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Treball fi de grau

Grau en Enginyeria Electrònica Industrial i Automàtica

Functional Verification of Power Electronic Systems

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Abstract

This project is the final work of the degree in Industrial Electronics and Automatic Engineering. It has global concepts of electronics but it focuses in power electronic systems.

There is a need for reliable testing systems to ensure the good functionality of power electronic systems. The constant evolution of this products requires the development of new testing techniques. This project aims to develop a new testing system to accomplish the functional verification of a new power electronic system manufactured on a company that is in the power electronic sector . This test system consists on two test bed platforms, one to test the control part of the systems and the other one to test their functionality. A software to perform the test is also designed. Finally, the testing protocol is presented.

This design is validated and then implemented on a buck converter and an inverter that are manufactured at the company. The results show that the test system is reliable and is capable of testing the functional verification of the two power electronic system successfully.

In summary, this design can be introduced in the power electronic production process to test the two products ensuring their reliability in the market.

Resum

Aquest projecte és el treball final del grau en Enginyeria Electrònica Industrial i Automàtica. Té conceptes globals d'electrònica, però es centra en sistemes d'electrònica de potència.

Es necessiten sistemes de testeig fiables per a garantir la bona funcionalitat dels sistemes electrònics de potència. L'evolució constant d'aquests productes requereix el desenvolupament de noves tècniques de testeig. Aquest projecte apunta a desenvolupar un nou sistema de testeig per a aconseguir la verificació funcional d'un nou sistema electrònic de potència fabricat en una empresa que treballa en el sector de l'electrònica de potència. Aquest sistema de testeig consta de dos bancs de proves, una per a provar la part de control dels sistemes i l'altra per a provar la seva funcionalitat. També es dissenya un *software* per a realitzar els testeigs. Finalment, es presenta el protocol de testeig.

Aquest disseny es valida i després s'implementa en un convertidor reductor (buck) i un ondulador (inverter) que es fabriquen en l'empresa. Els resultats mostren que el sistema de testeig és fiable i és capaç de provar amb èxit la verificació funcional dels dos sistemes electrònics de potència.

Resumen

Este proyecto es el trabajo final del grado en Ingeniería Electrónica Industrial i Automática. Tiene conceptos globales de electrónica, pero se centra en sistemas de electrónica de potencia.

Se necesitan sistemas de testeo fiables para garantizar la buena funcionalidad de los sistemas electrónicos de potencia. La evolución constante de estos productos requiere el desarrollo de nuevas técnicas de testeo. Este proyecto apunta a desarrollar un nuevo sistema de testeo para lograr la verificación funcional de un nuevo sistema electrónico de potencia fabricado en una empresa que trabaja en el sector de la electrónica de potencia. Este sistema de testeo consta de dos bancos de pruebas, una para probar la parte de control de los sistemas y la otra para probar su funcionalidad. También se diseña un *software* para realizar los testeos. Finalmente, se presenta el protocolo de testeo.

Este diseño se valida y luego se implementa en un convertidor reductor (buck) i un ondulador (inverter) que se fabrican en la empresa. Los resultados muestran que el sistema de testeo es fiable y es capaz de probar con éxito la verificación funcional de los dos sistemas electrónicos de potencia.

En resumen, este diseño se puede introducir en el proceso de producción de equipos de electrónica de potencia para probar los dos productos y garantizar su fiabilidad en el mercado.

Acknowledgement

I would like to thank my family, dad, mum and sisters, for the support and strength given throughout the last days of work.

I would like to thank all of the team of teknoCEA for giving me the opportunity to work there, the confidence to solve the problems and for letting me be part of the team from the first moment. Specially to Antoni for guiding me trough the project and making me have motivation for power electronics.

