h_da

HOCHSCHULE DARMSTADT
UNIVERSITY OF APPLIED SCIENCES

Test Set-up for Power Factor Correction Boost Converter Circuits

Author:

Javier Oroz Joven

Matrikelnummer: 759573

Supervisors:

Dr. Christian Weiner
Mr. Martin Denner

Final Master Project
Summer Semester, 2018

10.08.2018

Abstract

This thesis will be the second part of a project whose goal is to build a test set-up of a DC-DC boost converter in the power electronics lab at h-da. Thanks to this set-up, future students will be able to see the differences between several control techniques with Power Factor Correction (PFC) in a boost converter.

The main specification of the project is to transform the input energy into an output voltage of 50 DCV with a limitation of maximum 60 DCV. Since the power factor has become an element to take into account especially when it comes to charging batteries, it is very important to use power factor correction techniques. And this converter will be made by means of two different types of PFC control circuits: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM).

So, the goal of this project is to test if this build-up works, to improve the safety circuit, to research about the different types of PFC circuits and to design and build them the in some interchangeable PCBs in order to make the circuit more didactic for students.

Table of Contents

Index of Figures

Index of Tables

Index of Acronyms and Symbols

AC – Alternative Current.

CCM – Continuous Conduction Mode.

CrCM – Critical Conduction Mode.

DCM – Discontinuous Conduction Mode.

DC – Direct Current.

EIT – Elektrotechnik und Informationstechnik (department of h_da)

GND – Ground.

IC – Integrated Circuit.

PCB – Printed Circuit Board.

PFC – Power Factor Correction.

PWM – Pulse-Width Modulation.

N/A – Not Available.

RMS – Root Mean Square.

SELV – Safety for Extra-Low Voltage.

SMD – Surface Mount Device.

SMPS – Switch Mode Power Supply.

VDC – Volts of Direct Current.

1. Introduction

1.1. Project goal

The main goal of the project is to design and build a set-up where students will be able to test how a boost converter works. Being didactic is a requirement for this test table, so it has been built in a modular way so that the different components can be easily interchangeable by means of some socket connectors. And this way, it is easy to change the configuration of the circuit, to build a different kind of boost circuit with power factor correction, and to be able to test them.

The scope of the project has reached two different configurations of these circuits with power factor correction. On one hand, the PFC in Continuous Conduction Mode (CCM) and on the other hand the PFC in Discontinuous Conduction Mode (DCM).

As the built-up is modular, it can be modified to add another power factor correction controller, for example, a PFC in Critical Conduction Mode (CrCM). This circuit is not part of the work done in this project, but it can be implemented in future projects of the EIT department in Hochschule Darmstadt. Anyways, this PFC operation mode and the two previous ones are explained later in this paper.

1.2. Working specifications of the project

First of all, it is important to remark the project specifications, in which the ranges in which our circuit will work as expected. And these specifications are shown here below.

- For the Input:
    - Nominal Input RMS Voltage from AC line: 25V.
    - Minimum Input RMS Voltage from AC line: 20V.
    - Maximum Input RMS Voltage from AC line: 30V.
    - Line Frequency: 50Hz.
    - Input Power: 120W.
    - Maximum Input RMS AC Current: 6 A.
- For the Output:
    - Nominal Output DC Voltage: 50V.
    - Target Power Factor: 0.9.
    - Desired Efficiency: 0.8.
    - Output Power: 100W.

1.3. Previous works

The previous work which this project is based on is the thesis of Eric Tumpa [1], who has made some research about DC-DC boost converters with power factor correction and has already built a test set-up with the CCM circuit.

This initial design was tested before starting this project, it was a CCM configuration. However, after reading the report, it was found that the circuit was working but there were a few problems that made it difficult to get to the 50 VDC output requirement, and the maximum power factor correction obtained was around 0.81. So, finally it was decided to design a new CCM circuit because correcting the mistakes of the old one would have been a slower process.

1.4. Boost converters and PFC technical background

First, we need to have a previous knowledge about what is a boost converter and its Power Factor Correction (PFC). A boost converter is a DC to DC converter which transforms a determined input voltage into a higher output voltage. It is formed by a boost inductor, a boost diode, a transistor or switcher and an output capacitor. But in our case, the input voltage is generated by an AC source with a variable transformer so, first of all, it is needed a full bridge rectifier of diodes to rectify the AC and transform it into DC, and also an input capacitor to minimize the ripple. The PFC shapes the input current of the power supply to be synchronized with the mains voltage, in order to maximize the real power drawn from the mains. In a perfect PFC circuit, the input current follows the input voltage as a pure resistor, without any input current harmonics. [2]

In *Figure 1*, it can be seen the schematic of a regular boost DC converter with all these components previously named. Although active PFC can be achieved by several topologies, this boost converter is the most popular topology used in PFC applications.
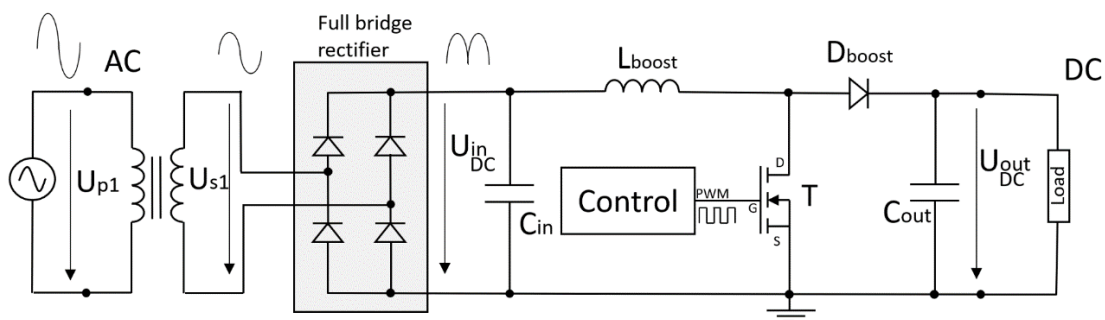
Figure 1. Electric scheme of the circuit of a standard boost converter.

As we can see in this circuit, it is needed a control circuit for generating the PWM signal which makes the transistor switch. The design of this control circuit is the main task of this project and it is a critical part since a good design of this circuit will have a good impact in the power factor and the efficiency of the conversion. This PFC control circuit adjusts the duty cycle of the PWM wave to make the transistor commute faster or slower and this way it controls when the transistor must conduct. Thanks to that, the PFC control shapes the wave of the input current of the power supply to be in phase with the mains voltage. That means that the diphase angle (φ) decreases, so the power factor

increases nearly to one and if we look at the power triangle in *Figure 2,* we can see that leads to an increase of the real power (P) and a decrease of the reactive power (Q), which is something beneficial.

Apparent Power: $S = U_{RMS} \cdot I_{RMS}$
Reactive Power: $Q = S \cdot \sin\varphi$
Active Power: $\quad P = S \cdot \cos\varphi$

$$\text{Power Factor} = \lambda = \frac{\text{Active power}}{\text{Apparent power}} = \frac{P}{S}$$
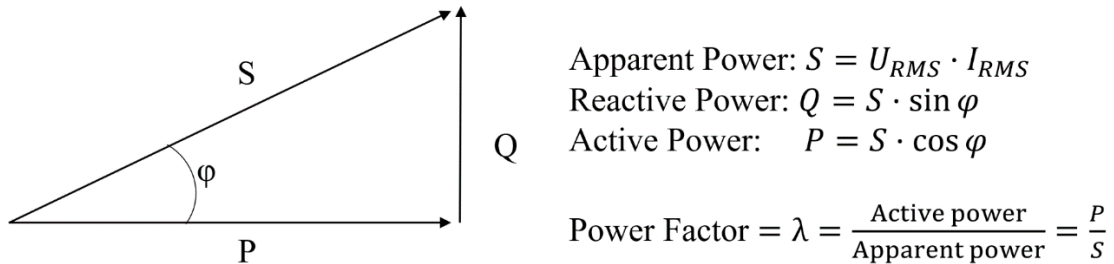
Figure 2. Apparent power triangle.

This power factor correction (PFC) is very important in many cases because it has several benefits [3] as:

- Reduction of the RMS input current.
- Improvement of the efficiency of downstream converters.
- Reduction of power losses in distribution system.
- Reduction of the heating in the source.

The efficiency of the circuit during the conversion is calculated as $\eta = \frac{P_{in}}{P_{out}}$, however, it is more difficult to control, because it doesn't depend that much on the PFC control circuit, it depends mostly on the power losses in other components. The main power losses in the circuit are in form of heat and are caused by the full bridge rectifier losses, the choke losses in the inductor (core loss and copper loss) and the boost diode losses (conduction loss and the reverse recovery loss).

It should also be noted that there are two different possibilities for power factor correction, passive PFC and active PFC. The difference is that in passive PFC it is not needed a controller generating a PWM and they are simpler to design, but they are quite limited, so that is why they are not as used in the industry as the active PFC, because they cannot be used in every kind of application.

In *Figure 3* it can be seen the different wave forms of the input current of a switch mode power supply with no PFC, with passive PFC and with active PFC.

1. Input current with no PFC
2. Input current with passive PFC
3. Input current with active PFC
4. Input voltage
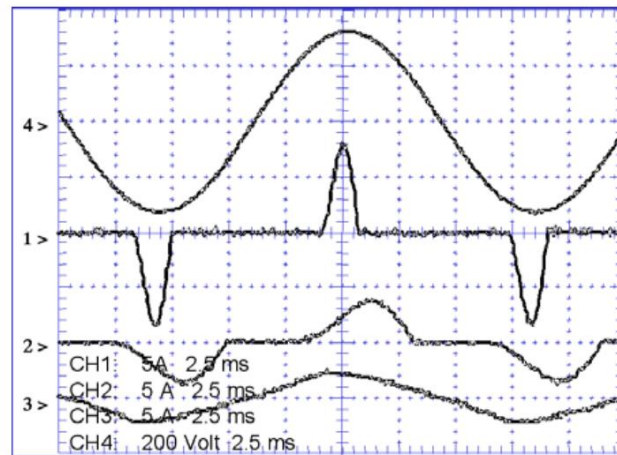
Figure 3. Input waves of power supplies with different PFC types.

Note that the current with no PFC and voltage are perfectly in phase, in *Figure 3*, in spite of the severe distortion of the current waveform. Applying the "cosine of the phase angle" definition would lead to the erroneous conclusion that this power supply has a power factor of 1.0. If we analyze the harmonic content of the current waveform with no PFC in *Figure 3* only the fundamental component produces real power, while the other harmonics contribute to the apparent power, the actual power factor is well below 1.0. This deviation is represented by a term called distortion factor and is primarily responsible for the non-unity power factor in SMPS. That is why it is needed a PFC to shape this current wave and obtain a higher real power.

Now below, are explained three different kinds of active power factor correction configurations that can be used to approach the problem of improving the power factor in a DC-DC boost converter:

A. Continuous Conduction Mode PFC

The Continuous Conduction Mode (CCM) control has been widely used in a wide range of applications because it offers several benefits. First, the peak current stress is low and that leads to lower losses in the switches and other components. [4]

Second, the switching frequency remains constant for the CCM operation, so the boost inductor design is easier. Also, the input ripple current is low and at constant frequency, making the filtering task much simpler. However, there is a hard-switching, and the inductor must to have a large value. [3]

The CCM operation is more popular at higher power levels as it has minimal peak and RMS currents. In comparison with the CrCM operation, the peak currents can be 50% lower and RMS currents can be 25% lower. [4]

In *Figure 4* it can be seen the waveform of the input line current (I_{in} in red) and the waveform of the current through the inductor (I_L in blue). The CCM PFC receives the measurement of this input current and it generates a PWM signal that makes the transistor

switch. While the transistor is conducting, the inductor is discharged, so the current I_L decreases until the transistor switches again.
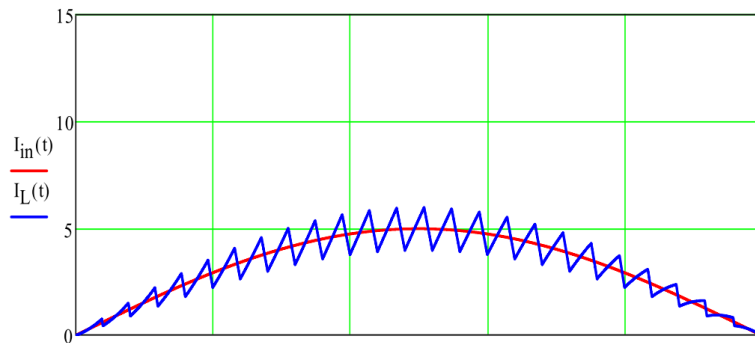
Figure 4. CCM PFC inductor and input line current wave. [2]

B. Discontinuous Conduction Mode PFC

On the other hand, the Discontinuous Conduction Mode (DCM) control is not as used as CCM for PFC applications due to it leads to the highest peaks of RMS current, compared with CCM and CrCM. That is why this operation is more convenient for light loads, because if the load is too high there are a lot of losses because of the high peak current.

Despite it is not the ideal mode in all situations as, the DCM operation also has some benefits, such us a greater stability and a smaller value for the needed inductor. Also, in this case the frequency is fixed so the filtering task should be simple too. And as we can see in *Figure 5* the current in the inductor goes up while it is charging and then it falls until zero, but as the switching frequency is constant, it stays in zero for a while waiting for the next period to go up. This way the RMS current is not as large as in the CrCM.
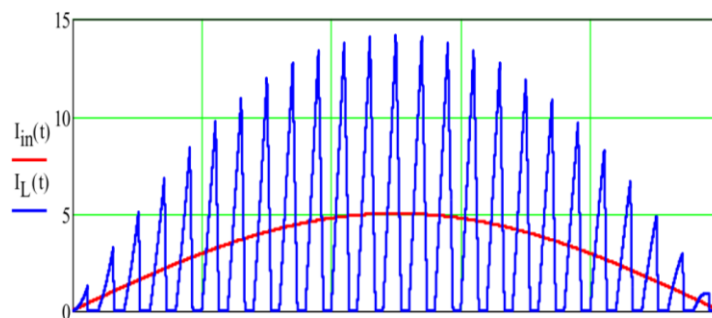
Figure 5. DCM PFC inductor and input line current wave. [2]

Despite its benefit of fixed frequency, the DCM is not the ideal mode in all situations as it leads to highest peak current levels

For DCM operation, the inductor is a smaller value and there is greater stability, but the RMS current is a lot higher.

C. Critical Conduction Mode PFC

The third control method is known as Zero Current Switching Mode, Borderline Conduction Mode or Critical Conduction Mode (CrCM). [3] It is very popular, and it may be considered a special case of CCM, where the operation is controlled to stay at the boundary between CCM and DCM.

CrCM usually uses constant on-time control, then the line voltage is changing across the 60 Hz line cycle, the reset time for the boost inductor is varying, and the operating frequency will change as well in order to maintain the boundary mode operation. CrCM dictates the controller to sense the inductor current zero crossing in order to trigger the start of the next switching cycle. However, that means that the switching frequency is not constant. [2]

In this case, as *Figure 6* shows the inductor current (blue) rises while the inductor is being charged and when it discharges it goes down until zero. Then as it has been said before, the zero crossing is detected and the transistor switches, so the current of the inductor rises again directly, not as in the DCM that it stayed for a while in zero.
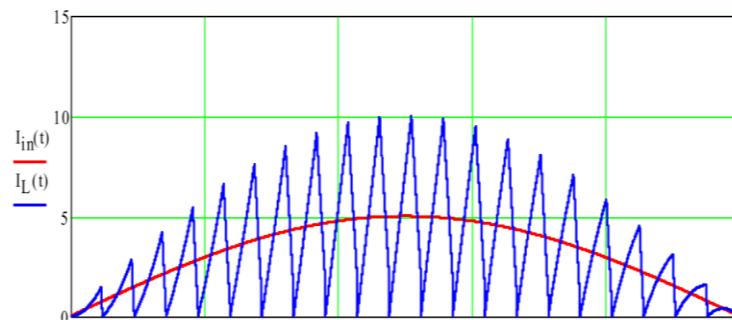
Figure 6. CrCM PFC inductor and input line current wave. [2]

A more convenient choice would be to allow the PFC to slide between the DCM and CrCM modes seamlessly and extract the best of both worlds. So, at light loads, when CrCM can go to high switching frequency, it is preferable to go into DCM. Similarly, when the load current is higher, it is desirable to stay in CrCM to avoid the high peak currents.

2. Set-up and initial assemblies

Before starting this project, a proto-circuit was already built on a steel rectangle, and this metal plate had some holes and connections for the basic components of a boost converter circuit. Those already existing components were the following:

- Full diode bridge rectifier. → It has not been modified, just added a heatsink.
- Input capacitor. → It has not been modified and its value is 0,47μF.
- Boost inductor. → It has not been modified for the CCM and its value is 188μH, but it has been re-designed and changed for the DCM, and its value is 11μH.
- Boost diode. → It has not been modified.
- Transistor. → It has been re-designed and changed.
- Output capacitor. → It has not been modified, and its value is 220 μF.

In the *Figure 7*, it can be seen how the initial set-up was. It was made by Eric Tumpa, but the goal of this project is to finish it and make it usable for student to learn how a boost converter with PFC works.
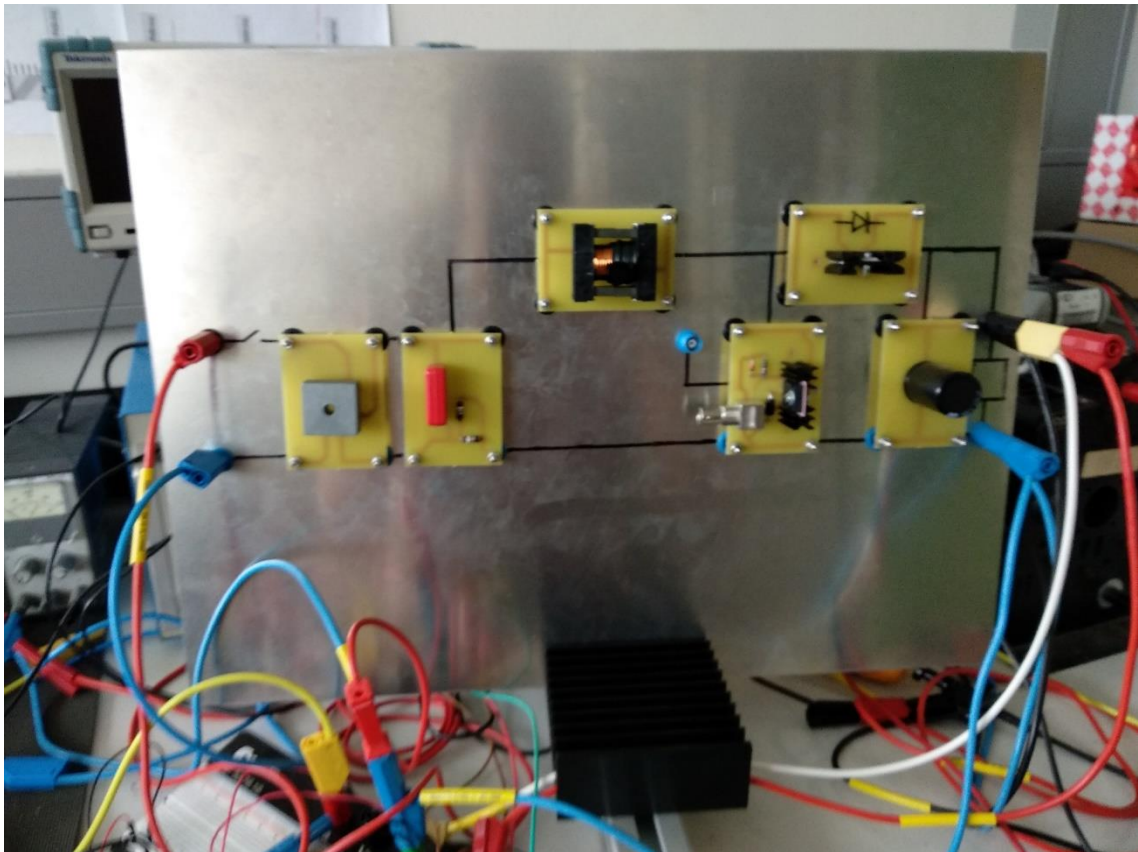
Figure 7. Initial set-up of the circuit built on a metal plate.

So basically, in this second chapter of the paper they are going to be explained all the peripheral circuits and structural modifications which have been made to the set-up, excluding the proper PFC control circuits which are explained in *Chapter 3* the CCM and in *Chapter 4* the DCM.

2.1.   Frame and structure

Starting from this base, the first improvement made to this design was to build a frame with legs in order to make the set-up more usable with an angle of declination of 45°. This way the set-up can be manipulated either sit on a chair or stand up in the lab. For this structure, some aluminum profiles were used. Specifically, they were used the following profiles shown in the *Figure 8*.
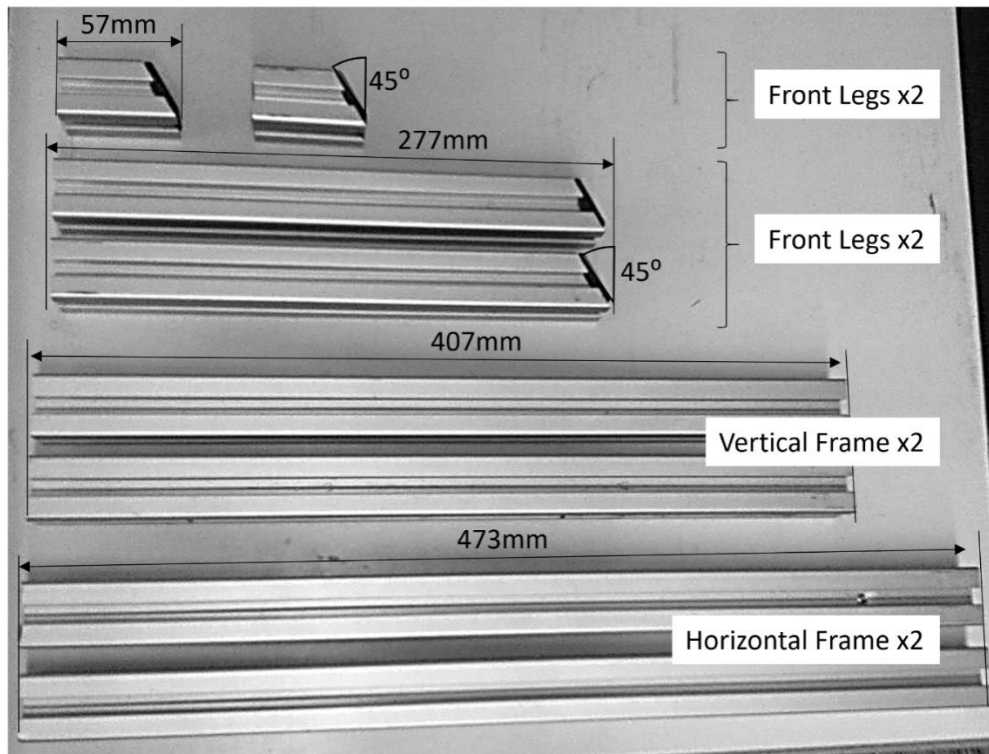
Figure 8. Aluminum profiles for the structure of the table.

