol as explained in Approach chapter. In the future work, Ethernet protocol can be adopted. In fact, as detailed above, it's a complex to use this particular interface with FPGA board but it's very powerful. This protocol is evolving by the time and its wide packets that can be associated with FPGA board can be a good work for improving the project and widen the use of its applications.

Second, as mentioned in the Approach chapter, the version adopted for achieving this project is based on a simple serial connection for displaying the output data. A futur work can consist on designing a specific interface board that enables the display of the output data on the PYNQ-Z2 board which will make it more in real-time since the one adopted is quite slow.

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