Glossary

- PCB (Printed Circuit Board)
- DUT (Device Under Test)
- ATE (Automatic Testing Equipment)
- PES (Power Electronic System)
- JTAG (Joint Test Action Group)
- FAT (Factory Acceptance Test)
- SAT (Site Acceptance Test)

Contents

1 Introduction

The production process is the key of the modern industry. Factories manufacture products in continuous flow with the objective of reaching to every customers. The sector that has taken the lead in the world is the technology. From the modern smart phones to the automotive industry, this new technologies should afford the increase of the demand. One of the main sectors of the technological era is the electronic industry. In the last decade the use of this technology has become a need in our daily life due to the facilities that it brings and it is constantly growing. That is the reason why many companies are investing in this sector. The growth in the electronic industry comes with a growth in the demand of their products, fact that obliges this companies to optimize their production processes. The main problem that companies deal with is the efficiency in production. The most important thing is to be capable of reaching all the demand, with the lowest possible time and with the maximum rate of satisfactory products. To accomplish a high number of successful products, it is important for the electronic industry to have good quality controls on their final products. For this need, the development of more reliable **testing system** is required. This will contribute to the efficiency that the companies are looking for. In addition, the continuous incorporation of new products to the market requires the development of new testing systems to ensure their correct production.

1.1 Aims

In order to analyze the reliability of the testing systems currently available, this project will focus on a company of manufacturing, testing and repair of power electronic systems (teknoCEA).

In teknoCEA there are different testing equipment that are used for the particular devices. When a new product has to be tested there is a problem. There is no specific systems for this new products and many times a manually approach is used.

The aim of this project is to create a specific testing system that will be valid for the new product. A power electronic system requested for a client of the company. This specific testing system will be more reliable in the assessment of the functionality of the product.

Different ideas have been proposed, but were either too expensive or complex. The final result is a test bed platform and a testing protocol that ensures the expected requirement: the correct test of the power electronic system.

Finally, possible future improvements will be discussed. This new suggestions could achieve a better testing system in the future.

2 Electronic industry

The electronic industry is based on the combination of design and production. The idea of a product starts with a brainstorm where different solutions to a problem are suggested. Many ideas are refused until one is unanimously chosen.

After a decision is made, the design stage appears. It is here where all the functionality calculations are discussed. It is important to take into account all the possible effects that can affect on the product to make sure that the final piece functions as it is desired.

The next stage is the manufacturing process. It is in this moment where the main problems appear. Although it might seem a less important issue, the time dedicated to design the manufacturing process is indeed one of the most necessary points to take into account. A bad management of this stage could bring enormous losses to the company so it is important to have a successful production line.

2.1 Electronic Manufacturing Services - EMS

There are some companies that can afford to have all the mentioned stages, from the design of the product, to the final export to the market. Nevertheless, there are many other companies that can only manage some parts of the stages. This is the reason why a service has been created. This service is responsible of providing the manufacture, test and repair of products to other bigger companies . They are called the Electronic Manufacturing Services (EMS). The main challenge of this service is to produce, with the shortest possible time and with the maximum rate of success. If this is accomplished it will directly mean an increase in the benefits.

The whole stage is divided into two main groups. The production part and the testing part.

The production section is considered the basis of a company due to the necessity for it to be effective. The section is based on a supply chain with different points of manufacture. In this project, the testing stage will be analyzed.

3 Testing

Every manufacturing industry has in its process a determined time dedicated to revise the quality of a product. For what is known, the more time spent on it, the higher the chances of getting successful products. In the electronic industry when we refer to the term of quality control we talk about tests. A test is defined by the Oxford dictionaries as a *procedure intended to establish the quality, performance, or reliability of something, especially before it is taken into widespread use.* Electronic industries do different tests during their manufacturing process to accomplish a high rate of success in their products.

Even though testing every product could seem a useless step or even a waste of time for the company, it ends up being one of the most important points. Testing the product is necessary to make sure that it is correct.

It is complicated to know if the final product is 100% correct. There are many variables that can affect its functionality. External conditions as the temperature or internal errors due to its production. Regardless this difficulties, the main idea is to find a complete test that encompasses all of the possible problems without exceeding the scheduled time and considering a practical method.

3.1 Testing concepts

There are several concepts about testing electronic systems that can be confusing and are necessary to understand it.