As it can be seen, the four legs have an angle of 45 degrees in one of their sides. This way, after assembling them, they form a structure as an inclined table, as we can see in the *Figure 9*. This position allows a better manipulation from the front part of the circuit, which is more convenient to measure, connect and disconnect circuits.

After building this structure, it has been needed to drill some holes in the plate to add more circuits and connections, such us:

- The safety circuit holes for its holding screws, its button and its LED.
- The power supply circuit holes for its holding screws and its LEDs.
- The big hole for the 230V input connector and its switcher.
- The PFC circuit holes for its holding screws and its pin connections.
- The hole for the pin connectors of the transistor circuit.
- The hole for the pin connectors of the boost inductor.
- Two holes in the bottom part to open the circuit and to add two connections for measuring the current.

So, comparing *Figure 9* and *Figure 10*, they can be seen these changes which have been done in the structure from the beginning of the project until the end of it.

Figure 9. Structure of the test table after building the frame and the legs.
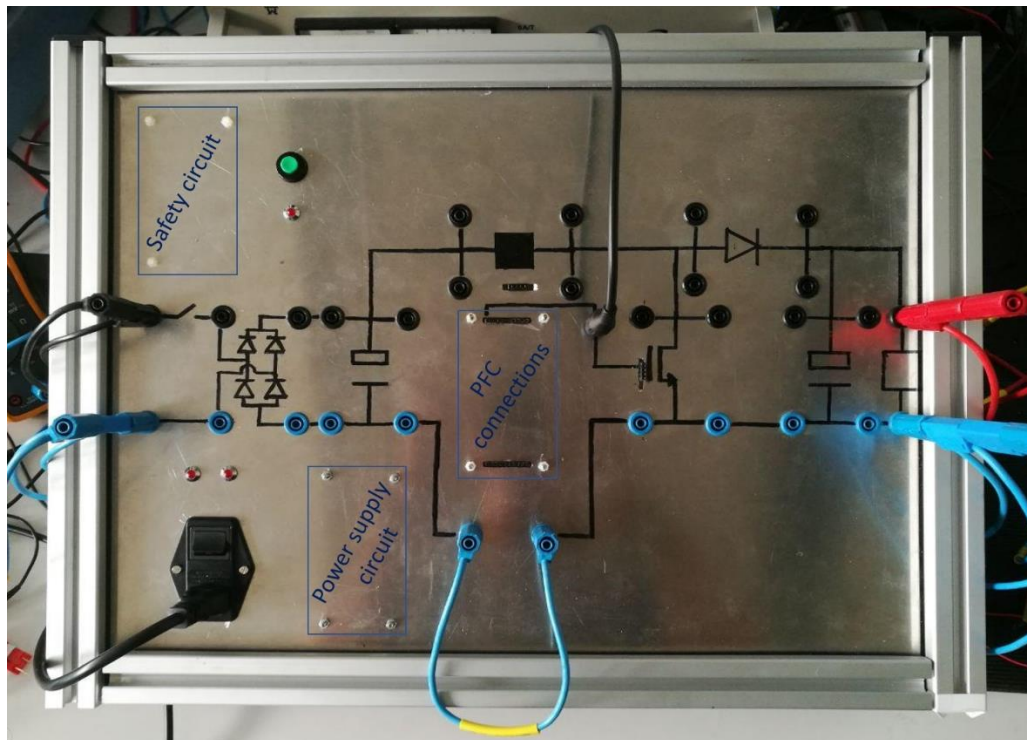
Figure 10. Final design of the table with all the connectors, holes and pins.

2.2. Power supply circuit

For the proper functioning of the boost converter, it is needed a power supply of 15V which will power the PFC circuit as well as the safety circuit and another one of 5V to feed the operation amplifier of the current measurement circuit.

Due to the simplicity of this circuit, it has been made on a proper PCB, and it doesn't require a lot of components, just the ones that appear in *Table 1*. The design of this circuit consists of two power supplies (230V to 15V and 230V to 5V), two fuses (160 mA and 60mA respectively) and two connectors. So, the connections are not really complex, as it can be seen in *Figure 11*.

Table 1. Power supply circuit parts list.		
Description	**Reference Number**	**Quantity**
160 mA Fuse	ESKA M160/250C	1
630 mA Fuse	ESKA M630/250C	1
1A Sand Fuse	F1AH250V	1
Fuse connectors	N/A	2
230V/15V power supply	VTX-214-005-115	1
230V/5V power supply	VTX-214-005-105	1
2-Wire connector	AK300/2	2
Red LEDs	N/A	2
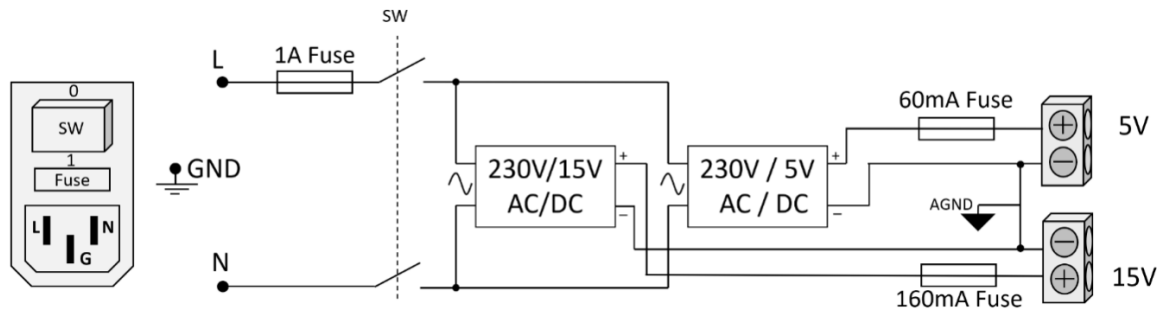
Figure 11. Electric scheme of the power supply circuit.

And as the scheme shows, the grounds of both DC outputs are connected to avoid future mistakes. There are also implemented two red LEDs to indicate if both power supplies are working correctly and this way, the user can know when the fuse breaks. Since this circuit is located in the back part of the test table, it is difficult to check if the fuses are broken. That is why the LEDs, the plug and the switch-on button are in the front part, as we can see in the left picture of *Figure 12*.

These LEDs are directly connected to the 5V and 15V power supply outputs respectively. But they both are should have a current limitation of 10mA, so they need different values for the resistors, as it is calculated below.

$$R_{LED} = \frac{V_{supply} - V_{LED}}{I_{LED}} \rightarrow \begin{cases} R_{5V\ LED} = \dfrac{5V - 1.8V}{10mA} = 320\ \Omega \\ R_{15V\ LED} = \dfrac{15V - 1.8V}{10mA} = 1320\ \Omega \end{cases}$$
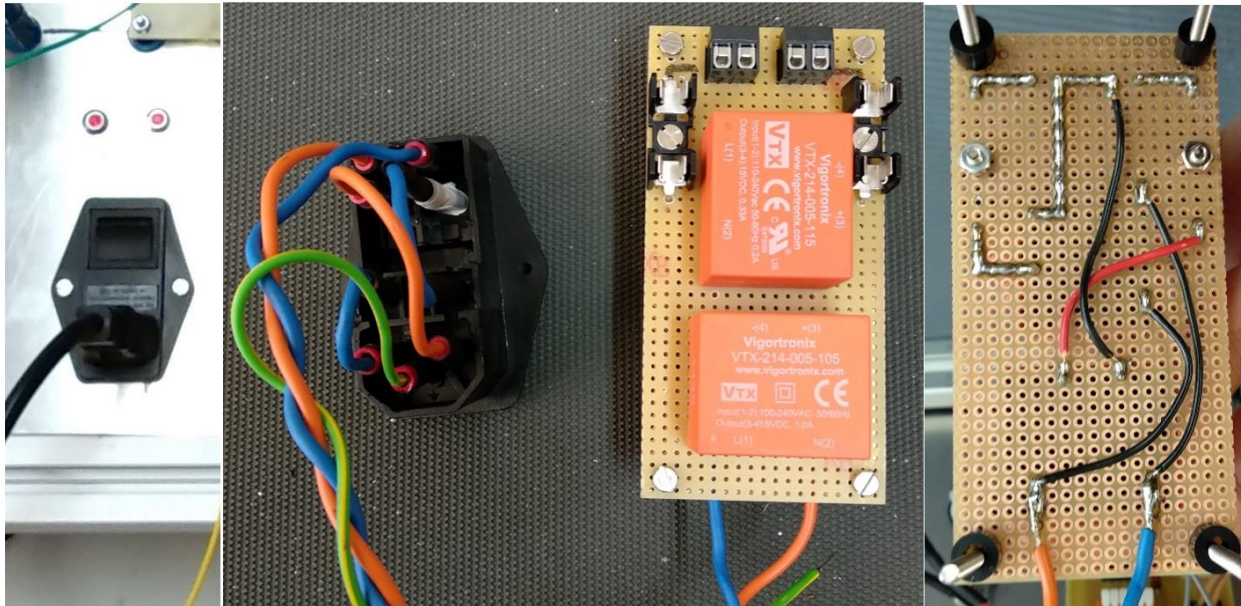
Figure 12. Power supply circuit prototype and its socket (left) to be plugged in 230V 50Hz.

2.3. Safety circuit [1]

The goal of this circuit is to act as a switcher and to open the circuit in case of some problem happens. It has been designed as an over-voltage protection for the user.

This circuit it is powered by the external 15 VDC source that it has been explained before this section. And the way it works is by means of measuring the output voltage of the boost converter and through a voltage divider it is compared to 5 VDC. When the voltage at the voltage divider is over 5 VDC, this safety circuit opens the main circuit, this way the AC input voltage will be cut. The circuit was designed by Eric Tumpa to turn the PFC circuit off if the output voltage of the PFC circuit is above the threshold of 73 VDC. That happens thanks to two SR flip flops created by a Quad input NAND gate IC.

This circuit has also been designed to be manually reset by pressing a button that closes the circuit again and allows the input current flow. After resetting the circuit, a red LED turns on, indicating that the input voltage has been reestablished. However, the circuit will stay cut until the output voltage drops under the threshold of 73 VDC, no matter if we press the reset button.

The components used for this circuit can be seen in *Table 2*. And the schematic and all the wiring connections are shown in the diagram in *Figure 13*. The final Eagle PCB design appears in *Figure 14*, where it can be seen that the traces used to connect the relay with the AC connector are thicker than the rest. That is because it is connected to the input AC power of the main circuit and the current is quite high compared with the other parts of the circuit.

Table 2. PFC safety circuit parts list.		
Description	**Reference Number**	**Quantity**
Comparator IC	LM2903	1
Quad NAND Gate IC	CD4011DE	1
5VDC Voltage regulator	7805	1
30kΩ Resistor	N/A	1
2.2kΩ Resistor	N/A	1
10kΩ Resistor	N/A	1
3kΩ Resistor	N/A	1
3.9V Zener Diode	1N5228	1
Diode	1N4148	1
N-Channel MOSFET	IRL540N	1
Relay	N/A	1
SPST Switch	N/A	1
6-Wire Connector	234-506	1
2-Wire Connector	AK300/2	1
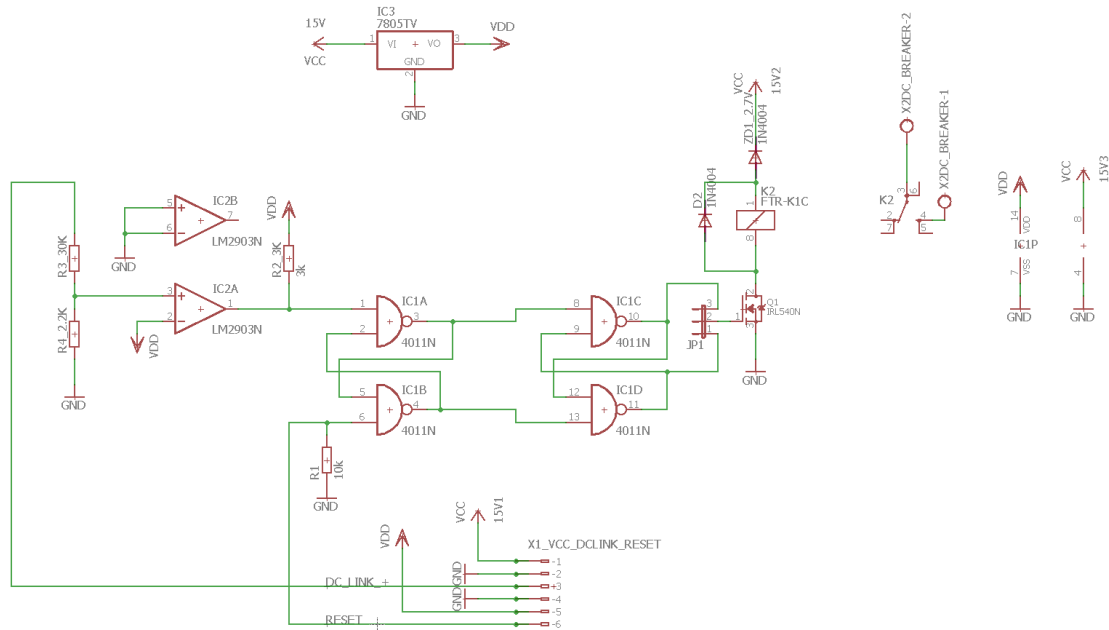
Figure 13. Schematic of the safety circuit.
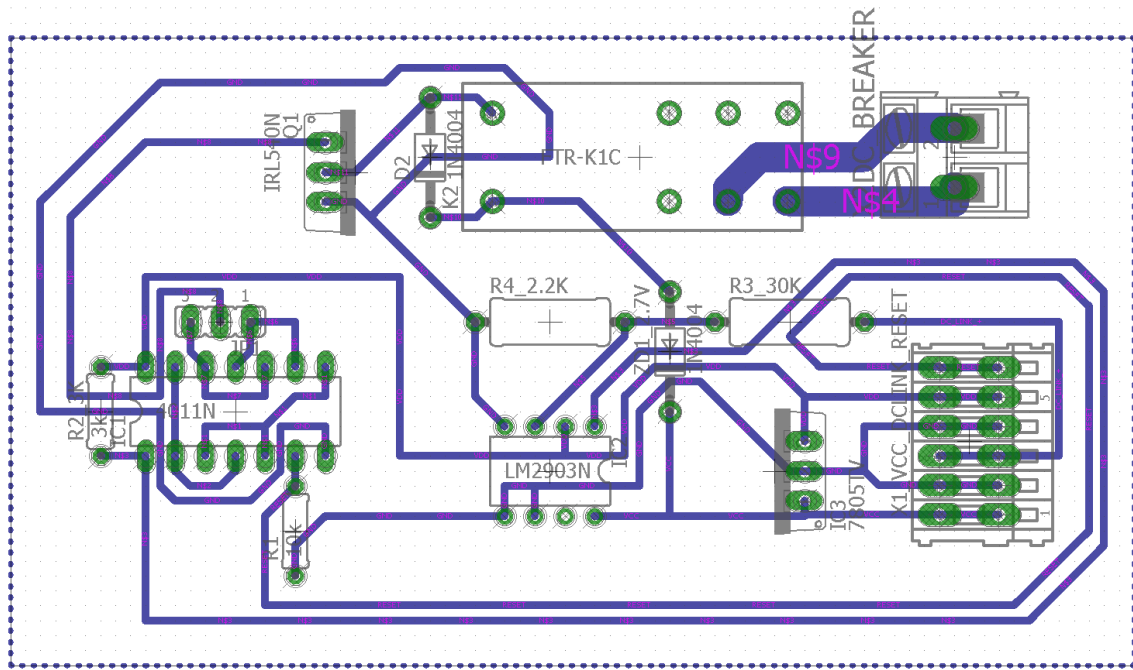
Figure 14. Board layout design of the safety circuit.

This design was made by Eric Tumpa and after being tested, it worked correctly. However, this circuit was design for an over-voltage protection of 73VDC, but it should have been changed to break the circuit when the output voltage is 60VDC. This limit is just to ensure that this circuit complies with the SELV (Safety for Extra-Low Voltage) EU regulations. Finally, this change was not made due to a lack of time, because these regulations were discovered at the end of this project. So, for the moment, the over-voltage protection is at 73VDC, which is still inside of the limits of the EU regulations, but to improve the safety, this circuit should be re-designed in the future.

The only thing that was added to the design was an LED which turns on if the circuit is closed and ready to work and which turns off when the safety circuit opens the main circuit due to an overvoltage. In *Figure 15* it can be seen the frontal part of the final safety circuit including the LED and the button. And *Figure 16* shows the bottom part of this circuit and there it can be seen where the LED is soldered. It also can be seen in this picture that the corners have been milled with a Dremel machine to avoid possible short-cuts between the ground of this PCB and the metallic parts of the main structure/table.
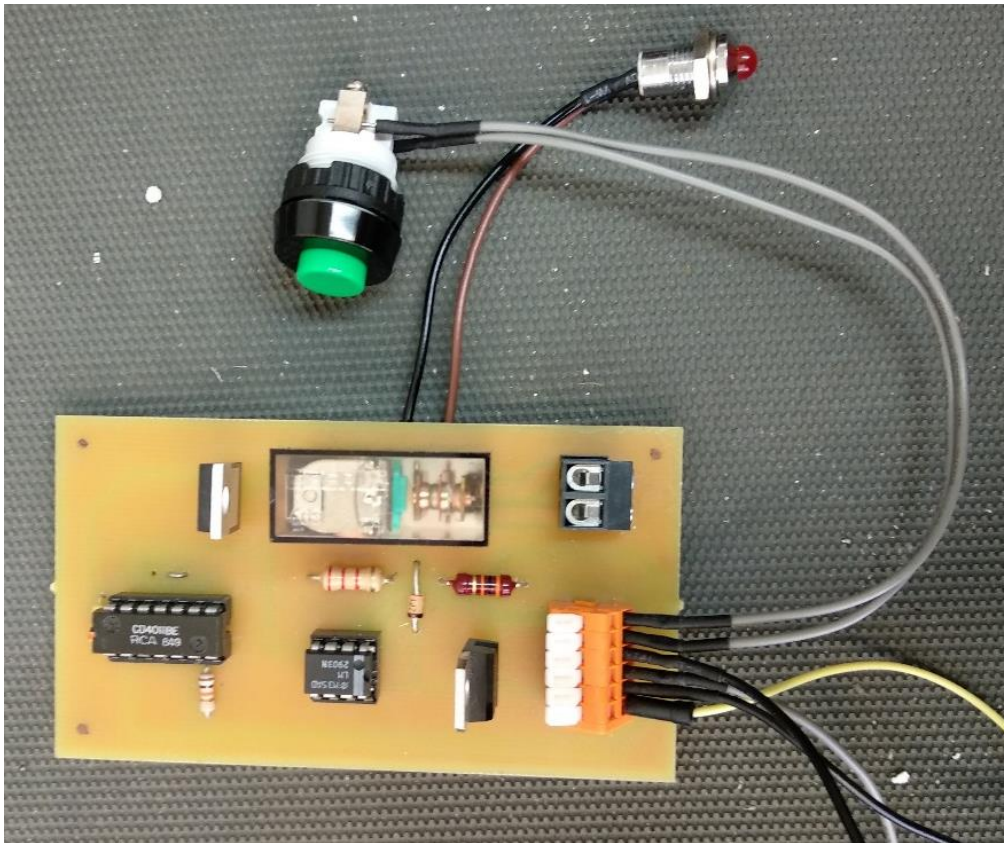
Figure 15. Final PCB of the safety circuit, including LED and button.
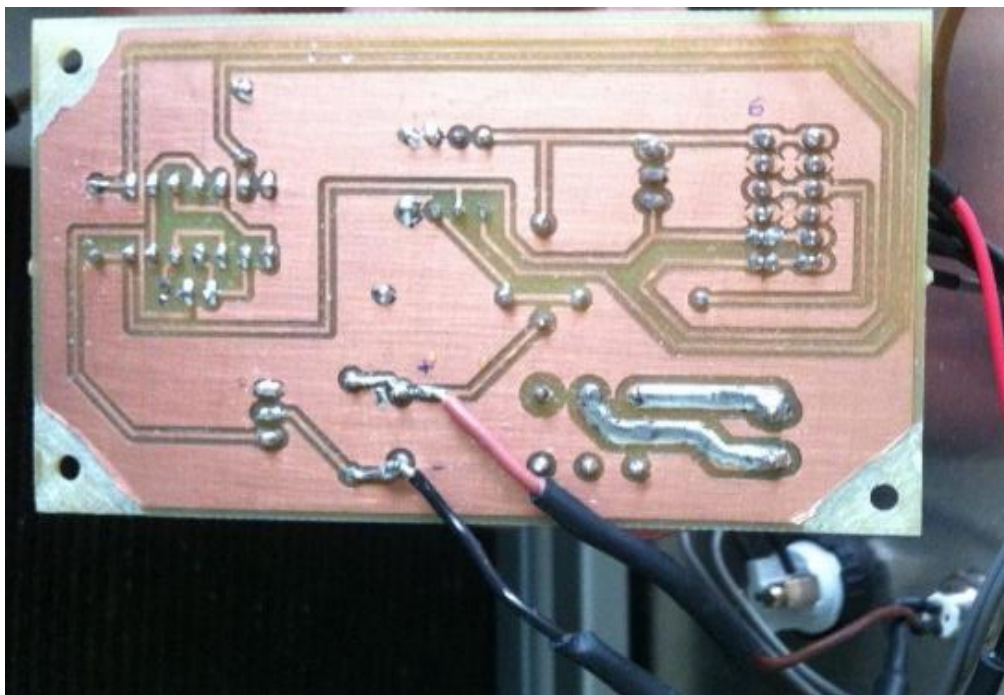
Figure 16. Bottom part of the safety circuit.