3.1.1 Validation vs verification

In the first place, the most important point is to differentiate between the Validation and the verification of a system. Both concepts are related to the condition of a product or system, or even a condition of a process. There are slight differences between them. When talking about a verification, it is usually referred to the act of verifying a system. It refers to the idea of testing it to ensure that it works properly. It is the action that determines the final state of the product. It can be tested by parts, for example, focusing in different PCB and test them individually, or it can be tested as a global thing (the whole system).

On the other hand, the validation of the system is the complete protocol done to assure that it is correct. If the verification is successful then the system can be validated. This concept can be used when a product is ready to begin its production process. If it is validated, there will be no modifications done on it.

3.1.2 Functionality test vs static test

Two more important concepts that determine the type of test done are the functionality test and the static test. When a DUT is being tested and verified, there can be different ways of checking it.

When a functionality test is done, the method done is called the Black-Box testing. It consists on a generic test where the idea is to revise the inputs and outputs of a system simulating the proper functionality of it without taking into account the internal devices.

The static test is different. The idea is to focus on a specific part of the system, for example the micro controller, or a specific chip and realize a singular test of that area. The DUT is not going to be working in its function characteristics. Only the part tested will be checked. The static test is done when there is an idea of what the problem might be.

In terms of production process, the general methods applied are the functionality tests.

3.2 Test Strategy

The main use of testing processes is to have an improvement in the quality of the final product. In order to have a good testing process there has to be not only a simple analysis of a system and then an application of a test, it is essential to have a strategy of how the testing is going to be carried.

The realization of the testing strategy begins with an approximate planing of the different tests that will be taken. It is very important to organize the timing of the several stages and to determine the number of tests done.

Once is known the number of tests that will be realized, the next step is to decide how this are going to be done. All the equipment required and all the space needed has to be thought. It is essential to have the equipment controlled because it requires a big investment. An error in the equipment chosen would mean a negative result.

All in all, the elected strategy will be essential to have good results because it gives an idea of the time dedicated on the process, the tools needed to proceed with it and the investment required. During the process, the test strategy can be modified, but the idea is to follow it through out the hole process. It is why the strategy must be saved in a specific document where it is all commented. [1].

3.3 Testing stages

The area where the testing occurs is very wide. The action can happen at any point of the production process, from the moment where the idea has been designed, to the moment before launching it to the market. Depending on when it happens, there is either a type of tests or another. We differentiate two categories: the test that is done after the designing stage and before the production process, known as the qualification test procedure; and the test that is done during or after the production process, the production test plan. [2].

3.3.1 Design Test

The qualification test procedure or design test occurs when a product has been designed and the company is ready to start the manufacturing of it. It is a way of assuring the correctness of the design and to know if it follows the needed requirements. The idea is to virtually simulate the functionality of a system to find out any possible mistakes and without having the need to manufacture any prototype. There are lots of tools that facilitate this job and can make specific simulations such as *Spice* or *CAD* software. The procedure that is followed is based on three aspects as it is explained in the article [3]: formalization, abstraction and decomposition.

First of all the formalization of the system is needed to clarify the proper system and facilitate the verification of it. Then the abstraction of unnecessary parts of the system to reduce the time spent on the testing has to be done. To end up, the decomposition of the system in to smaller parts is necessary to makes the verification easier and more effective. [3].

If the design part is successful and there are no errors, the manufacturing process begins.

3.3.2 Production Test

The other type of test is done in the production process. While it is being held, there are several stages of testing to assure a good quality of the product. This control is formed by different types of tests depending on the characteristics that are revised. It also depends on the company itself. This tests are generally known as the acceptance tests.

The main objective is to detect if there is any product with a functioning problem. To be capable of detecting it is the responsibility of this tests. There is a wide list of possible tests that can be done.

The first and more important point is to detect if the manufacture of the electronic system has been correct, as a hardware point of view. When done, the next point is to revise the functionality of it with functionality or static tests, mentioned previously in this document.