2.4.   Current measurement circuit

In order to control the output voltage of our boost circuit and to control the power factor, the PFC circuit needs to know the current of the circuit. It is needed for both kinds of PFC circuits, CCM and DCM.

First, the main idea was to use a shunt resistor to measure the current in the boost converter circuit. But after doing some tests with the CCM PFC, we notice that the current was too high, and the shunt resistor was getting quite hot until burning. The solution was to measure the current by other means. That is why it was decided to design a board with a current transducer that is placed behind the set-up.

So, in this chapter it is going to be explained this circuit, that at the beginning it was going to be used for measuring the current in the CCM and DCM. However, after designing this circuit, it was only used for the CCM PFC circuit, because the DCM PFC circuit needs the measurement of the current in the inductor. So, for the DCM, it was added a secondary coil to the inductor to measure de current, instead of using this board, but this is explained in *Chapter 4.3* of this paper.

For the design of this current measurement circuit board for CCM, first of all, it was chosen the current transducer, which is a LEM CAS15, and after it, the rest of the components which are listed in *Table 3*.

Table 3. Current measurement circuit parts list		
Description	**Reference Number**	**Quantity**
Current sensor	LEM CAS15	1
Operational Amplifier IC	LM358N	1
10kΩ Trim Potentiometer	3266 Bourns W103	1
33kΩ SMD Resistor	N/A	4
3-pin female connector	N/A	1
2-Wire Connector	AK300/2	1

Before starting the design of the board for this circuit in Eagle, it was needed to create a library with the measurements of this LEM current transducer. *Figure 17* shows the finished design of the symbol and the package of the library containing this current transducer. The critical part was to design it with the proper sizes and distances between holes and these measurements were taken from the LEM CAS datasheet [7].
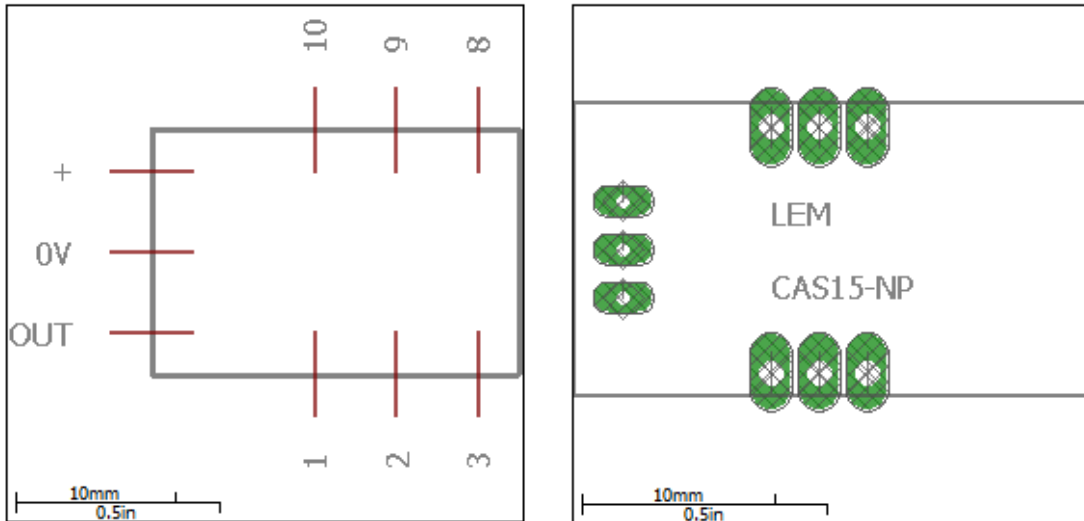
Figure 17. Design of the library package for the LEM CAS15 current transducer.

After de design of this package, the next step is to design the whole current measurement circuit, just as it looks in *Figure 18*. The LEM CAS 15 needs a power supply of 5VDC, this way the range of its output is between 0 and 5V, but if we take only the positive current, the output range is from 2.5V to 5V. As it can be seen in *Figure 18*, the output of the LEM current transducer goes to a differential amplifier, that is because the range of the LEM output is between 2.5V and 5V, but the pin 3 of the CCM PFC circuit needs an input between 0 and 2.5V. That means that when the current is 5A, the voltage on the pin 3 of the CCM should be 2.5V. So, for that reason, it was added a 3-pin connector (JP1) to the board, including connections for 5VDC, GND and the output voltage for sending the measurement to the CCM PFC board.
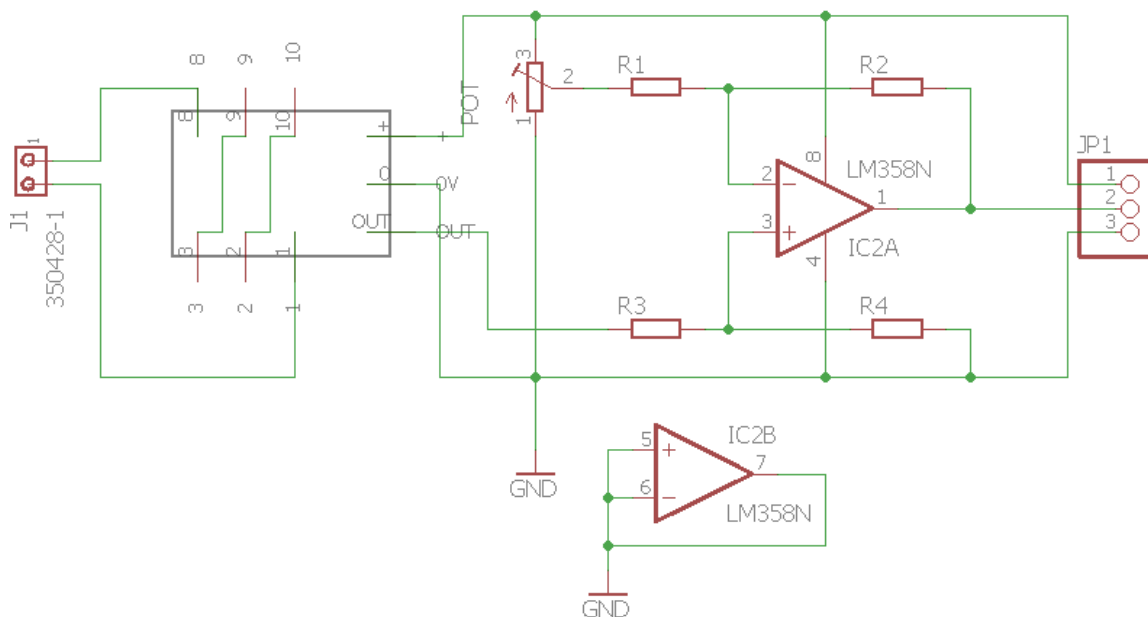
Figure 18. Schematic of the current measurement circuit.

For the calculation of the resistors of the circuit, it has been used the formula of a differential amplifier, they are shown here below:

$$\text{Being } \left.\begin{array}{l} R_1 = R_3 \\ R_2 = R_4 \end{array}\right\} \text{ then } V_0 = \frac{R_2}{R_1} \cdot \left(V_{out} - V_{ref}\right) \rightarrow \begin{cases} V_0 = 2{,}5 = \frac{R_2}{R_1} \cdot \left(5 - V_{ref}\right) \\ V_0 = 0 = \frac{R_2}{R_1} \cdot \left(2.5 - V_{ref}\right) \end{cases} \rightarrow$$

$$\begin{cases} V_{ref} = 2.5V \\ R_2 = R_1 = 33k\Omega \end{cases}$$

So, once we know that the V_{ref} value must be 2.5V, then to obtain it, the easiest way is to use a voltage divider, using a potentiometer connected between 5VDC and GND. And for the other resistors we just know that all of them must have the same value, so it has been chosen a middle value, not to high, not too low, 33kΩ, in this case.

This LEM current transducer is formed by a coil that produces a variable voltage when the current in the cable that goes through the coil. In the particular case of the CAS 15, according to its datasheet [5], the maximum current that it can measure is 15 A. So, knowing that in our circuit the current shouldn't be higher than 5 A, to take advantage of the whole measuring range, the cable to measure should pass through the coil three times. This way, to make this happen, the LEM transducer has three cables which go through it, and which can be soldered in different ways, so to meet this specification, they have been soldered in series as it is shown in *Figure 19*.
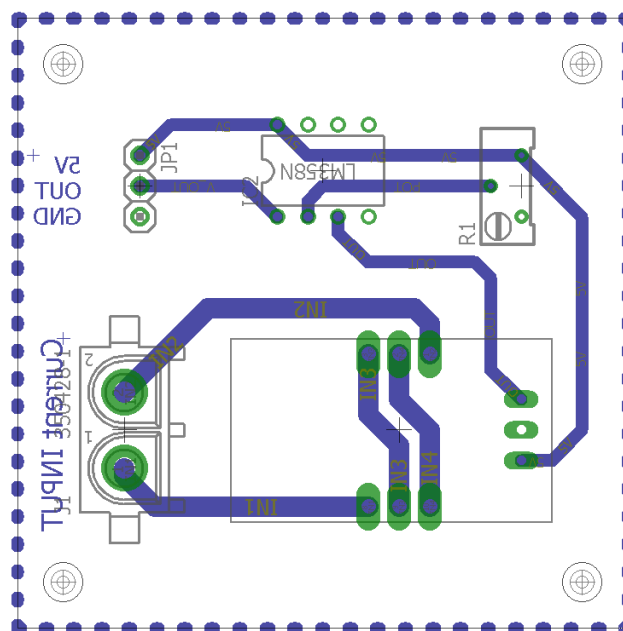
Figure 19. PCB layout of the current measurement circuit designed with eagle
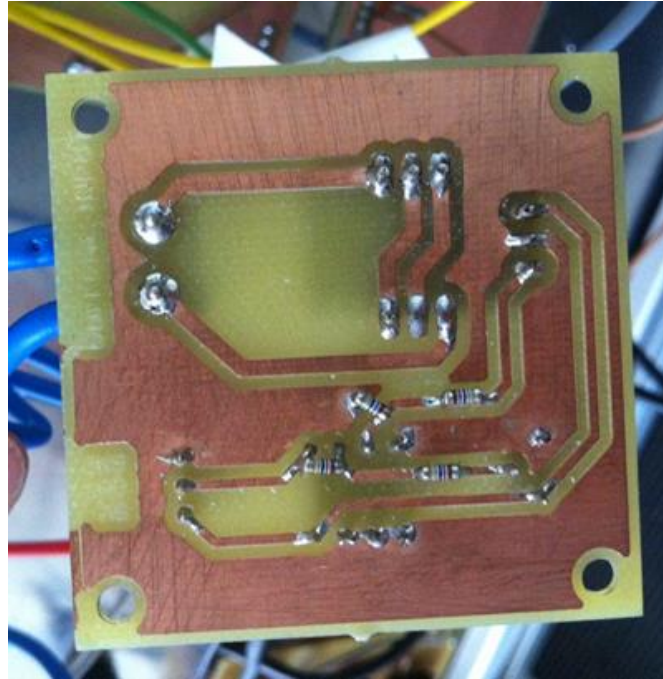
Figure 20. Bottom part of the current measurement circuit, including the SMD resistors.

But as it can be seen in *Figure 20*, the original design of *Figure 19* was modified after being printed the PCB, because the resistors were not added to the board design. So, the optimal solution was to add 4 SMD resistors of 33kΩ soldered to the bottom part of the board to make the differential amplifier work properly.

After soldering all the components to the board and after making all the connections from this circuit to the cables in the back part of test table, the assembled board looks like in *Figure 21*.
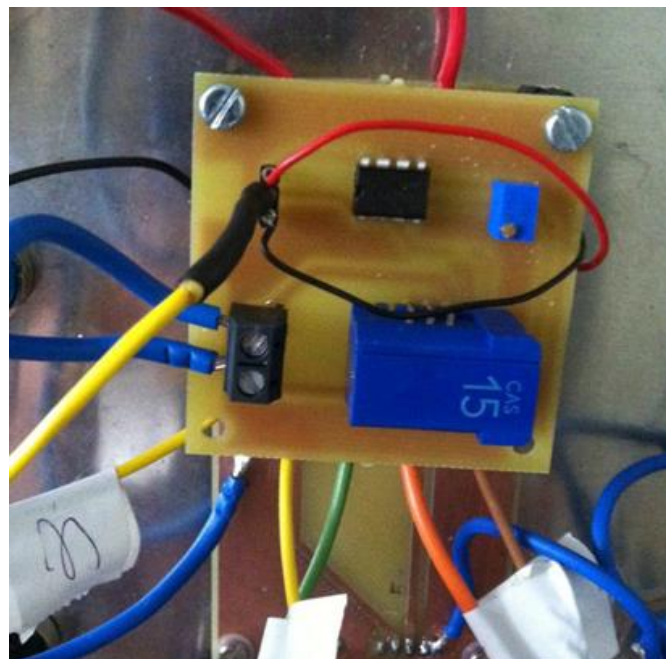
Figure 21. Front view of the current measurement circuit board.

2.5.   Bottom socket boards with pin connectors.

Basically, these boards placed in the bottom part of the test table are not really circuits, they are just PCBs which have some soldered pins which allows to connect the circuits from the front side of the table to their connections in the back side of the table.

The main is the PFC socket, which has the 18 pins to connect the CCM and the DCM PFC circuits, *Figure 22* shows the pinout layout of this board and the name of each pin.
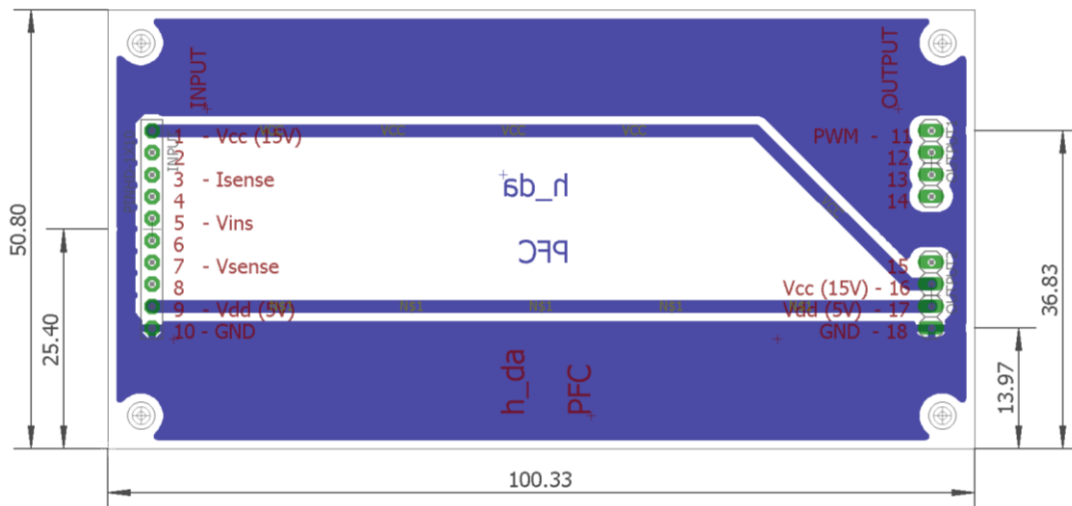
Figure 22. Socket board for connecting PFC circuit pins.

On the other hand, we have two more sockets as the board shown in *Figure 23*, and one of them is for connecting the pins of the transistor circuit and the other is placed under the inductor circuit and it is used to connect the secondary coil of the DCM inductor.
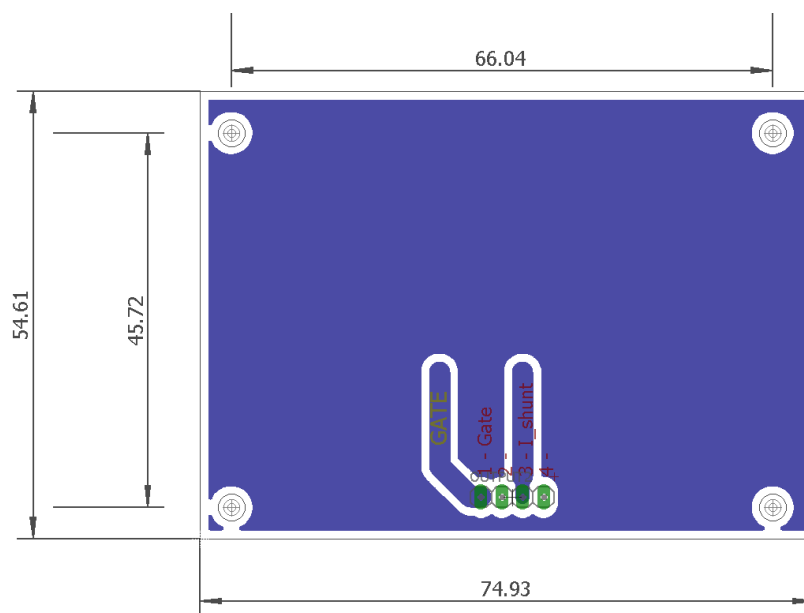
Figure 23. Socket board for connecting transistor circuit pins.

2.6.   Measuring devices and equipment used from the lab

Apart from the built table with the circuit, to make it work, they have been also needed some devices which are listed below.

- 1 Yokogawa WT500 power analyzer.
- 1 Tektronix TPS2014 four channel digital oscilloscope.
- 2 Tektronix 10x probes.
- 1 MA 230V Messadapter for the external trigger of the oscilloscope.
- 2 Fluke 115 true RMS multimeter.
- 1 Chauvin Arnoux current probe 10-100A / 1V
- 1 Load 145Ω Variable Resistor.
- 1 Trennstelltrafo LTS 606 AC Power Supply.
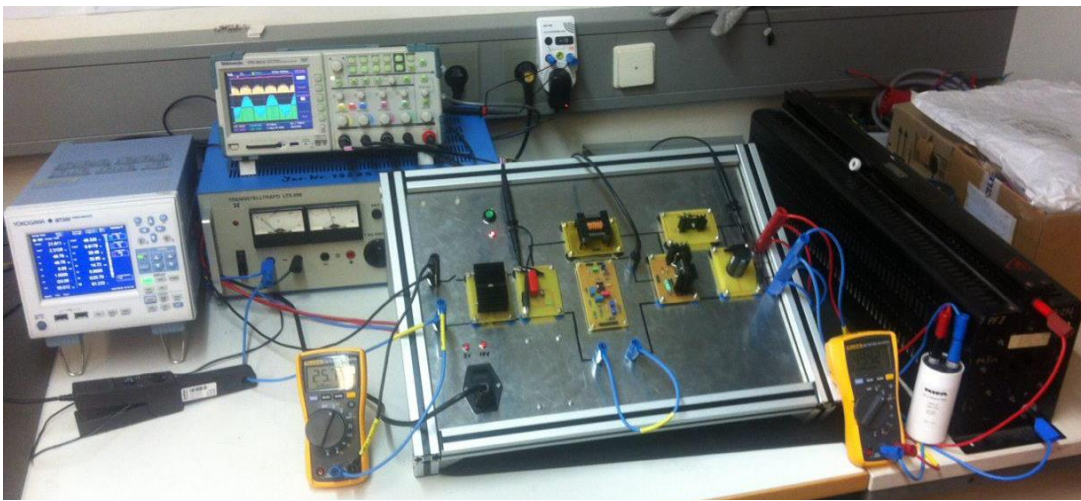
Figure 24. Whole set-up, including measurement devices, load, power source and circuit.

Here in *Figure 24* we can see how all these mentioned devices are connected to each other. In the right part of the picture it appears the variable load (black), connected to the output of the circuit. In the background there is the power supply which is connected to the input of the circuit. On the top of it, it can be seen the oscilloscope, whose four channels are connected to the input voltage, to the output voltage, to the gate PWM signal and to the current probe.

On the other hand, the Yokogawa analyzer is used to measure the efficiency and the power factor. And its connections are maybe the most complex and the most interesting ones to pay attention. For this reason, it is necessary to connect the element 1 and 2 of the Yokogawa as it is shown in *Figure 25*.
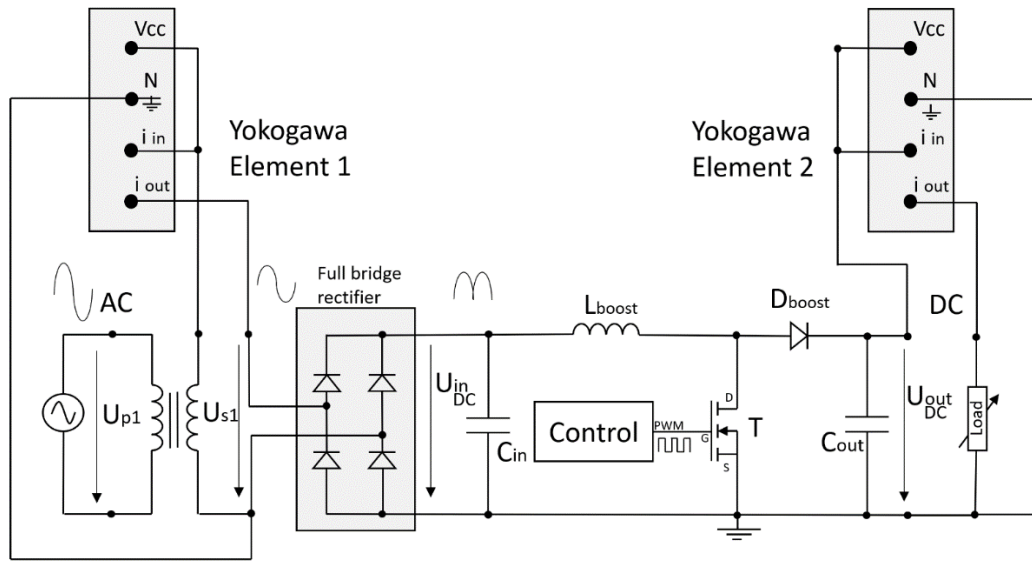
Figure 25. Scheme of the whole circuit with the Yokogawa connections.

3.   CCM PFC Control circuit

Here in this section, it is explained the design and testing process of the Continuous Conduction Mode PFC control circuit. After adding the already commented safety circuit and power supply circuit to the table and after connecting the input transformer, the load and all the measurement equipment, it was time of designing the main part, the control board.

There was already a CCM PFC control board designed by Eric Tumpa, but it wasn't working correctly, so it was decided that it was more convenient to design a new board from the scratch than trying to improve the existing one. Here in *Figure 26* we can see how the whole circuit is built after the design and construction of the new CCM board.
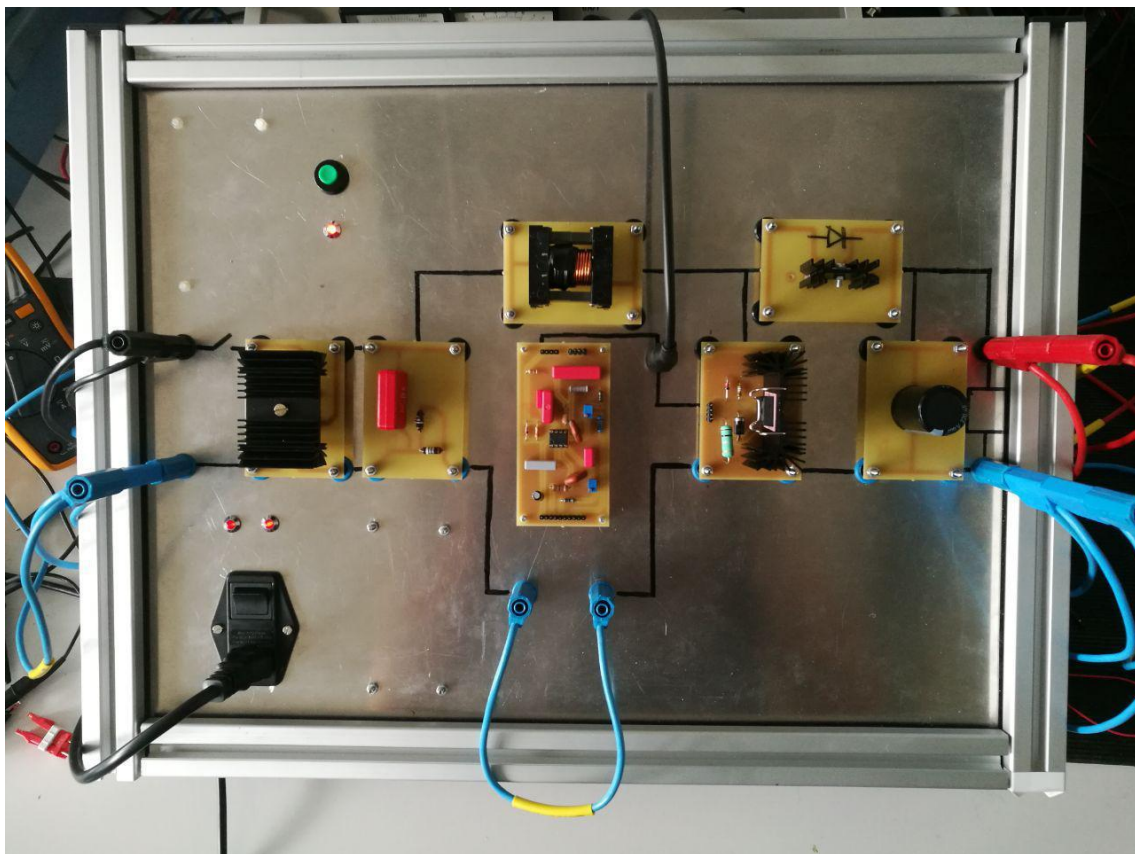
Figure 26. Whole circuit with the components needed for the CCM PFC disposition.

The chosen IC for controlling this circuit was the same one that Eric chose, the UCC28019 from Texas Instrument. In its datasheet [6] we can find all the needed information, and here below it is explained all the design process.

3.1.　Design of the CCM control circuit

First of all, for designing this circuit, it is needed to create a library for the PFC IC, but in this case, it was already made by Eric Tumpa, and here below in *Figure 27* it can be seen the design of the library package for the UCC28019 IC.
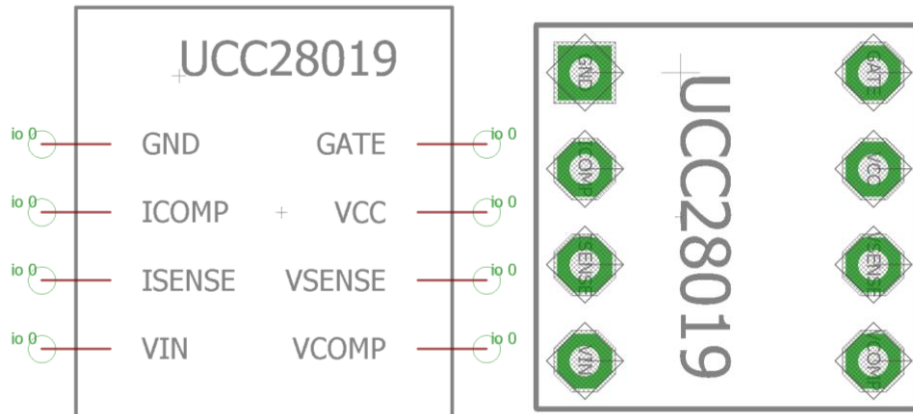
Figure 27. Design of the library package for the UCC28019 (CCM IC).

Once we have the library the next step is to create the schematic of the circuit in Eagle. The first circuit was made like the example in the datasheet [6] without paying attention yet to the values of the components. After that, the circuit was as the one that appears in *Figure 28*.
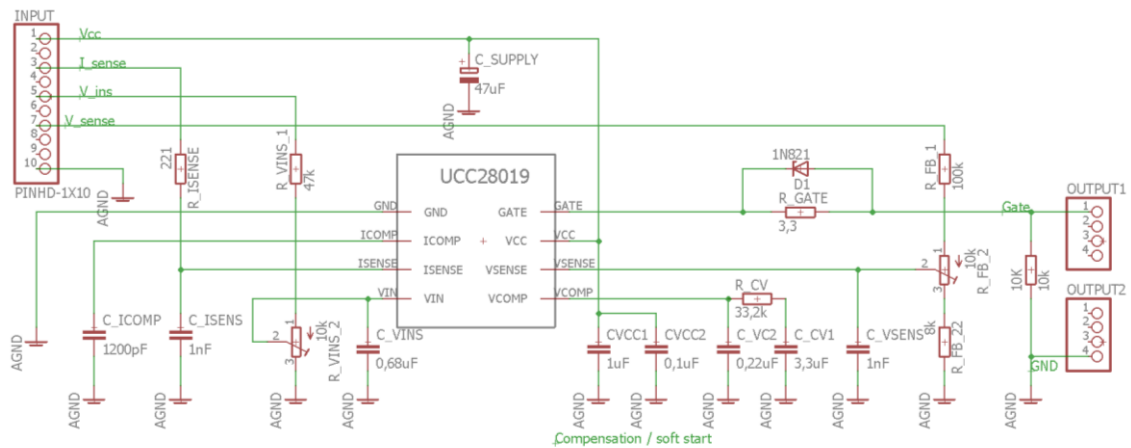
Figure 28. Schematic of the CCM PFC circuit.

After that, it is time to do some calculations in order to assign some values to the components. Most of the capacitors for the moment were selected with the same values than the example in the datasheet [6] because despite of that our circuit has different specifications for input and output, changing the values of these components don't make a big difference. However, there are some other components that are critical for our design and they must be different. These critical components are the ones which are in the input and output voltage dividers, because depending on the values of their resistors, we can set up the nominal input and output voltages. In this case they should be set up as 25V the input and as 50V the output.

In the datasheet it can be found this formula below, to calculate the values of the resistors for the output voltage divider. So, we just assign a value to one of the resistors, and we calculate the other one.

$$R_{FB2} = \frac{V_{REF} \cdot R_{FB1}}{V_{OUT} - V_{REF}} = \frac{5V \cdot 100k\Omega}{50V - 5V} = 11.1k$$

Due to this is a rough calculation, a potentiometer has been added to the voltage divider, just to do some adjustments of the value of the resistor after building the circuit, in order to obtain the desired output voltage level.

For the input voltage divider, the same process was done, assigning some values to the resistors similar than the values of the output voltage divider. And after that, the potentiometers were adjusted to obtain the desired input voltage level.

In order to find the values for these resistors and test if the circuit works correctly, it was created a prototype built on a protoboard. In *Figure 29* it can be seen this set-up, in which the calculated components were plugged. After connecting some cables to the main circuit input, output and gate, then the circuit was tested, and some components were replaced.
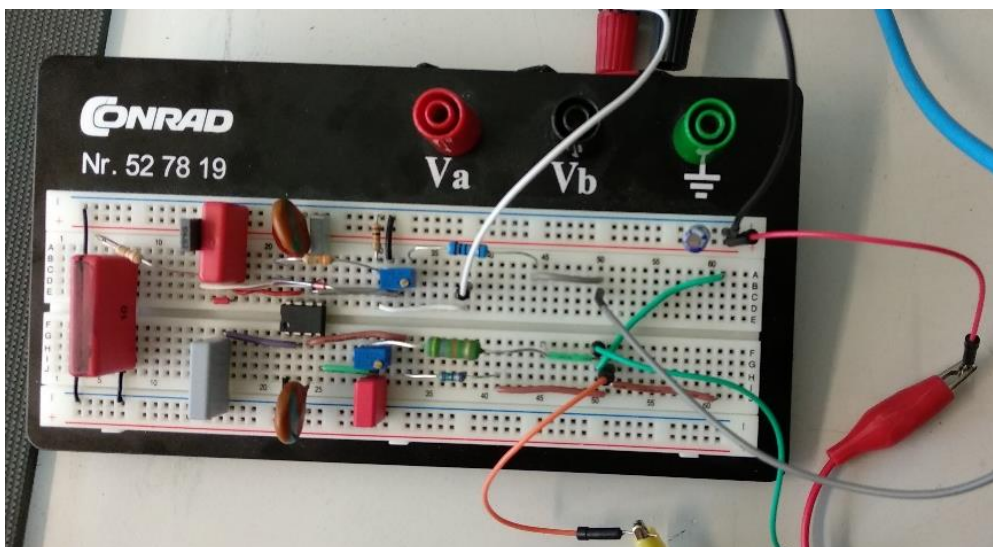
Figure 29. CCM control prototype circuit set-up.

Once that everything was working correctly it was decided to start the design of the definitive circuit on a PCB. For this design it was used the previous schematic created in Eagle, shown in *Figure 28*, and from it, the board was designed using the components used in the prototype design. *Figure 30* shows this PCB Eagle design after being finished.
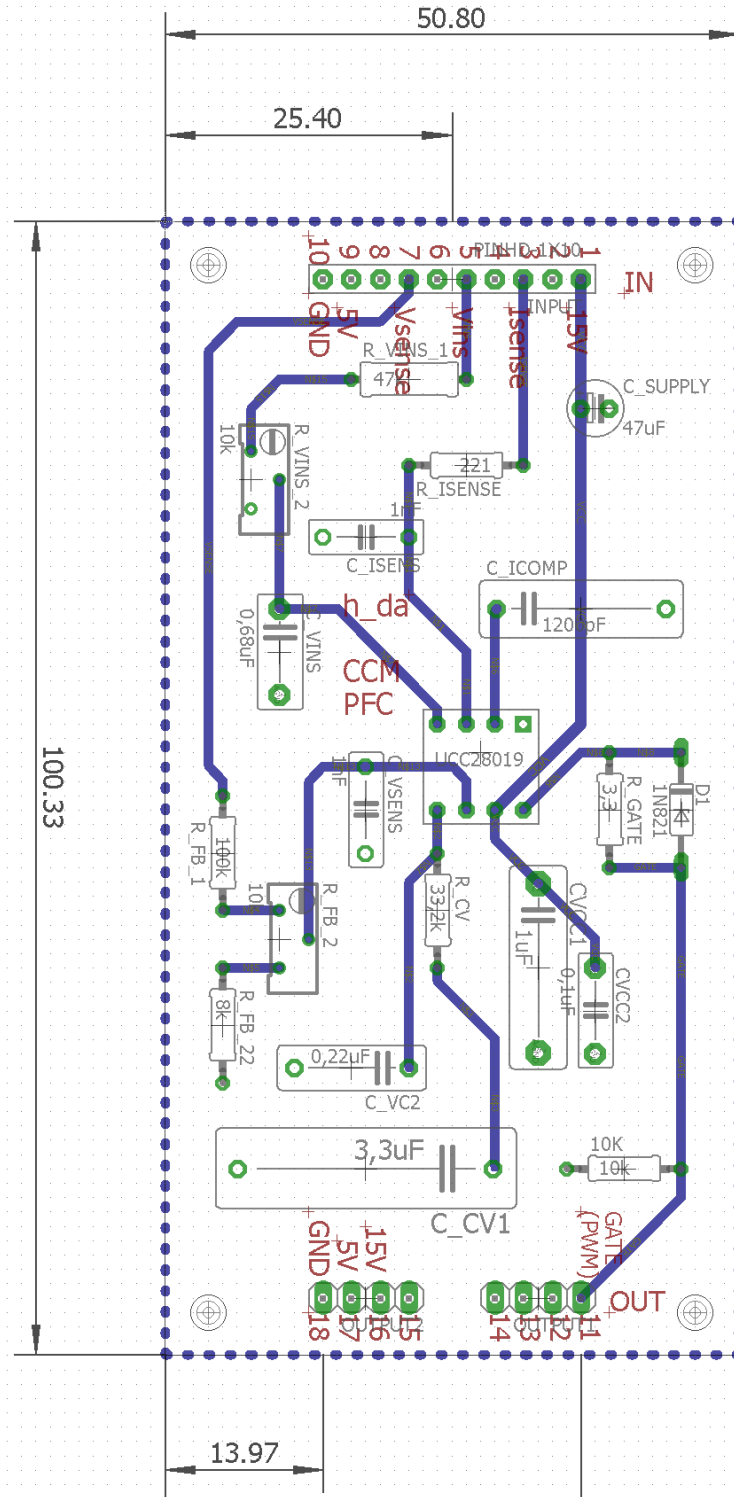
Figure 30. PCB Eagle design for the CCM circuit.

One of the critical parts of the PCB design was the selection of the components. That is due to the fact that every component can have different dimensions, so the chosen components for the design were selected according to the available ones in the lab, measuring the distances between the pins of the components to make them fit in the holes of the PCB. Finally, the components that were used in this design are shown in *Table 4*, and they were soldered to the PCB after printing the board.

Table 4. CCM PFC control circuit parts list.		
Description	**Reference Number**	**Quantity**
CCM PFC control IC	TI - UCC28019	1
8-pin adapter for ICs	N/A	1
10-pin connector	N/A	1
4-pin connector	N/A	2
10kΩ Trim Potentiometer	3266 Bourns W103	2
3.3Ω Resistor	N/A	1
220Ω Resistor	N/A	1
8.2kΩ Resistor	N/A	1
10kΩ Resistor	N/A	1
33kΩ Resistor	N/A	1
47kΩ Resistor	N/A	1
100kΩ Resistor	N/A	1
Diode	1N4148	1
1nF 400V Capacitor (C_Vsens & C_Isens)	560-2	2
1.5nF 2000V Capacitor (C_Icomp)	385 MKP L1322	1
0.1µF 100V Capacitor (C_Vcc2)	WIMA MKS3 0.1/100- V0	1
0.22µF 100V Capacitor (C_VC2)	N/A	1
0.68µF 63V Capacitor (C_Vins)	WIMA MKS3 0.68/63-B B1	1
1µF 100V Capacitor (C_Vcc1)	WIMA MKS4 1/100- V5	1
3.3µF 100V Capacitor (C_VC1)	WIMA MKS4 3.3/100- K9	1
47µF 25V Capacitor (C_supply)	Jamicon 732C2(M)	1

This CCM board was made thanks to the miller which is in the EIT lab in the H-DA. And in *Figure 31*, we can see the result after milling this PCB and soldering all the components to it.
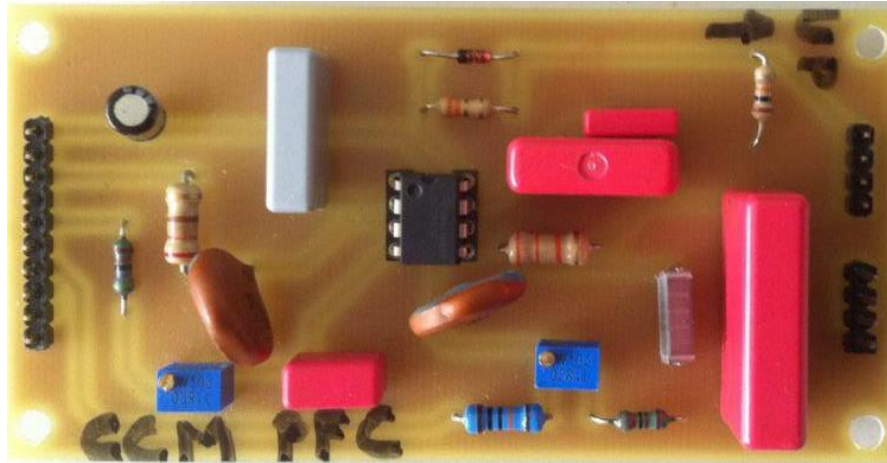
Figure 31. Final CCM PCB with all the soldered components.

3.2.   Test and results of the CCM circuit

After the PCB was milled and every component was soldered to it, the PCB was connected to the pin connectors built in the table. Once everything is connected, including the measurement systems such as the oscilloscope and the Yokogawa, the circuit is ready to be tested.

First, the load which is a big potentiometer must be set to its maximum value of resistance, because otherwise the current would be too high, and the fuse of the input transformer can be burnt. After that, the input voltage must be increased until 25V adjusting this value in the input transformer.

Now below are going to be shown the waveforms in the oscilloscope, and thanks to that we will decide if the obtained results are the expected ones. In all the graphs from now on, the colors of the waves are the ones below:

- Pink: output voltage.
- Yellow: input voltage after the rectifier.
- Blue: current.
- Green: gate PWM wave.

When the input voltage is set to 25V and the potentiometer is in its maximum value, the output value is constant at 50VDC, as we can see in *Figure 32*. In this case the load resistance is high, that means that the consumed current is low, as it can be seen in the blue waveform in the graph.
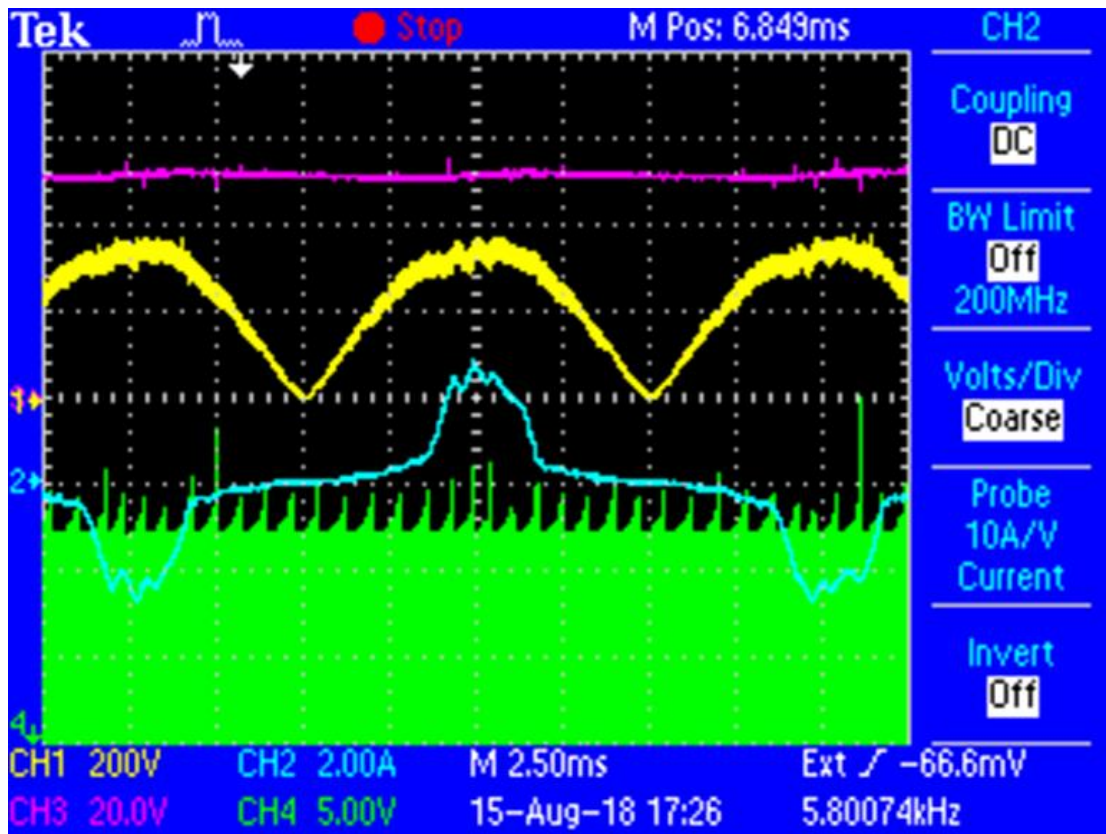
Figure 32. Oscilloscope showing CCM waves with high resistance load.