A few decades ago, when the electronic industry was not as advanced as it is today, the hardware recognition of systems was done in a non-automatic way. A human checked every product without the help of any external machines. Nowadays, with so complex systems that are produced and with large production processes it is practically impossible to do it manually. Therefore, automatic testing equipment (ATE) have been created.

3.3.2.1 Automatic testing equipment - ATE

In the last few years there has been a revolution of the testing methods due to the continuous improvement of the facilities that the industrial sector brings. What used to be done in a more complex and long way, is now done automatically. This is possible by cause of the automatic testing equipment. The main idea of an ATE is to do tests with high efficiency and controlled by a computer. Different types of ATE will be analyzed in this project.

3.3.2.2 Manufacturing Verification

The manufacture of the systems requires a testing verification to ensure the good quality of the hardware of the product. The hardware is the physical part of a device, the connection and components that form the proper system. The way of testing the hardware of a product is to detect if all the parts are connected in a proper form.

- AOI

In the modern companies, the principal test done to ensure the quality of the manufacture of a system is the automatic optic inspection system (AOI). It consists on a machine that works with computer visioning an is capable of detecting if there are any mistakes in the assembly. With the help of a camera, the AOI detects the DUT and registers it. Then it sends the information to a microprocessor that has in its memory the facts of a correct product. If the information registered is correct, the testing is successful and the system remains in the production process. Otherwise, the DUT is excluded from it.

In the case of PCBs, there are tests that recognize if the components on the boards have been placed as desired or if there is any component in a wrong place. In other electronic systems such as motors or inverters, the AOI can also determine if the finishes are as expected.

It is important for a company to have a good AOI to ensure a low rate of hardware failure. The main characteristics that are requested are the high speed and the high precision. The quality of the AOI is directly proportional to the inversion needed to have it but the results are worth it.

An example of an AOI is the XCEED system from the company Ab Electronic Devices S.L.

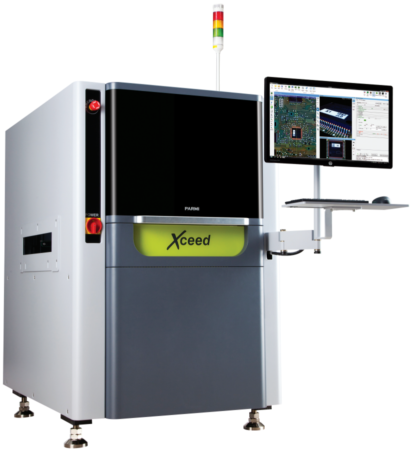


Figure 1: Example of an AOI. XCEED from AB Electronic devices. [4].

- Mechanical vibration

There is another test applied in the manufacture sector that is related to mechanical aspects. It is done applying a small force on the DUT to ensure that the different pieces on the device are correctly placed.

For example, there are different equipment that produce small vibrations on the boards. If there was any piece not welded properly, it would fall from the board. The force that this equipment apply is regulated by different protocols. It must not be too big to avoid possible failures.

It is also correct to apply small force manually on the devices to check if they are correctly manufactured.

- X-Ray

If the propose of the tests is to satisfy the quality of the product in a more precise way, the X-ray test is used. In the revision of PCBs it is commonly used to detect the quality of welds. With an AOI it is not possible to access to the detailed areas and the X-ray test gives the opportunity to reach to this areas. Nevertheless, there are some components that have X-ray opacity and require other kind of testing methods to be detected: the in-circuit-test.

- In-Circuit test

When the DUT has passed the previous test and it is certain that the manufacture of it has been correct, the next test appears in the production chain: the In-Circuit test.

It is in this moment when the supply voltage is applied on the system for the first time. The aim of the test is to revise if all the points have the right voltage or if there is any short circuit in it. There are several ways of doing this testing. Until the last decade the more commune test was the In-Circuit test and although it is still used now, it has some difficulties with the new prototypes of systems.

The In-Circuit-Test, also known as the White-box testing, consists in checking different test points on a PCB. When electric stimuli is applied on the circuit, test points have different signals. The test system gets the information of this points and compares it with the correct values. The way of getting the information is through a bed of nails. It consists on a structure made of a number of conductor pins that contact the different test points on the circuit.

This type of testing has two principal problems. In the first place, it is a system that requires a physical contact between the testing machine and the DUT. It means that the test points have to be in a determined position to be easy for the machine to access them. It has a very important limitation because there are some spaces in the PCB that are impossible to be reached.

The other problem has to do with the number of test-points needed to satisfy a successful test. The more points proportioned, the better the test, but also, the harder it is for a bed of nails to reach to all of them. Taking into account that recently designed PCBs have a big quantity of components, it emphasizes even more the need of numerous test-points to be placed. Therefore there are either longer tests with better results, or shorter test but with low quality.[5][6].

Figure 2: Bed of nails [7].

- JTAG

Seeing that the evolution of PCBs is making problems, a new method of testing was created. It is Known as the JTAG.

JTAG refers to IEEE Std. 1149.1, Standard Test Access Port and Boundary Scan Architecture. It was formed in 1990 and it is the basis of the boundary scan test method.

To test electronic systems the JTAG protocol is used. It consist on a method where a computer with a JTAG software is connected to the DUT through a converter (usb to JTAG). It follows the master-slave connection with a bidirectional channel. All the electronic chips on the DUT are connected in a chain to the PC.

For the Master to begin a connection with the DUT it has to have two components. The test access port and a boundary scan register to connect the integrated chips with the JTAG software. The JTAG connector, responsible for the inputs and outputs of the DUT, uses 5 pins for the boundary scan test, the Test Mode Select (TMS), the Test Clock (TCK), the Test Reset (TRST), and the Test Data Input (TDI) and Test Data Output (TDO).[6].

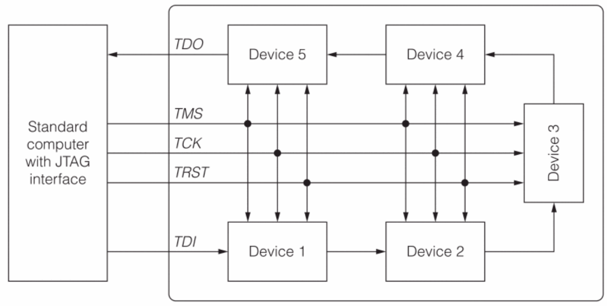


Figure 3: Structure of JTAG [8].

The idea is to have access to all the pins on the PCB of the DUT so it is possible to know if there are any incorrect connections.

On a PC, there must be a JTAG software to then be applied on the DUT. To do so, it is necessary to create a boundary scan description file where the specific test will be made. When the JTAG software is ready, digital data is sent to the DUT. If there are any incorrect connections, the JTAG software will show so. The use of the JTAG protocol has become unanimous in the electronic sector. Although some time has to be spent to generate the specific file for the software, it is rewarding due to the efficiency in the detection of faults. A study made by the University of Texas shows that the use of boundary scan test increases the rate of solder open detection from 80% to 99%.[5][8].

3.3.2.3 Functional Verification

The previous tests explained have the objective of detecting manufacturing errors. This are the physical faults that are done due to an error in the production chain. If the testing of the devices is correct, the next and final stage of testing appears. It is here where the functionality of the DUT is tested.

The principal point of the functionality verification is to put the DUT under real working conditions. The test has to be capable of analyzing the system and detecting if there is any fault in it.

Depending on the type of DUT, one ore another test will be applied. All in all, the basis of this stage is to configure the micro-controller of the system in order to simulate the working situation.

The extension of the possibilities that appear when talking about functionality tests covers more than the limits of this project. It will only study the functional verification applied on PES, explained on chapter 4.

3.4 FAT vs SAT

In the industry sector, when the testing process has finished and it is the moment to launch the final product to the marked there are two protocols that are commonly done. They consist on special tests that are related to bureaucratic conditions. They are tests that give a certification of correctness. They are known as acceptance tests.