After analyzing the results with a load of high resistance, we decrease the value of the potentiometer resistance. And in this case, the opposite thing will happen, the current increases, so the current wave (blue) becomes more sinusoidal, as it can be seen in *Figure 33.* It also shows how the output and input voltages stay similar than in the previous case. That proves that our circuit is working properly, because de goal of the project is to obtain a constant value for the output voltage, which must be 50VDC in this case.
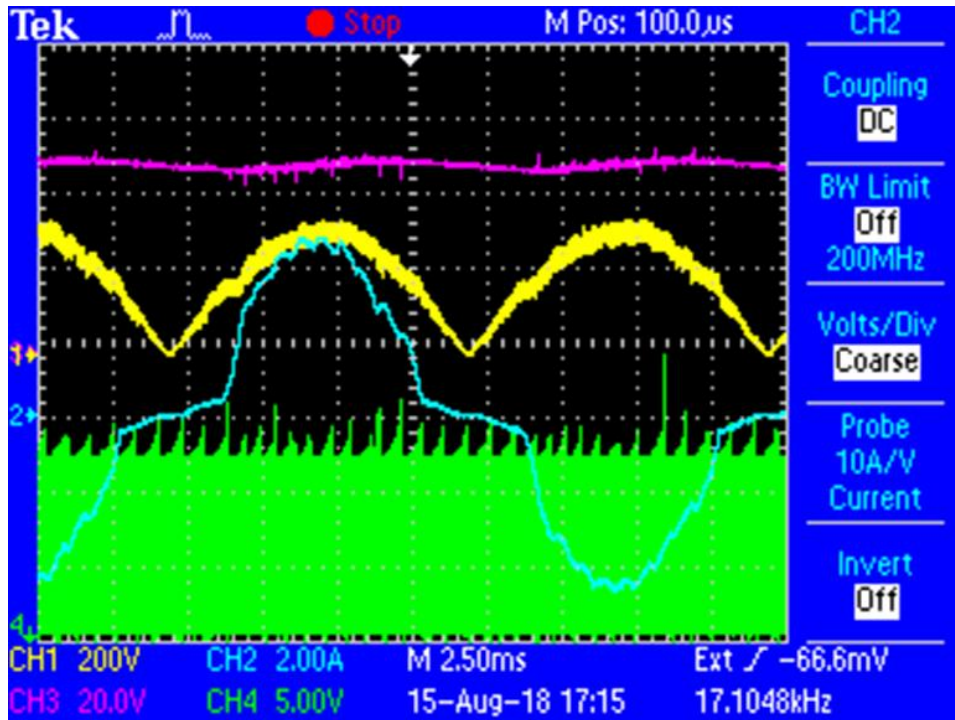
Figure 33. Oscilloscope showing CCM waves with low resistance load.

Once that the waves have the desired form, it is time to check the switching frequency of the transistor. For that, it is enough with zooming in the oscilloscope to measure the period of the gate PWM wave. *Figure 34* shows clearly in both images that the period of the gate wave is 15μs. So, the switching frequency must be $f = \frac{1}{T} = \frac{1}{15\mu s} = 66.66 \, kHz$.
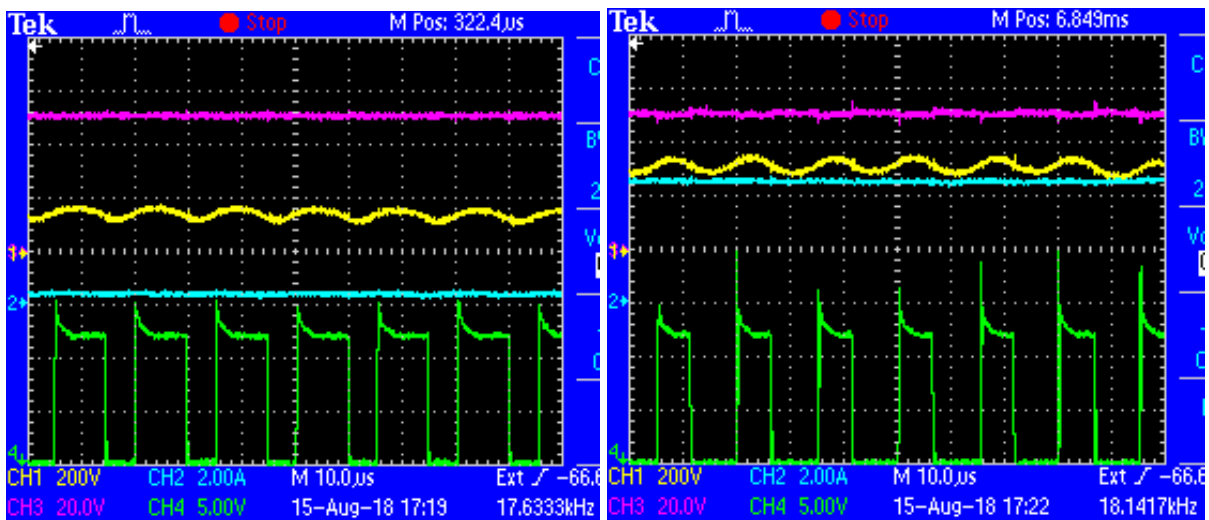
Figure 34. Oscilloscope showing the detail of the gate PWM wave in CCM.

And the switching frequency remains constant, independently of the value of the load and of the value of the current. For example, *Figure 34* shows that current is minimum in the image of the left and maximum in the image of the right, but the period of the gate remains constant. Only the duty cycle of the PWM wave changes.

Now, concerning to the Yokogawa, the results also have been checked with high resistance load (shown in *Figure 35*) and low resistance load (shown in *Figure 36*). The images show that the input and output voltages are constant, 25V and 50V, respectively, as it could be seen in the oscilloscope.
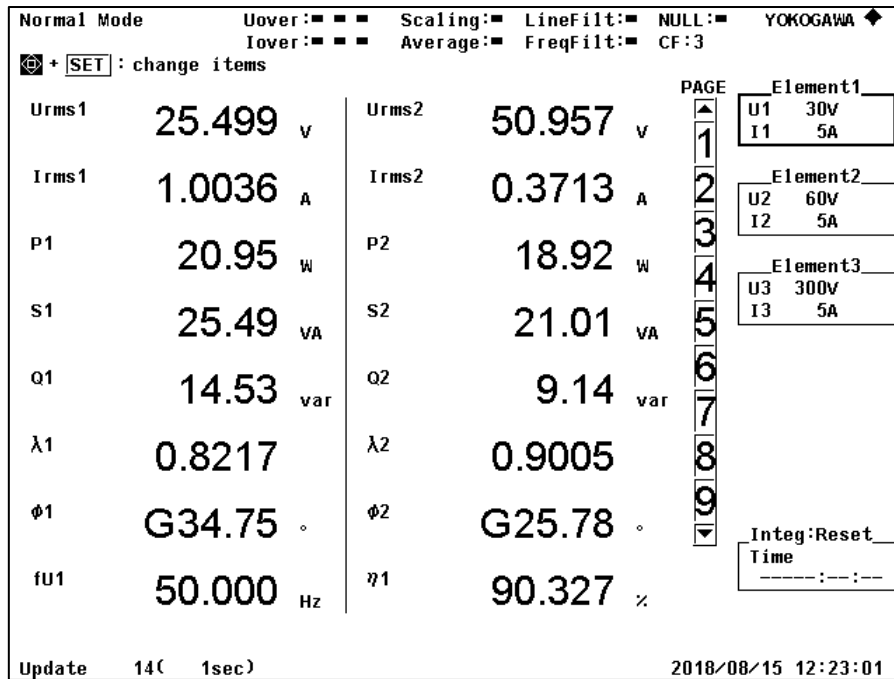
Figure 35. Yokogawa showing results of CCM with high resistance load (PF=0.82).
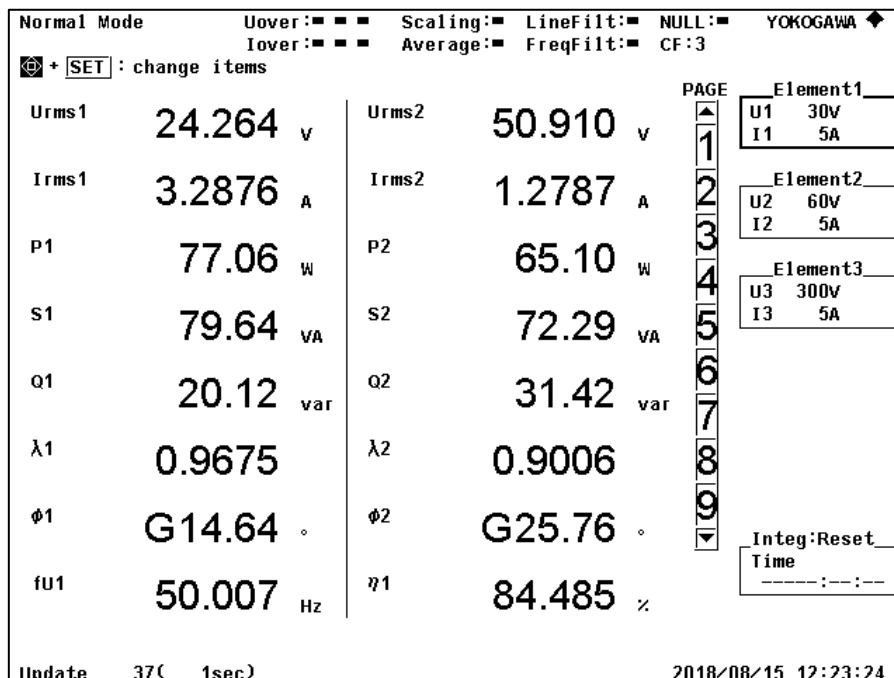
Figure 36. Yokogawa showing results of CCM with low resistance load (PF=0.97).

Despite of that the results are very similar in both cases, we can see that the power factor is higher when the load has lower resistance. That is because when the resistance is decreased, the current increases and becomes more sinusoidal, as we have seen before

in the oscilloscope. And the more sinusoidal the current wave is, the higher the power factor is.

In the Yokogawa results we also can check that the efficiency of the transformation of power works the other way around. That means that when the current is higher, the circuit has more heat losses, so the efficiency decreases. However, we can conclude that the obtained power factor, between 0.83 and 0.97, is quite good, and the efficiency, between 0.84 and 0.90, too.

3.3. Comparison with theoretical values of the CCM circuit

After testing the circuit and checking that everything was working as expected, it was found an Excel file [7] which allows to calculate the values of some important components for the CCM circuit design. So, now below in *Table 5*, they appear the input and output values, that have been introduced in the Excel file according to the circuit specifications.

Table 5. Output and input values for the CCM PFC set in the excel file[7].			
OUTPUT:			
Maximum Output Power of PFC Stage:	$P_{OUT(max)}$	100	W
Output Voltage (Note: Must be > $V_{IN\_RECTIFIED(max)}$):	V_{OUT}	50	V
Target Power Factor, $V_{IN(nom)}$, Full Load:	PF	0,99	
Predicted Efficiency:	η	0,9	
Maximum Ambient Temperature:	$T_{AMB(max)}$	40	°C
Maximum Output Current of PFC Stage:	I_{OUT}	2,00	A
INPUT:			
Minimum Input Voltage from AC Line:	$V_{IN(min)}$	20	V_{RMS}
Maximum Input Voltage from AC Line:	$V_{IN(max)}$	30	V_{RMS}
Nominal Input Voltage from AC Line (i.e.115 VRMS):	$V_{IN(nom)}$	25	V_{RMS}
Minimum Line Frequency:	$f_{LINE(min)}$:	45	Hz
Maximum Line Frequency:	$f_{LINE(max)}$:	55	Hz
Nominal Line Frequency (i.e. 50 Hz):	$f_{LINE(nom)}$	50	HZ
Minimum Rectified AC Line Voltage:	$V_{IN\_RECTIFIED(min)}$	28,28	V
Maximum Rectified AC Line Voltage:	$V_{IN\_RECTIFIED(max)}$	42,42	V
Maximum Input Power Drawn from the Line:	$P_{IN(max)}$	111,11	W
Maximum RMS AC Line Current:	$I_{IN\_RMS(max)}$	5,61	A
Maximum Peak AC Line Current, assuming sinusoidal:	$I_{IN\_PEAK(max)}$	7,93	A
Maximum Average AC Line Current, assuming sinusoidal:	$I_{IN\_AVG(max)}$	5,05	A
Minimum Input Fuse Rating:	I_{FUSE}	8,42	A

After introducing the specifications, the Excel file makes some calculations and generates a table with the recommended bill of materials and it is shown below in *Table 6.*

Those values were not chosen because the circuit was already finished, but after comparing them with used components shown in *Table 4*, we can see that the important components, which are the ones in the input and output voltage divider, have similar values.

Table 6. Results for the components of the CCM calculated in the excel [7].			
RECCOMMENDED BILL OF MATERIALS			
Reference Designator	**Description/Comments**		
C_in	Value:	1,80	μF
	Voltage Rating:	30	V_RMS
L_boost	Inductor Value:	0,19	mH
	Peak Current Rating:	8,45	A
	Ripple Current:	1,02	A
Risense	Type:	Resistor, 1/16W	
	Value:	220	Ω
Cisense	Type:	Capacitor, Ceramic, 100V, X7R, ±10%	
	Value:	1113	pF
Cout	Type:	Capacitor, Aluminum, ±20%	
	Value:	5800	μF
	Voltage Rating:	53	V
	2 x f_LINE Ripple Current Rating:	1,414	A_RMS
	HF Ripple Current Rating:	2,450	A_RMS
Rfb1	Type:	Resistor, Total Voltage Rating 400V, ±1%	
	Value:	100	kΩ
Rfb2	Type:	Resistor, 1/10W, ±1%	
	Value:	12	kΩ
Cvsense	Type:	Capacitor, Ceramic, 50V, X7R, ±10%	
	Value:	833	pF
Cicomp	Type:	Capacitor, Ceramic, 50V, X7R, ±10%	
	Value:	1000	pF
Cvcomp	Type:	Capacitor, Ceramic, 10V, X5R, ±10%	
	Value:	3,3	μF
Rvcomp	Type:	Resistor, Chip, 1/10W, ±1%	
	Value:	33	kΩ
Cvcomp_p	Type:	Capacitor, Ceramic, 10V, X5R, ±10%	
	Value:	0,22	μF
Rvins1	Type:	Resistor, Chip, Total Voltage Rating 400V, ±1%	
	Value:	0,047	MΩ
Rvins2	Type:	Resistor, Chip, 1/10W, ±1%	
	Value:	6,5	kΩ
Cvins	Type:	Capacitor, Ceramic, 10V, X5R ±10%	
	Value:	0,680	μF
VCC Bypass Capacitors:	Type:	Ceramic, Low ESR/ESL, placed close to the VCC and GND pins with short traces	
	Values:	0,1	μF
		1	μF

4.   DCM PFC Control circuit

After the design of the Continuous Conduction Mode (CCM) control circuit and its testing, it was time to start with the design of the Discontinuous Conduction Mode (DCM) control circuit. In this chapter, it is explained not only the design and the testing of this DCM circuit, but also the design of the new transistor board and the new inductor board that were replaced for this circuit.

Now, here below, *Figure 37* shows the set-up of the whole circuit with all the components needed for the DCM circuit, after finishing the design and testing of this circuit.
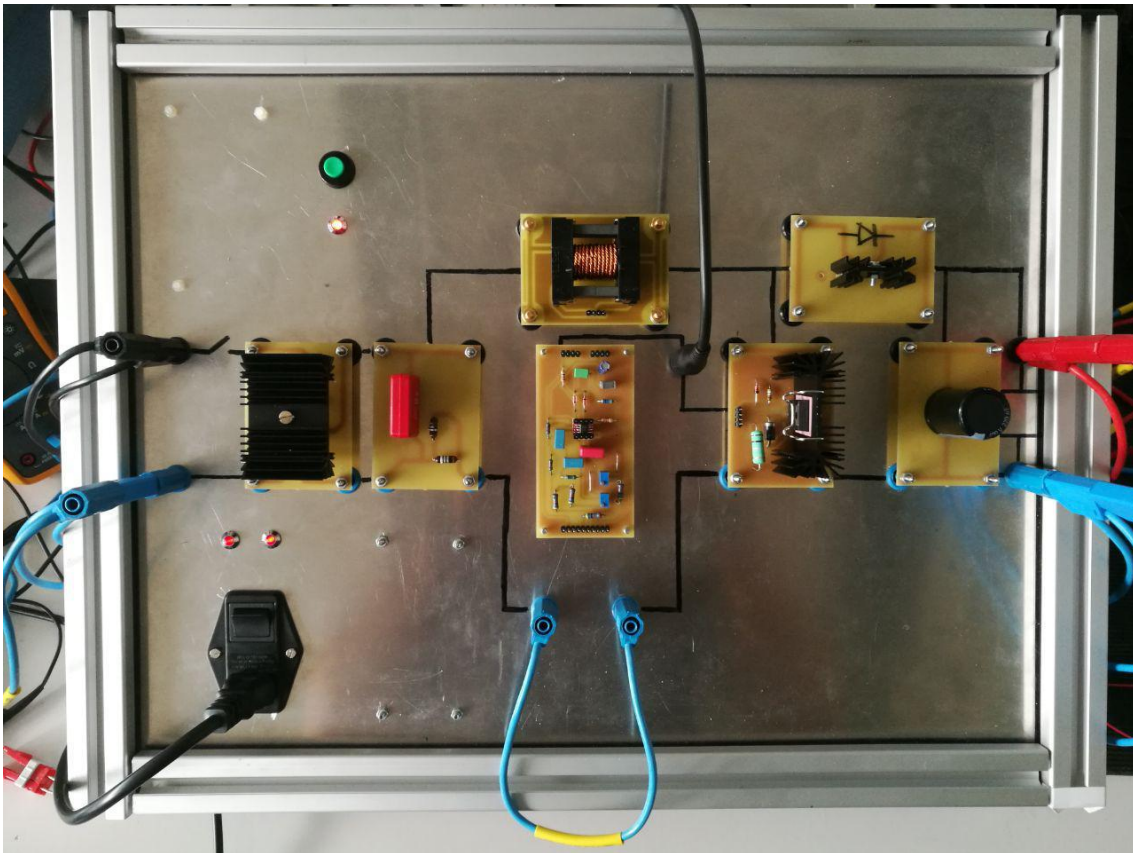
Figure 37. Whole circuit with the components needed for the DCM PFC disposition.

In this case, before starting the design process it was needed to choose an IC for controlling the circuit. After comparing some different models available in the market, the chosen one was the TDA4863-2 from Infineon. Then this chip was added to an order list including other components needed for this project. This part was critical because once the EIT department of the H-DA makes an order, the components last some days to arrive.

4.1.   Design of the DCM control circuit

Before the ordered components arrived, the design process was started. The first step was to create a library package for the TDA4863-2, which is our DCM PFC chip. Checking the information in its datasheet [8], this library package for the IC was created and its final result is as shown in *Figure 38*.
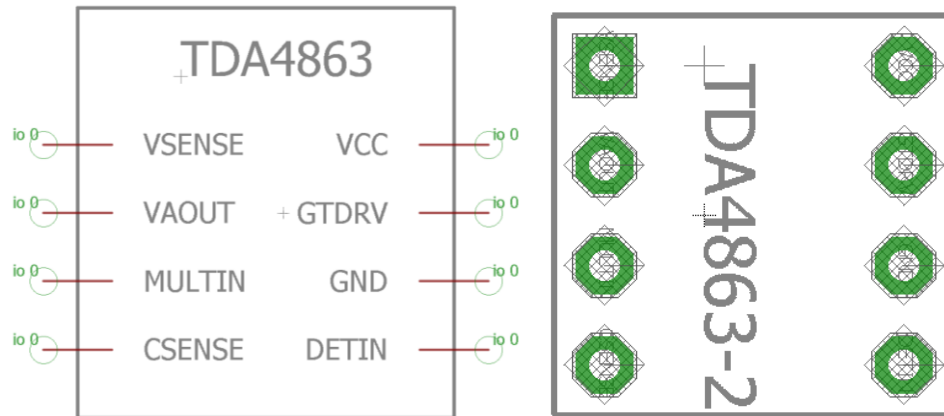
Figure 38. Design of the library package of the TDA4863 (DCM IC).

After that, the Eagle schematic was created, connecting this chip to some components in order to create the circuit for the DCM PFC. Following the example in the IC datasheet [8], the created circuit looks like in *Figure 39*. The reason why those values were chosen, are explained below in this section.
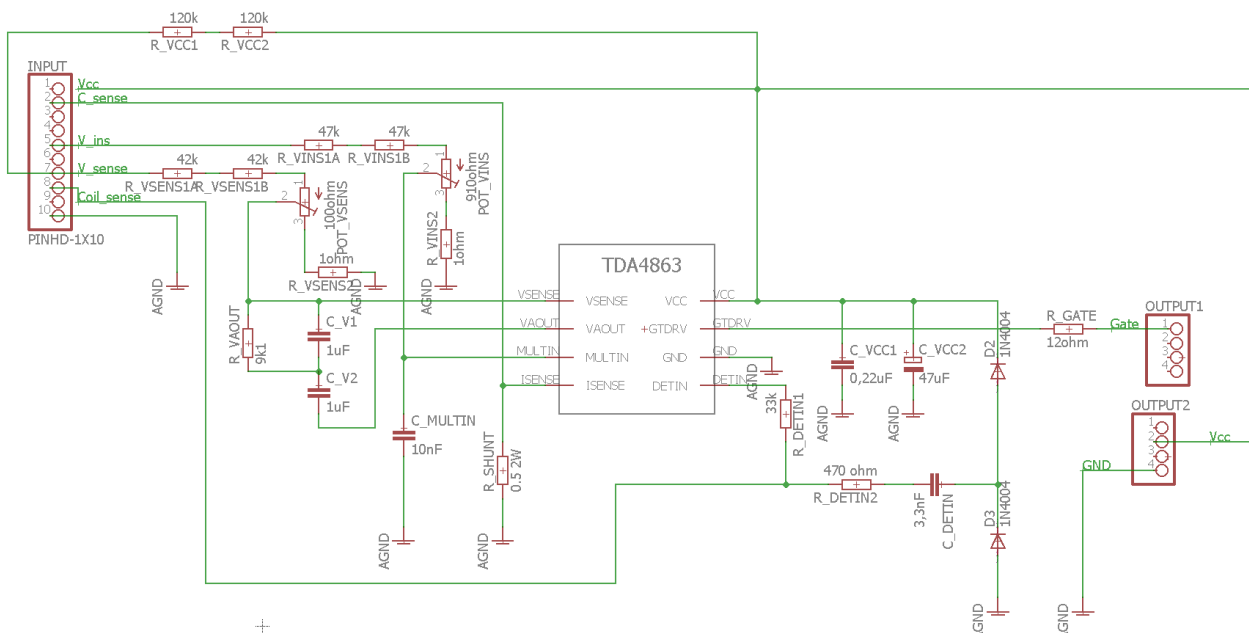
Figure 39. Schematic of the DCM PFC circuit.