The first concept is the factory acceptance test or FAT. It is the test that is done in the same factory where it is produced. Generally, this products have certain characteristics that have been previously accorded with the respective client. It is a must for them to accomplish this characteristics and, before the client of the product pays the specific price, he has to go to the factory to see how the system performs the FAT. The testing process that has been explained in this document would be part of this FAT. This would be the test that all the industries do to their products to have this certification in order to be able to sell the proper product. If the test is correct, then the client accept to buy it. This test is normally accorded between the company and the client before the contract is signed, and there are some requisites established, as the duration of the process and the FAT done.

The other concept is the site acceptance tests or SAT. This test is done when the product is installed in the clients space. It is normally a repetition of the steps done in the FAT but it is necessary to be done to assure that there has been no damage in the shipment of the product. Other aspect that can affect the functionality of the product when the commissioning is done are the conditions of the area, or the conditions of the electric network. It is a contract done by the client and the company.

4 Power Electronic Systems

Power Electronics is defined as the study of electronic circuits intended to control the flow of electrical energy.[9]. The finality of this specialty of the electronic sector is to convert the electric energy to a desired level.

This energy is obtained from the electrical network produced at the electrical centrals. It is used to supply all the electric devices that require to be plugged.

4.1 Alternating and Continuous source

There are two possible forms of energy flow that can power up a Power Electronic System (PES).

The first one is the alternating, or AC. It is the source that comes directly from the electric network. It consists on a signal of current that modifies its value through out the time as in a sinusoidal wave. It has certain characteristics. Its pick value is approximately 325 V, but the most known value is the root mean square of the wave, 230 V. It repeats periodically from its high pick value to its low pick value with a determined frequency. To apply it in the industry, it is used in a three-phase form. Instead of having a single wave, there are three waves with a gap of 120° between them. The pick value in this case is approximately 400V. For other applications, as in the domestic environment, a single wave is used. As it is shown in the figure, number 1 refers to the pick value, number 2 refers to the value from the high pick to the low pick (pick-to-pick); number 3 refers to the root mean square value; and number 4 refers to the period of the wave that will constantly repeat.

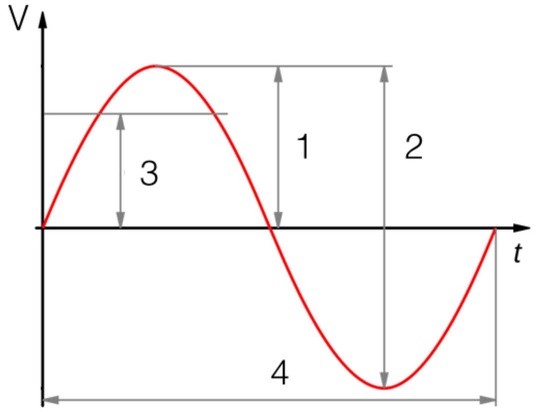


Figure 4: Sine wave.

The other type of energy is the continuous or DC, that consists on a signal with a constant value of current over the time. The PES can convert from an alternating to a continuous source of energy and vice versa.

4.2 Use of Power Electronics

There are many applications that need a specific type of power, therefore, PES are responsible for adapting this energy to a specific value.

There are some applications that appear due to the conversion of this energy. In the industrial sector, there are many electrical engines. With a modulation of the electric energy the speed of this engines can be modified to a desired value. Power electronics is the responsible of this modulations.

Another example of a power electronic use would be the charge of electronic devices such as mobile phones, computers, etc. that require a continuous source. In the last years, there has been an enormous movement around power electronics with the increase in the demand of electric vehicles.

Therefore, it is known that power electronics are everywhere, and the companies that manufacture this systems have the need to have successful items.

4.3 Structure of Power Electronic Systems

There two determined blocks that conform a Power Electronic System. The power part and the control part.