To assign the proper values to the components, some calculations are needed. Starting from the datasheet [8], we chose the same values for the capacitors which appear in the example of the datasheet. The main calculations were done for the voltage dividers which are the most critical components in the design of this PCB. *Figure 40* shows the formulas and results for the output voltage divider. In it, we can see that the output voltage must be between 25V and 60V, that means that we need to adapt this level of voltage to the range that the DCM IC admits, which is a range between 0.2V and 2.5V. To achieve it, we need a voltage divider, and in our case, it is formed by 2 resistors and one potentiometer.

$$V_{sense} = \frac{R_{Vsens2}}{R_{Vsens1} + R_{Vsens2}} \cdot V_{out} \rightarrow \frac{R_{Vsens1}}{R_{Vsens2}} = \frac{V_{out}}{V_{sens}} - 1$$

$$if \ V_{out} = 25V \ \rightarrow V_{sense} = 0.2V \ \rightarrow \frac{R_{Vsens1}}{R_{Vsens2}} = 124$$

$$if \ V_{out} = 60V \ \rightarrow V_{sense} = 2.5V \ \rightarrow \frac{R_{Vsens1}}{R_{Vsens2}} = 23$$

$$\Rightarrow choosing \ R_{Vsens1} = 94k\Omega \ \rightarrow R_{Vsens2} \in (750\Omega, 4k\Omega)$$
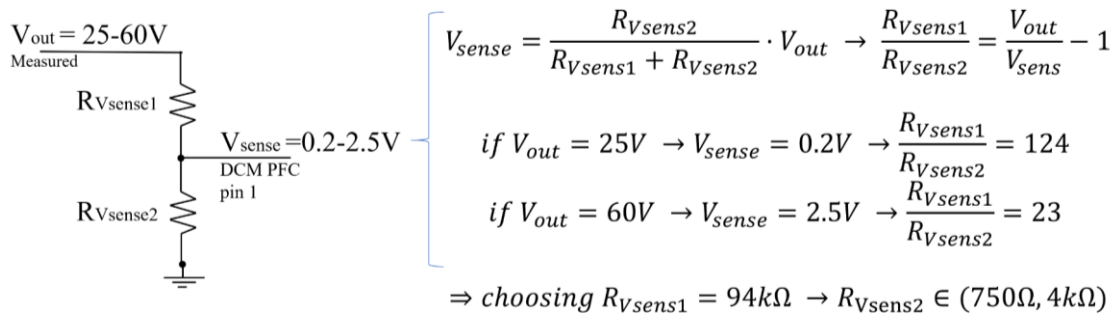
Figure 40. Calculations for the output voltage divider in the DCM circuit.

In these calculations, we can see that the value of the upper resistor is just assigned as 94 kΩ (42 kΩ + 42 kΩ). Once we have this value, the bottom resistor can be calculated and then we obtain a value between 750 Ω and 4 kΩ. That means that the bottom resistor is not needed, adding a potentiometer is enough. And then the potentiometer is set in any value between those two resistances.

The same process is repeated for the input voltage divider. We also choose 42 kΩ for the both upper resistors. And for the bottom resistor, we also use just a potentiometer which is adjusted later during the testing period.

After the calculations of the needed components, it was designed the distribution of these components on a PCB, also by using the software Eagle. Here below, *Figure 41* shows this design after placing the components and routing them. As we can see, the pin connectors of this board are placed in the same position as the ones in the CCM board, 10 pins in the bottom part and 4+4 pins in the upper part. This allows to connect both PFC boards in the same connector on the table.
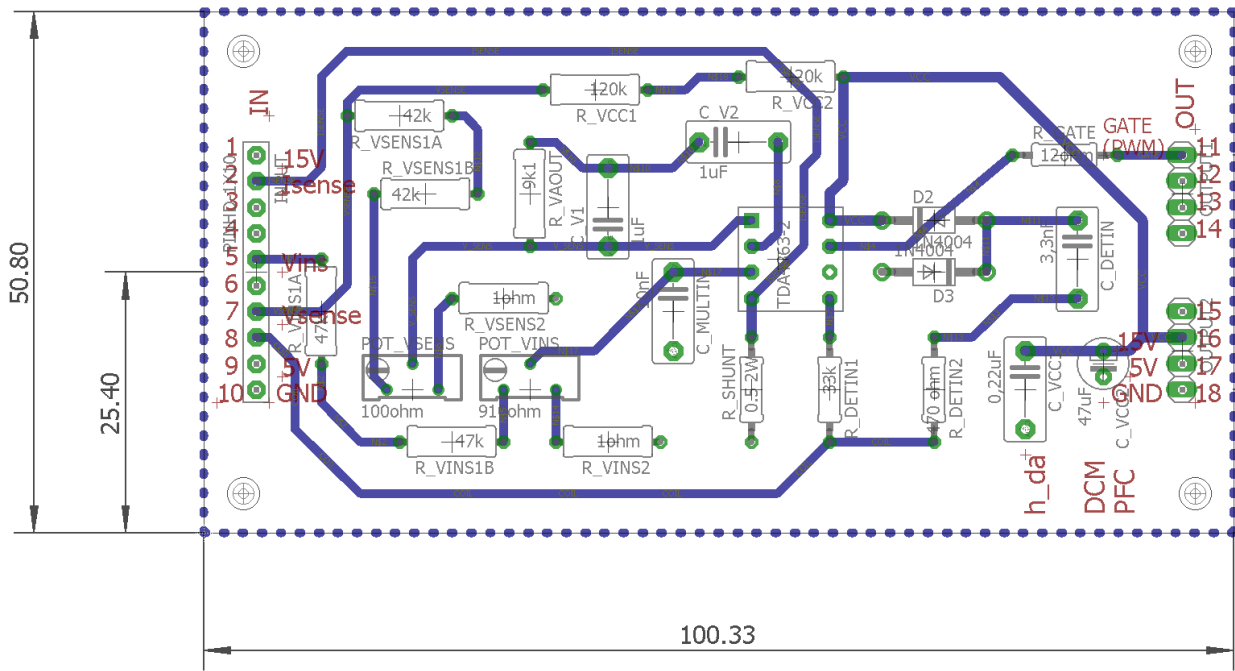
Figure 41. PCB layout of the DCM PFC control circuit.

In this case, it was not created a prototype on a protoboard as in the CCM case. That is due to the lack of time at the end of the project, but it was also because in this case the design was clearer than the first time, so not many changes were needed. Only some resistors were changed from the original design. Well, and obviously the values of the potentiometers also were adjusted afterwards.

Table 7. DCM PFC control circuit parts list		
Description	**Reference Number**	**Quantity**
DCM PFC control IC	Infineon TDA4863-2	1
8-pin adapter for ICs	N/A	1
10-pin connector	N/A	1
4-pin connector	N/A	2
10kΩ Trim Potentiometer	3266 Bourns W103	2
12kΩ Resistor (R_gate)	N/A	1
470Ω Resistor (R_detin2)	N/A	1
8.1kΩ Resistor (R_Vaout)	N/A	1
33kΩ Resistor (R_detin1)	N/A	1
47kΩ Resistor (R_Vins & R_Vsens)	N/A	4
102kΩ Resistor (R_Vcc)	N/A	2
Diode	1N4148	2
3.3nF 63V Capacitor (C_Detin)	WIMA 3300/63U C1	1
0.01µF 100V Capacitor (C_Multin)	WIMA MKS4 0.01/1000- B5	1
0.22µF 100V Capacitor (C_Vcc1)	N/A	1
1µF 63V Capacitor (C_V1&2)	A1µK63	2
47µF 35V Capacitor (C_Vcc2)	SD COE PET	1

The values of most of these components of *Table 5* has been taken from the Infineon TDA4863-2 Datasheet [8], in which we can find an example of a boost converter using

this chip. However, there are some critical components which cannot be fixed, because it is needed to adjust them depending on the input and output voltage. In particular, the critical components are the values of the resistors and potentiometers which are part of the input voltage divider and output voltage divider, because depending on their value, they adjust the desired input and output voltage. The values of this resistors have been calculated before. And as it has been said before, the bottom resistors form the input and output voltage dividers are not needed, so they were replaced by a cable to connect the potentiometers to GND. In *Figure 42*, it appears the final DCM board and these two gray cables can be seen next to the potentiometers replacing the resistors, R_{Vsens2} and R_{Vins2}. On the other hand, in this picture it also can be seen that another resistor is missing, this one is the shunt resistor which should be next to the IC connected to its fourth pin. But finally, it was decided to place the shunt resistor in the transistor board, because it can be burnt if the current id too high, and this way it is easier to replace. This transistor board is better explained in *Section 4.2*.
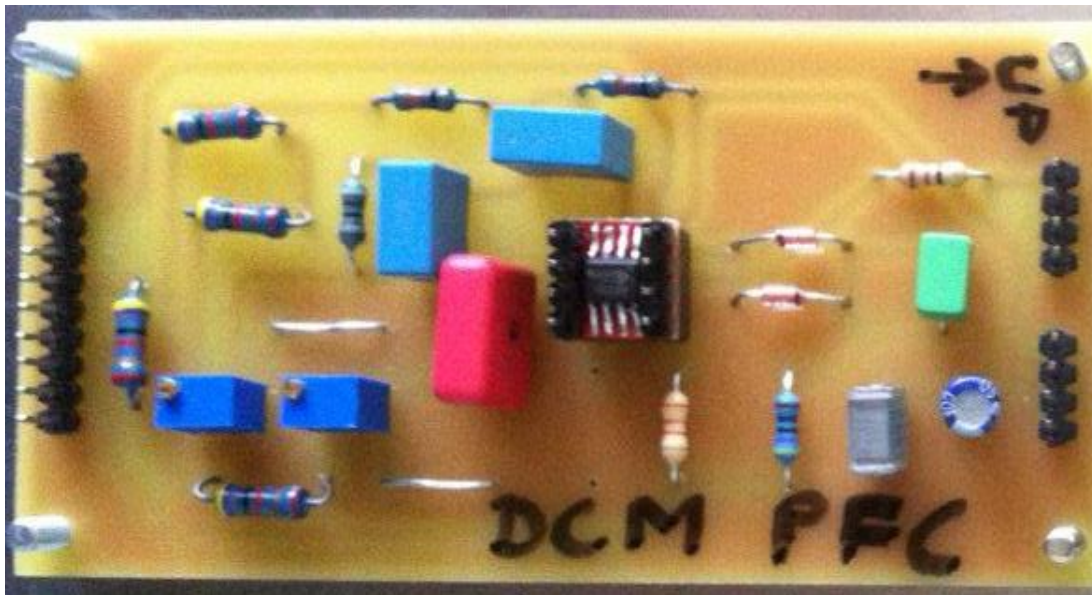
Figure 42. Final DCM PCB with its components soldered.

4.2. Re-design of the transistor circuit for this DCM composition

This board has had to be changed because it was not possible to adapt the previous design made by Eric Tumpa to the DCM circuit. That is due to the fact that the DCM chip needs the measurement of the transistor's source current as input in the IC. So, for that it is needed to add a shunt resistor to the transistor board and to add a connection from the transistor board to the pin 4 of the TDA4863-2 PFC board. That is why the BNC connector of the old design has been replaced by a 4-pin connector, as it can be seen in *Figure 43* comparing both designs.
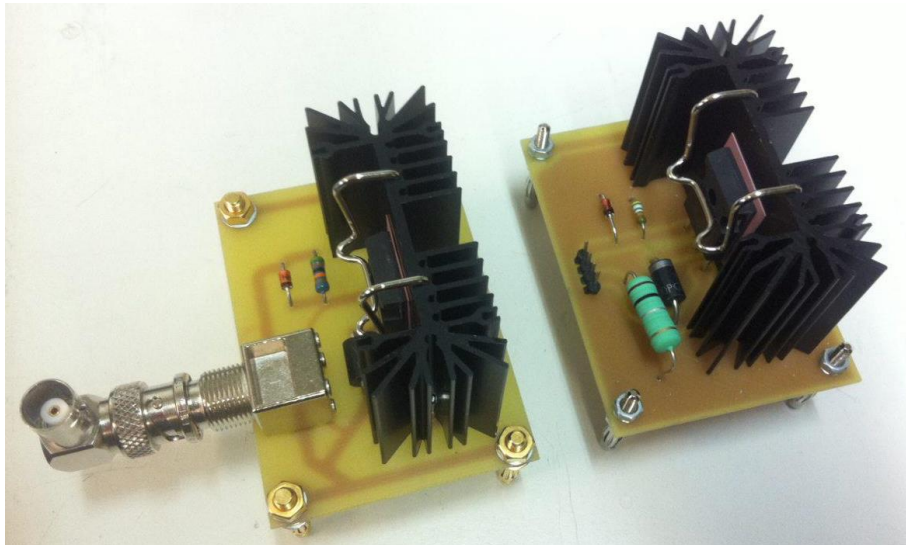
Figure 43. Comparison between the old (left) and the new (right) transistor board.

This new 4-pin connector goes through the table and allows to connect the transistor's gate signal and the shunt resistor's voltage to the PFC circuit under the table. Now that the circuit is connected to the shunt resistor, it can be calculated the current through the transistor's source by comparing the voltage in the shunt resistor, connected to pin 4 of the TDA4863-2 with the internal control voltage for PWM control.

For the design of this board, first, it was needed to create a library package for the heatsink 678-39-C, which is used to dissipate the heat that the transistor generates while switching. Here below in *Figure 44* it can be seen the design of this heatsink library.
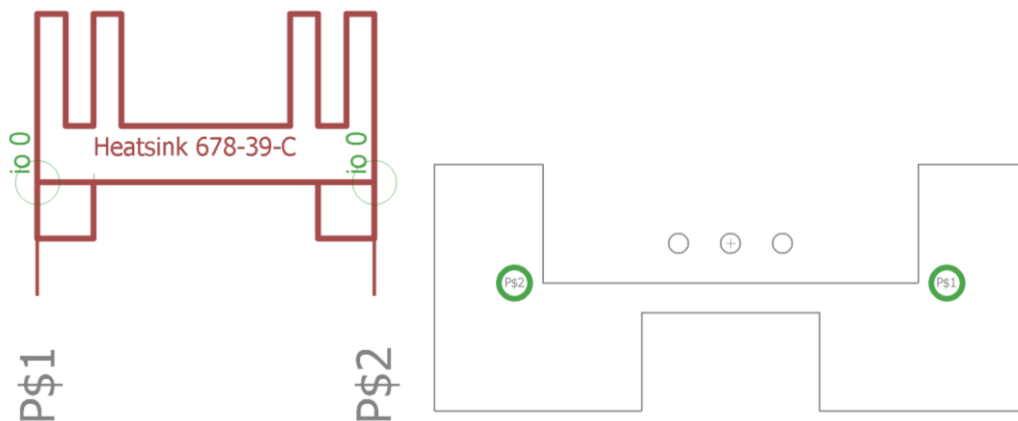
Figure 44. Design of the library package of the heatsink.

Once we have it, the rest of the transistor board is designed. It is not a really difficult circuit, it consists of a MOSFET transistor, the heatsink, the 4-pin connector that has been explained before, the shunt resistor and some components which allow to make a faster switching. Those components are a Zener diode and a resistor connected between the gate

and GND and another diode connected between the drain and the source of the MOSFET. In *Figure 45*, we can see how these components have been distributed on the PCB, and in *Table 6*, it appears the parts list. The critical component is the shunt resistor, because depending on the current, it gets too hot, so we have to use resistors of 2W. And after trying different 2W resistors, for our range of current, from 0 to 6 A, the one with the smaller value of resistance was chosen, 0.1Ω.
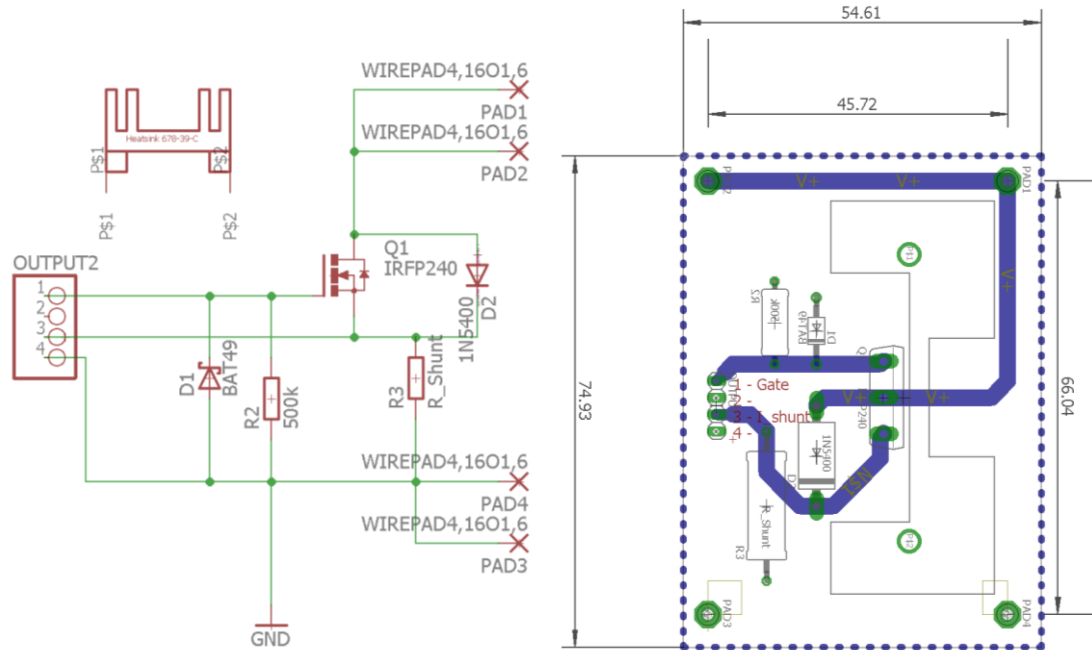
Figure 45. Transistor board schematic and PCB design.

Table 8. DCM transistor board parts list.		
Description	**Reference Number**	**Quantity**
Banana Test Connector	72918	4
Component Board	N/A	1
Heatsink	678-39-C	1
4-pin connector	N/A	1
Thermal Pad for Transistor	SP900S-0.009-00-104	1
MOSFET	IRFP240PBF	1
TVS Diode	1.5KE130CA	1
15V Zener Diode	N/A	1
0.1Ω 2W Shunt resistor	N/A	1
500kΩ Resistor	N/A	1

The best thing of this new design for the transistor board is that it can be use for both CCM and DCM circuits. Because the MOSFET is the same one as in the old design and it has been added only a new connector and a shunt resistor which is not used in the CCM.

4.3. Re-design of the inductor for this DCM composition

In this case, the inductor board has been re-designed because the DCM PFC circuits have a different operation mode and they require a smaller value of the boost inductor than the CCM PFC circuits. Furthermore, for this DCM circuit, it is needed a secondary coil which must be rolled up around the same core than the boost inductor, in order to measure the current through the inductor, and this way detect the zero crossing of the current. In *Figure 46*, it can be seen the differences between the inductor board for the CCM (left) and for the DCM (right). In this new board, a new 4-pin connector has been added to connect the secondary coil to the bottom part of the table and from there to the eighth pin of the DCM board.
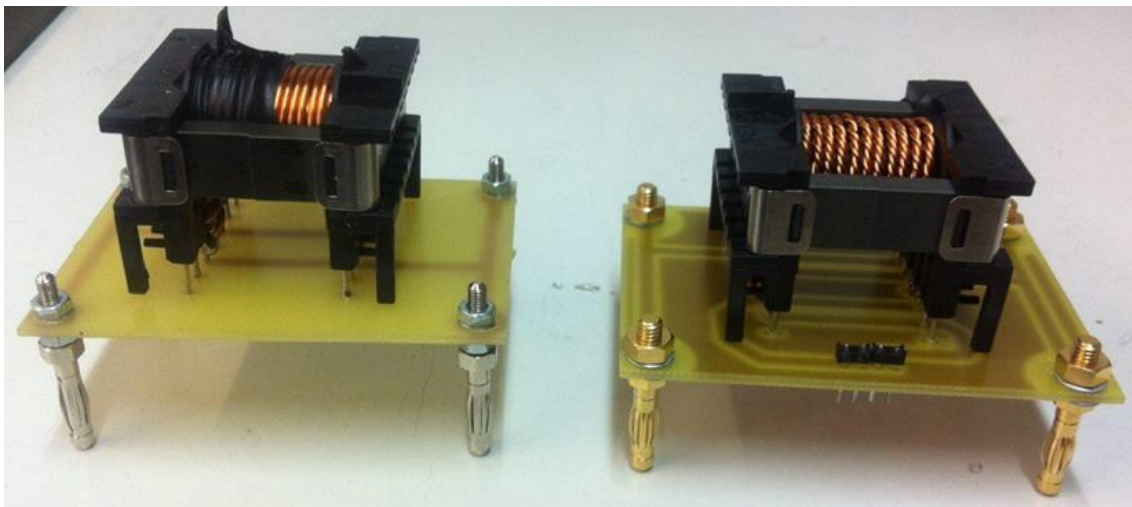
Figure 46. The old CCM (left) and the new DCM (right) inductor board.

For the calculations of this inductance, it has been checked the value that has been used in the example in TDA4863 (DCM chip) datasheet [8]. This value is $L = 750\ \mu H$, and thanks to that and knowing that the input power in the example is $P = 120W$ and the input voltage is $V_{IN} = 205V$, we can calculate the slope of the ripple of the current in the inductor. And as it can be seen in *Figure 47* with this slope, it is calculated the switching frequency that we need for our inductor.

$$\rightarrow P = 120W, \qquad V_{IN} = 205V \rightarrow i = \frac{120}{205} = 0,6A$$

$$\rightarrow L = 750\mu H \rightarrow \pmb{\Delta t} = L\frac{\Delta i}{U} = 4.4\mu s \rightarrow f = \frac{1}{2\Delta t} = 113\ kHz$$
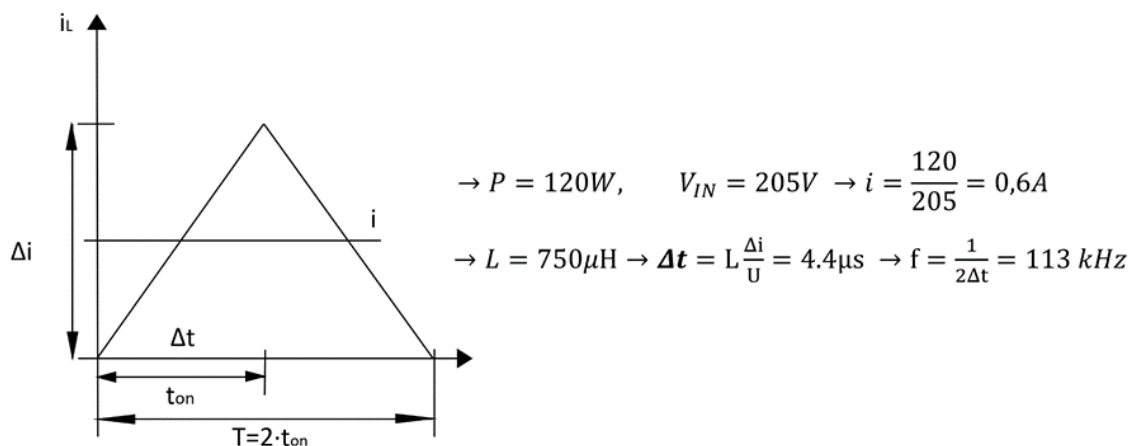
Figure 47. Calculations of the slope of the ripple of the inductor in the DCM IC datasheet example [8].

After we know the slope of the ripple in the example, we can apply this same switching frequency to our case, to calculate the inductance which is needed. The calculations for our circuit are shown here below:

$$\rightarrow P = 120W, \ V_{IN} = 25V \ \rightarrow i = \frac{120}{25} = 5A$$

$$\rightarrow L = U_{L}\frac{\Delta t}{\Delta i} = 25V \cdot \frac{4.4\mu s}{5A} = 11\mu H$$

Then we obtain an inductance of $L = 11\ \mu H$, which is smaller than in the CCM circuit, as we have said before. Once we have the value of the boost inductor, it is needed to build the coil on a coil adapter which is soldered to a PCB.

First, it is needed to know how many windings the cable must have around the coil support. For that, we use an inductor calculator which can be found in the webpage of Schmidt-Walter [9]. In this webpage, as we can see in *Figure 48*, we write as input, the inductance, 11µH, and the max current, 5A. And then, it gives as output, some of the more recommended configurations for the inductor that we need, including the type of core, the number of windings, the diameter of the wire, etc.

Calculation of the inductor

L/H: 11E-6

Input example:
100E-6 for an
inductor L=100µH

I_max/A: 5

Calculate

No.	Core	Ident.	Manufacturer	A_L/nH	A_{in}/mm²	l_{in}/mm	A_{min}/mm²	W_{max}/µWs	B_{max}/mT	N1
1	ETD29	0.2	Siemens	383	76	70	71	592	145	6
2	ETD29	0.5	Siemens	201	76	70	71	1129	105	8
3	ETD29	1.0	Siemens	124	76	70	71	1829	82	10
4	ETD34	0.5	Siemens	251	97	79	92	1504	91	7
5	ETD34	1.0	Siemens	153	97	79	92	2468	71	9
6	ETD39	0.5	Siemens	326	125	92	123	2088	77	6
7	ETD39	1.0	Siemens	196	125	92	123	3473	60	8
8	ETD44	0.5	Siemens	438	173	103	172	3039	64	6
9	ETD44	1.0	Siemens	262	173	103	172	5081	49	7
10	ETD44	1.5	Siemens	194	173	103	172	6862	42	8
11	ETD49	0.5	Siemens	525	211	114	209	3744	57	5
12	ETD49	1.0	Siemens	314	211	114	209	6260	44	6
13	ETD49	2.0	Siemens	188	211	114	209	10456	34	8
14	ETD54	1.0	Siemens	393	280	127	280	8977	37	6
15	ETD54	1.5	Siemens	287	280	127	280	12293	32	7
16	ETD54	2.0	Siemens	229	280	127	280	15406	28	7

L=11µH

The core is...
very good
good
suitable
too small

Help

Print

Wire dimensions:

d ≥ 1.46 mm
A ≥ 1.67 mm²

Figure 48. Results of the calculation of the inductor in schmidt-walter.de web [9].

As *Figure 48* shows, the recommended values for our inductor are: *N1=9* windings*, gap=1mm, ETD34* core and a wire diameter *d=1.46mm*. But finally, it was not possible to find that diameter of cable, so it has been made a wire of around 1.3mm with 4 braided cables.

And for the calculation of the number of windings of the secondary coil, it has been extrapolated also from the example in the DCM chip datasheet [8]. So, taking the same proportion, if the primary coil of the boost inductor has 9 windings, then the secondary coil should have 2 windings.

Once we have built both coils around the coil support, for finishing the inductor board, we just need the PCB. And for the design of this board, the first step is to create a library for the coil support or adapter. In *Figure 49*, it appears this design of the library package for the inductor support. In the left part is the symbol of the component and in the right part is the footprint of it. As we can see, the element has 14 holes, but in our case we only have used four of them, because two coils are been used and they need two connections each.
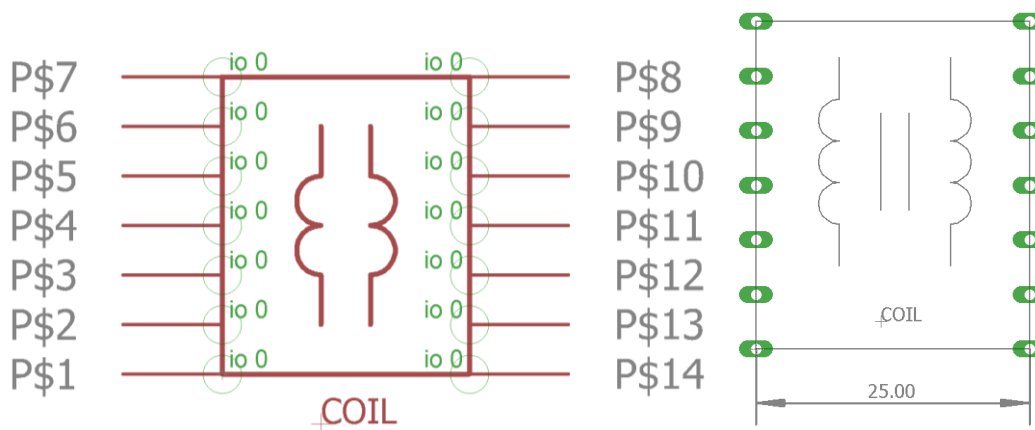
Figure 49. Design of the library package of the inductor.

After that, the inductor board was redesigned, as *Figure 50* shows, including the footprint of the library which has been created, four banana jack connectors for the primary coil and another 4-pin connector for the secondary coil. In *Table 7*, they appear all the components which have been used for this board.
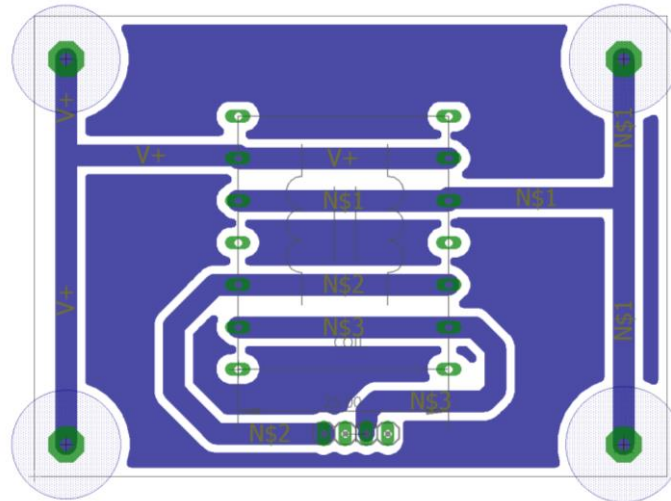
Figure 50. PCB design for the new coil board.

Table 9. DCM inductor board parts list.		
Description	**Reference Number**	**Quantity**
Banana Test Connector	72918	4
Component Board	N/A	1
4-pin connector	N/A	1
Coil Adapter	N/A	1
Copper wire d=0.63mm	N/A	2 m
Coil Core ETD34/17/11	B66361	1

4.4. Test and results of the DCM circuit

In this section, it is explained how the whole circuit behaves after connecting the DCM control board, the new transistor board and the new inductor board. The rest of the connections remain as same as they were connected in the CCM configuration, i.e., the input connected to the transformer with a voltage of 25V and the oscilloscope measuring the same waveforms as in the previous section. Here below the colors of each wave are explained:

- Pink: output voltage.
- Yellow: input voltage after the rectifier.
- Blue: current.
- Green: gate PWM wave.

Once the input is set to 25V, if the output potentiometer is set in its maximum resistance value, the current will be in its minimum value. But in this case, the output voltage does not reach 50VDC, as it can be seen in *Figure 51*. That is because in the DCM operation mode, it has not been possible to set the output voltage constant in 50VDC it changes between around 42VDC and 56VDC, depending whether the load resistance is high (*Figure 51*) or low (*Figure 52*). But this thing happens because the input transformer is producing some noise, so the input voltage is not as smooth as it should be, and it can be seen in the yellow wave. And when the load changes the input voltage also changes, and it should not, that is why the output voltage varies too.
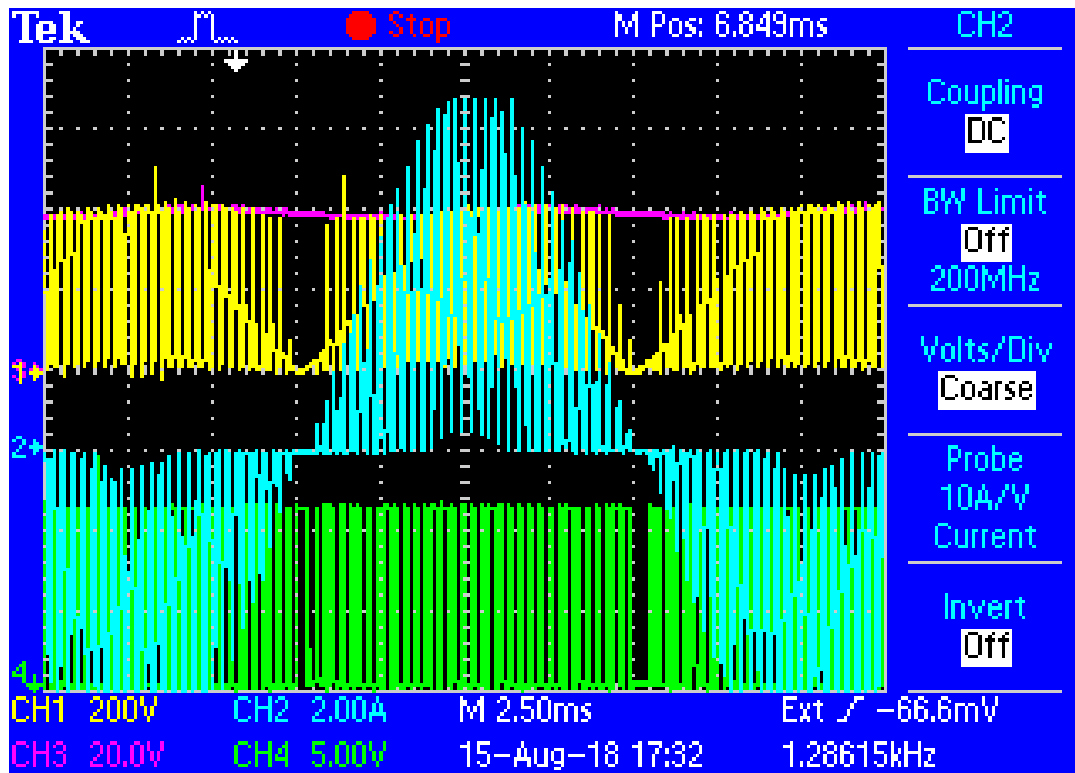
Figure 51. Oscilloscope showing waves of DCM with high resistance load.
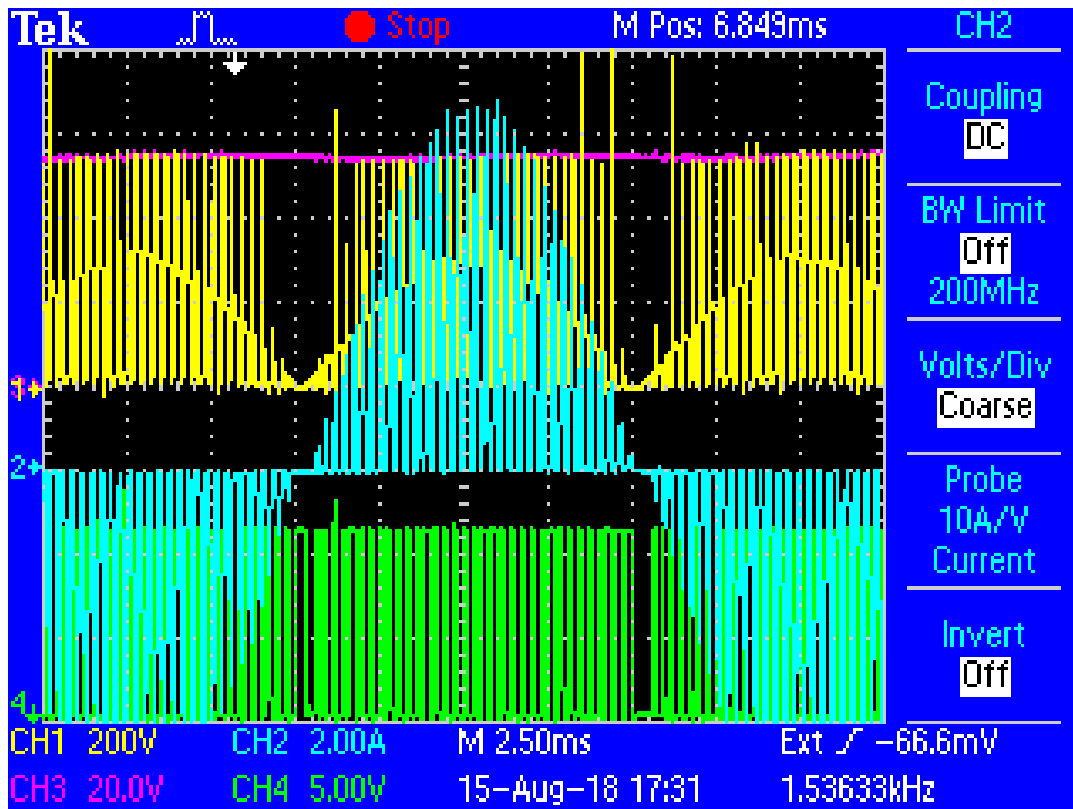
Figure 52. Oscilloscope showing waves of DCM with low resistance load.

We also can see in these oscilloscope images that the output voltage (pink) is quite flat as in the CCM case, but not as constant as before. However, now the current has a perfect sinusoidal waveform, but we can see that the current goes up while the transistor is OFF and then when it switches the current goes down until zero and it stays in zero until the next period of the PWM wave. And it is the expected behavior of the general case of a DCM PFC, so that means that our circuit is working fine. And in *Figure 53*, we can see it more in detail. In this image we also can see that the switching period of gate is 250 μs. So, the switching frequency must be $f = \frac{1}{T} = \frac{1}{250 \mu s} = 4 \ kHz$.

This switching frequency stays constant, it doesn't matter if the load value changes. However, if we compare this obtained frequency of 4 kHz, it can be seen that it is quite lower than the 66.6 kHz of the CCM PFC calculated in the previous section. This low frequency will lead in some noise problems with the input transformer, and they are explained below when the results are analyzed in the Yokogawa power analyzer.
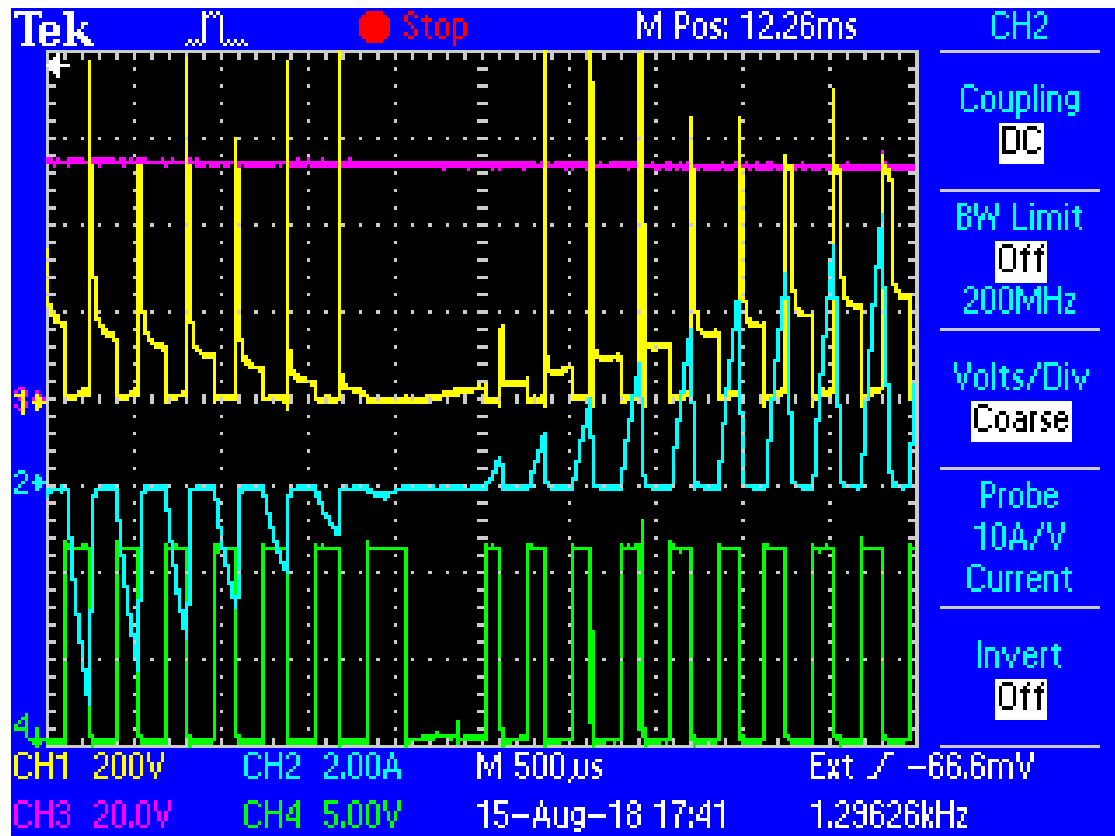
Figure 53. Oscilloscope showing a zoom of the signals of the DCM PFC circuit.

After analyzing the oscilloscope results, in the Yokogawa screenshots we can see how influence of this low frequency is affecting the power factor and we also can see the effect of the variation of the load, as we checked in the previous section in the CCM operation mode.

First, we can see that the input voltage is set in 25 V. In *Figure 54*, the Yokogawa shows that the power factor is around 0.54 while the potentiometer is placed in its maximum value of resistance. And in *Figure 56*, the load resistance is decreased, but in this case the power factor, does not improves a lot, now is 0.6. So, it looks like that our circuit is not correcting the power factor. However, the output voltage changes between 55.9V (high resistance load) and 45.2V (low resistance load), but it should not change that much, as we have seen before in the oscilloscope images.

Nevertheless, if a 500Hz line filter is added in the Yokogawa configurations, the results change. Now due to the filter, the measured input voltage is around 19V, and the power factor has improved a lot. It is 0.998 in the case with high resistance load (*Figure 55*) and it is 0.994 in the case with low resistance load (*Figure 57*). That means that our circuit is working and correcting the power factor, but it should be needed a filter between the input transformer and the full bridge rectifier, to avoid the noise in the trafo caused by the low operation frequencies. However, despite of this filter, the output power is still varying between 55.7V and 54.2V.

```
Normal Mode        Uover:■ ■ ■   Scaling:■  LineFilt:■  NULL:■    YOKOGAWA ◆
                   Iover:■ ■ ■   Average:■  FreqFilt:■  CF:3
⊕ + SET : change items
                                                        PAGE  ___Element1___
  Urms1    25.317  v    Urms2    55.905  v              ▲    U1    30V
                                                        1    I1     5A
  Irms1    2.8455  A    Irms2    0.4076  A              2    ___Element2___
                                                             U2    60V
  P1       30.12   W    P2       22.79   W              3    I2     5A
                                                        4    ___Element3___
  S1       55.05   VA   S2       25.31   VA             5    U3   300V
                                                             I3     5A
  Q1       46.08   var  Q2       11.01   var            6
                                                        7
  λ1       0.5471       λ2       0.9004                 8
                                                        9
  φ1       G56.83  °    φ2       G25.79  °              ▼    __Integ:Reset__
                                                             Time
  fU1      49.989  Hz   η1       75.668  %                   ----:--:--

Update    30( 1sec)                              2018/08/15 13:23:24
```

Figure 54. Yokogawa with no filter showing results of DCM with high resistance load.

```
Normal Mode        Uover:■ ■ ■   Scaling:■  LineFilt:▓  NULL:■    YOKOGAWA ◆
                   Iover:■ ■ ■   Average:■  FreqFilt:▓  CF:3
⊕ + SET : change items
                                                        PAGE  ___Element1___
  Urms1    19.421  v    Urms2    55.768  v              ▲    U1    30V
                                                        1    I1     5A
  Irms1    1.9752  A    Irms2    0.4065  A              2    ___Element2___
                                                             U2    60V
  P1       38.15   W    P2       22.67   W              3    I2     5A
                                                        4    ___Element3___
  S1       38.22   VA   S2       25.18   VA             5    U3   300V
                                                             I3     5A
  Q1       2.36    var  Q2       10.95   var            6
                                                        7
  λ1       0.9981       λ2       0.9004                 8
                                                        9
  φ1       G3.54   °    φ2       G25.79  °              ▼    __Integ:Reset__
                                                             Time
  fU1      49.995  Hz   η1       59.427  %                   ----:--:--

Update    10( 1sec)                              2018/08/15 13:23:46
```
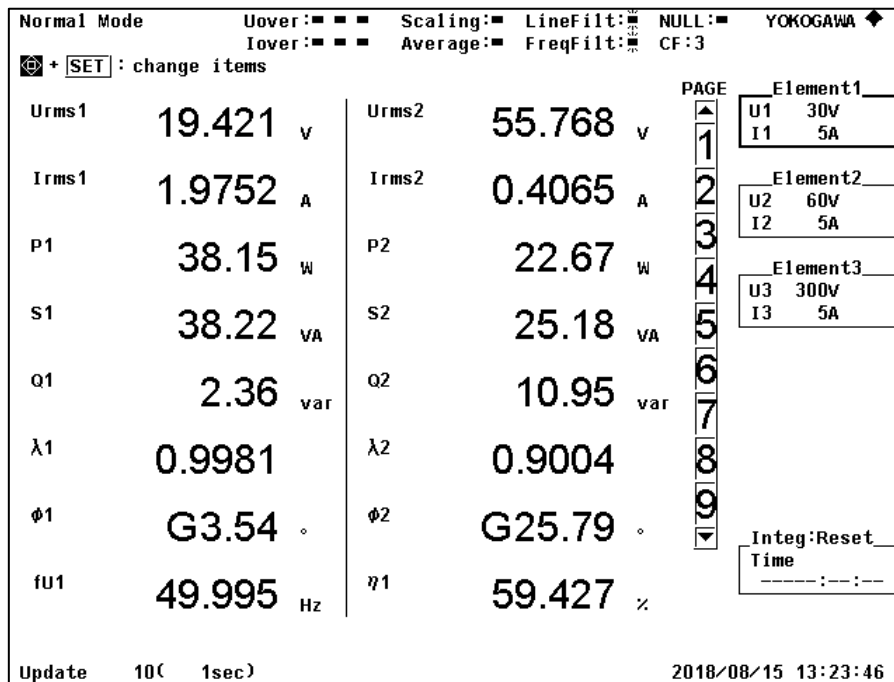
Figure 55. Yokogawa with 500Hz line filter showing results of DCM with high resistance load.

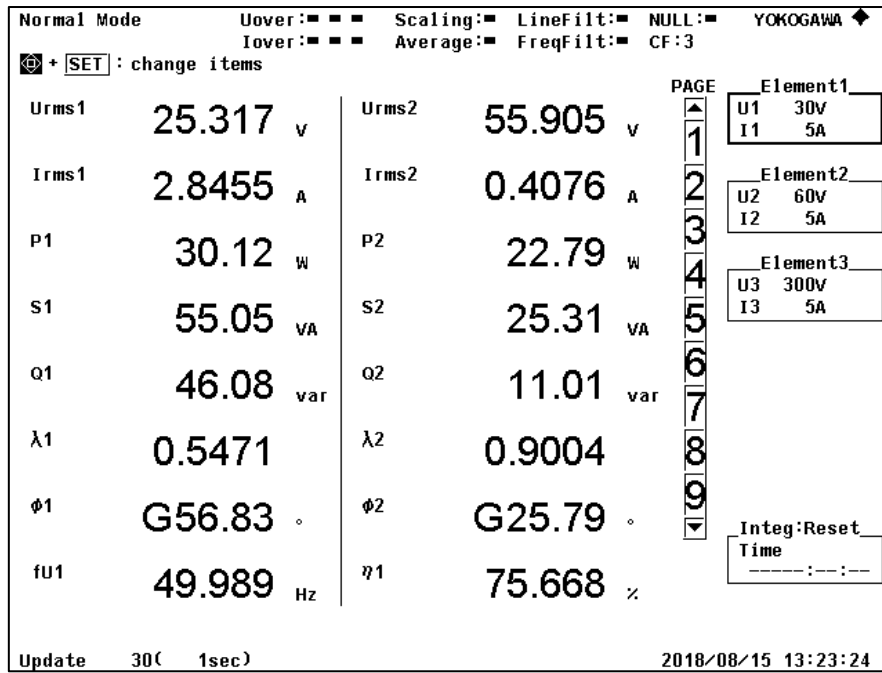*Figure 56. Yokogawa with no filter showing results of DCM with low resistance load.*

Figure 57. Yokogawa with 500Hz line filter showing results of DCM with low resistance load.
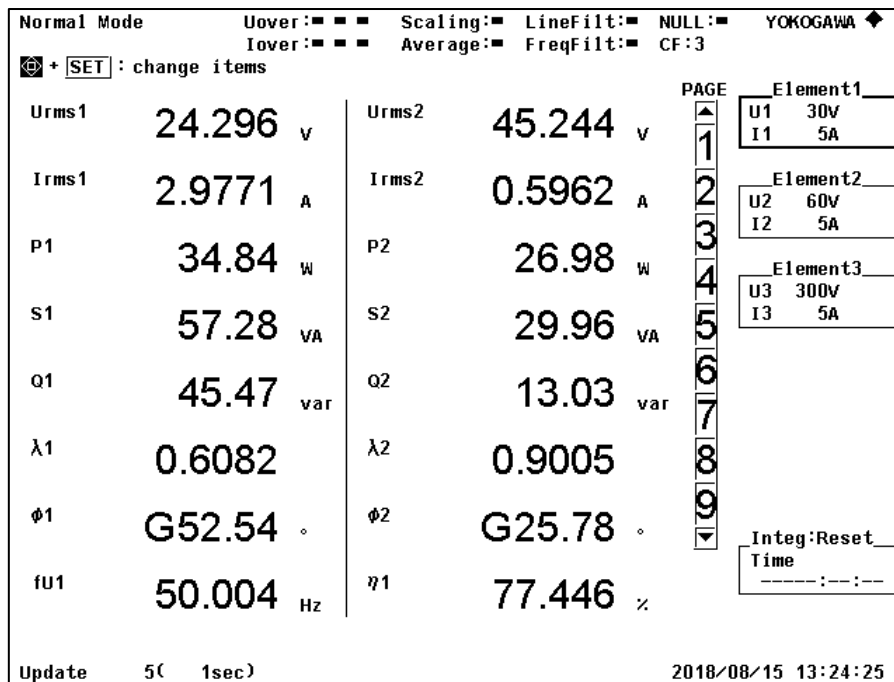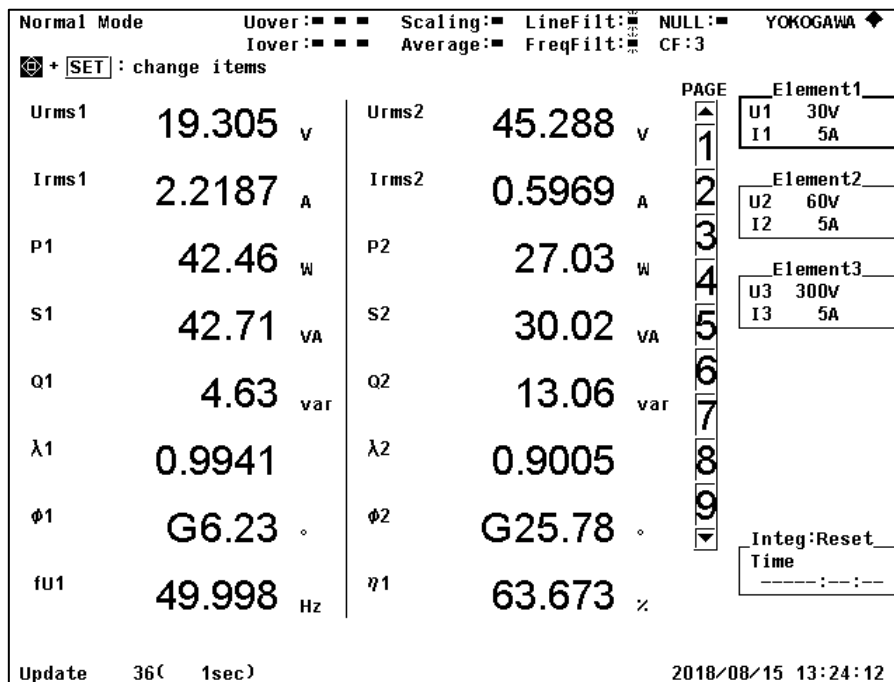
In conclusion, the noise in the input transformer seems to cause harmonic distortion, leading to a low power factor. The TDA4863-2 IC is capable of nearly 100% power factor correction but cannot correct for total harmonic distortion.

4.5. Comparison with theoretical values of the DCM circuit

In order to try to improve the efficiency, the power factor and the operation of the circuit, it is needed to check if the values for the components which have been used can be changed. Those values have been compared with the theoretical values obtained in an excel file [10]. First in *Table 10* and *Table 11*, they appear the specifications introduced into the spreadsheet (in the yellow cells) and the results of the calculations for the needed components (in the light green cells). Then we can check that, the values of some components are not similar, comparing the calculated ones and the chosen ones. But the initial components that were chosen were calculated before, without using this spreadsheet, so that is why they differ. However, there are some components such as the inductor having same core and same number of turns.

Tabla 10. Results for the input and output components for the DCM PFC calculated in the excel file [10].			
Input section		Unit	
Lowest AC input voltage (RMS-value)	V_{inmin}	V	20
Highest AC input voltage (RMS-value)	V_{inmax}	V	30
Rated output power	P_{out}	W	25
Estimated efficiency	eta		0,80
Minimum pulse frequency	f_p	kHz	5
Input power	P_{in}	W	31,3
Lowest peak input voltage	V_{inpmin}	V	28
Highest peak input voltage	V_{inpmax}	V	42
Maximum input peak current of RMS-value	I_{inpmax}	A	2,21
Maximum input peak inductor current	$I_{inpmaxHF}$	A	4,42
Shunt resistor recommended	R11	Ohm	0,23
Shunt resistor selected	R11	Ohm	**0,1**
Output section			
Internal reference voltage	V_{ref}	V	2,50
Nominal output voltage	V_{bus}	V	50
Overvoltage threshold	V_{OV}	V	60
Minimum Busvoltage During operation	V_{busmin}	V	40
Maximum Holdup-Time	T_{holdup}	ms	20
Controller current at pin VAOUT @ Overvoltage	I_{VAOUT}	µA	40
Output voltage divider lower resistor	R5	Ohm	13158
Select output voltage divider lower resistor (1% tolerance)	R5	Ohm	1070
Output voltage divider upper resistor	R4	Ohm	24196
Select single value output voltage divider upper resistor (1%)	R4	Ohm	100000
Effective Value for output voltage divider upper resistor			200000
Real Bus voltage	V_{bus}	V	469,8
Real Overvoltage shut down level	V_{OV}	V	477,8
Output capacitor for given Holdup-time	C8	µF	23,3
Output capacitor selected	C8	µF	**220**

Tabla 11. Results for the other components for the DCM calculated in the excel file [10].			
Multiplier section			
Multiplier input M1 dynamic range	V_{m1R}	V	4,00
Multiplier input M2 dynamic range	V_{m2R}	V	1,50
$V_{m1} = V_{m1lim} = 1,2$ V @ $V_{inpmin} =$			28,28
Select upper resistor of input voltage divider	R6	Ohm	100000
Two of them in Series	R6serial	Ohm	200000
Input voltage divider lower resistor	R7	Ohm	8861
Select voltage divider lower resistor	R7	Ohm	1000
TEST: Input range $V_{m1}(V_{in} = V_{inpmax}) < V_{m1R} = 4,0$ V ?			OK
	$V_{m1Vinpkmax}$		0,21
	$V_{m1Vinpkmin}$		0,14
Inductor section			
Inductor	L_P	µH	436
Select Ferrite Core Type	ETD34/17/11-N67		
Cross section of selected core	A_{min}	mm²	91,60
Required inductance factor of selected inductance factor	A_L	nH	157,56
K1 factor	K1	nH	153,00
K2 factor	K2		-0,713
Required air gap for selected core	s	mm	0,96
Select air gap	s	mm	1
Resulting A_L-value for selected core and air gap	A_L	nH	153,00
Number of turns	N_cal		53,40
Selected number of turns	N_1		9
Effective inductance	L_P	µH	12,39
Effective primary current saturation limit	I_{sat}	A	33,26
TEST: I_sat > I_inpmaxHF			OK
Min. Number of turns for Detector winding	N_DET		1,8
Selected number of turns for Detector wiring	N_2		2

5. Conclusions

5.1. Project conclusions and future works and circuits.

The main goal of the project, which was finishing the set-up for PFC testing, has been reached successfully. This set-up will be helpful for future students of the power electronics lab in the h_da, because they will be able to understand and test the operation of boost converters and its different types of control techniques por the power factor correction. Since DC-DC converters and switch mode power supplies are becoming more popular used in the industry, it is very important for the students to understand how they work. And in this case, having a modular design, it will be more didactic for students.

Regarding to the power factor correction and the efficiency, in the case of the CCM PFC control circuit, both are quite good however, in the DCM PFC control circuit, the power factor is not really high, due to the noise in the AC power supply which seems to cause harmonic distortion. However, it can be solved adding an RF-Filter in the input, after the AC power supply.

If we look at *Table 12*, we can see the results of this project. In the case of the CCM the input and output voltage are really constant independently of the value of the load, as it was required in the specifications. Nevertheless, the same thing does not occur for the DCM, in this circuit, the input voltage varies significantly between 21V and 19V when the load changes. And as a consequence, the output voltage also varies, and the current is mostly constant, but it should be the other way around.

Table 12. Comparison between results of the project.				
Circuit:	Specifications	CCM (no filter)	DCM (no filter)	DCM (500Hz filter)
Input Voltage	25V	23V-26V	21V-29V	21V-29V
Output Voltage	50V	49V-51V	46V-54V	46V-54V
Power Factor	0.9	0.962	0.633	0.993
Efficiency	0.8	0.85	0.81	0.73
Switching frequency	-	66kHz	4kHz	4kHz

As it has been said, the DCM problems are due to the noise caused by the input transformer and due to the low switching frequency of the transistor. That happens because the impedance of the transformer of the input power supply has not been taken in account in the calculations, and the value of the inductor used for the DCM boost converter is really low, just 11μH. So, the inductance of the transformer can be affecting to this other one.

5.2.   Future Works

So, with all this work done, the future tasks will be to improve the DCM PFC adding an RF-filter between the transformer and the input to the bridge rectifier or maybe changing some components such as the boost inductor to try to increase the switching frequency. This way the impact of the harmonic distortion in the DCM PFC can be minimized, obtaining a higher power factor.

Another problem that can be fixed in the future is the voltage range in the safety circuit. This circuit was designed for being an overvoltage protection that opens the circuit when the output voltage is 73VDC. That maximum value for the output voltage should be decreased to 60VDC, because this is the limit from which the user does not need to use protective equipment, in accordance with the regulations.
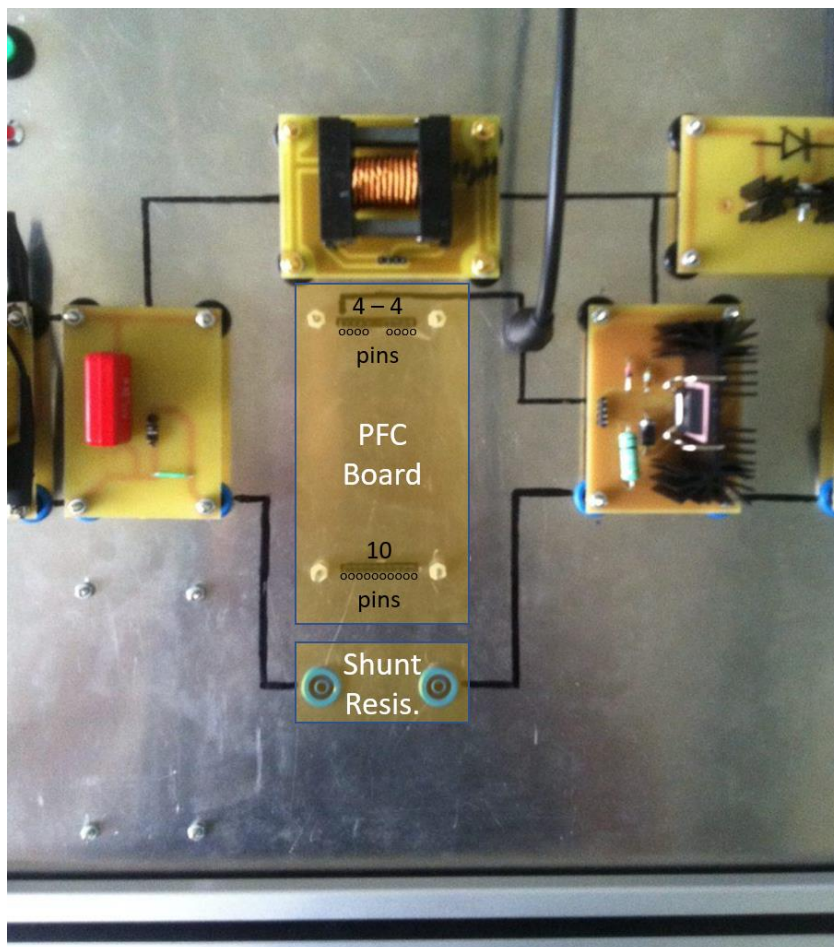

Figure 58. Detail of the shunt resistor connector and PFC connectors.

On the other hand, as future work, it also can be done the new design and develop the third PFC control circuit, the CrCM. It should have the same size as the CCM and DCM boards with the same kind of connections to be able to plug it in the same connector which is shown in *Figure 58*. This kind of circuit also needs to measure the zero-crossing of the current, so it could use the same design of inductor used in the DCM circuit, but probably it will be needed to design a new one because the values of inductance will be different.

Also, as alternative, it could be added a shunt resistor as a second method of measuring the current. It just will be needed to design a board with a resistor and two banana test connectors, because the holes for connecting these banana connectors are already made in the table, as it can be seen in *Figure 58*.

5.3. Personal conclusions

The main conclusion reached at this point of the development of the project is that it was much harder than it seemed at the beginning. It has required much more time and effort than it was planned at first. But at the same time, it has been really enriching, because it has allowed me to improve some skills and knowledges in which I wasn't really good, such as: soldering, boost converters and power factor correction. And I also have really enjoyed the design part of the project because Eagle, was a software that I already knew how to use.

But I think that the most important thing learned during the development of this thesis is the capacity of facing problems and finding solutions to them. Because when a project is being developed, problems always appear, and it is critical the time which is spent on it to solve it. In this particular case, I have seen an evolution comparing the time needed to solve a problem at the beginning and at the end of the project, and that reflects the learning process.

6.   References

[1] Eric Tumpa, "**Power Factor Correction Test Setup**", Master thesis, Hochschule Darmstadt, 2018.

[2] S. Abdel-Rahman, F. Stückler and K. Siu, "**PFC boost converter design guide**" Application Note, INFINEON, 2014. [Online]. Available: https://www.infineon.com/dgdl/Infineon-ApplicationNote_PFCCCMBoostConverterDesignGuide-AN-v02_00-EN.pdf?fileId=5546d4624a56eed8014a62c75a923b05 [Accessed: 06- Aug- 2018].

[3] ON Semiconductor. "**Switch-Mode Power Supply Reference Manual**", onsemi.com, 2014. [online] Available at: https://www.onsemi.com/pub/Collateral/SMPSRM-D.PDF [Accessed 06 Aug. 2018].

[4] ON Semiconductor. "**Power Factor Correction (PFC) Handbook**", onsemi.com, 2014. [Online] Available at: http://www.onsemi.com/pub/Collateral/HBD853-D.PDF [Accessed 06 Aug. 2018].

[5] LEM, "**CAS / CASR / CKSR series Current Transducers Datasheet**", Lem.com, 2018. [Online]. Available: https://www.lem.com/sites/default/files/marketing/lem%20leaflet%20cas%20casr%20cksr.pdf. [Accessed: 06- Aug- 2018].

[6] Texas Instrument, "**8-Pin Continuous Conduction Mode (CCM) PFC Controller UCC28019**", Ti.com, 2007. [Online]. Available: http://www.ti.com/lit/ds/slus755b/slus755b.pdf. [Accessed: 06- Aug- 2018].

[7] Texas Instrument, "**CCM PDF UCC28019 Calculation Tool Excel**", Ti.com, 2018. [Online]. Available: http://www.ti.com/general/docs/lit/getliterature.tsp?baseLiteratureNumber=sluc117&fileType=zip. [Accessed: 07- Aug- 2018].

[8] Infineon, "**PFC-DCM IC Boost Controller TDA4863-2G Datasheet**", Infineon.com, 2005. [Online]. Available: https://www.infineon.com/dgdl/Infineon-TDA4863_2-DS-v02_01-en.pdf?fileId=db3a304412b407950112b41802de24ab. [Accessed: 06- Aug- 2018].

[9]H. Schmist-Walter, H. Wenzel, T. Zänker, R. Morgan and J. Kegan, "**Inductor calculation**", Schmidt-walter-schaltnetzteile.de, 2015. [Online]. Available: http://schmidt-walter-schaltnetzteile.de/smps_e/l_smps_in_e.html. [Accessed: 23- Jul- 2018].

[10] Infineon, "**DCM PDF TDA4863-2G Calculation Tool Excel**", Infineon.com, 2005. [Online]. Available: https://www.infineon.com/dgdl/DT_TDA4863G-2_PFC_Calculation.xls?fileId=db3a304412b407950112b417fae42496. [Accessed: 07- Aug- 2018].