The power part is responsible for supporting the high energy flow. It is made of electronic components that have big capability to support high energy. It is the block that has the input and the output of a determined power. On the other hand, the control part is responsible for acting over the power part and to order the way of modulating the electric energy. It not only gives orders but it also supervises the power part, and acts if there are any inconsistencies. For it to be possible, the control part must have an additional power part, normally obtained from a modification of the external electric source. It is controlled by a master, generally a microprocessor. It has a program that is made with a determined purpose by the client of the system. The programming of this controller is done with an embedded software. The control part is generally placed on a PCB whereas the power part can either be on boards or on other materials, such as radiators or other structures. The combination of all of the materials and components is what makes a PES.

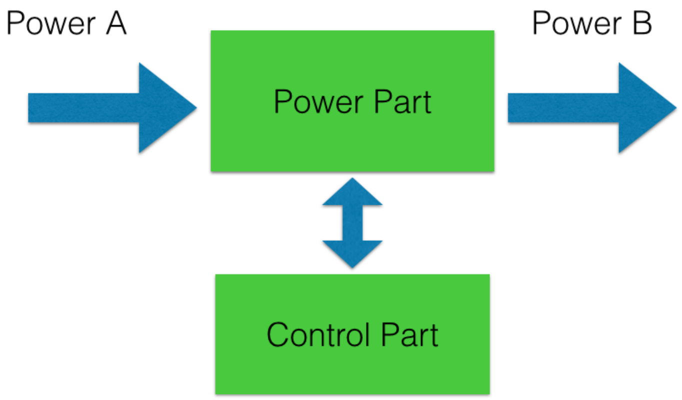


Figure 5: Energy flow diagram of power electronic systems.

4.4 Types of Power Electronic Systems

The use of PES is to modified a type of energy that can be either alternating or continuous. Depending of the input and the output of the system, its functionality and name variate. There are different possibilities: rectifiers, DC-DC converters, inverters, etc.

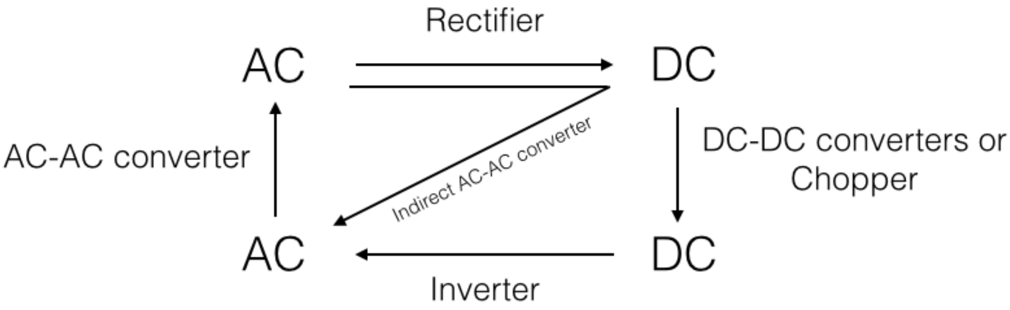


Figure 6: Different types of electronic power conversions.

4.4.1 Rectifiers

The system which aim is to modify an AC source to a DC source is a rectifier.

It is generally composed by a a diode or thyristor bridge, to convert the sinusoidal wave (AC) into a rectified wave with only positive values of voltage. It is then followed by a big capacitor to filtrate this wave and convert it to an approximate constant value, a continuous source. When the rectified wave increases, the capacitor is charging and keeping this energy that is then applied on the circuit when the rectified wave decreases. It is a form of keeping a constant level at the output of the capacitor. The final signal has a small ripple shaped with a triangular wave depending on the characteristics of the capacitor.

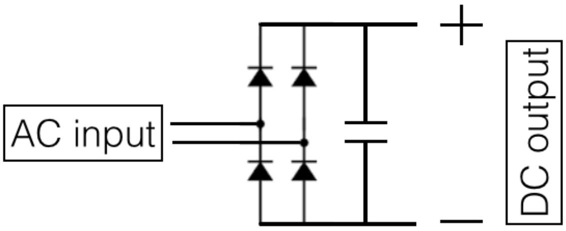


Figure 7: Diagram of a rectifier.

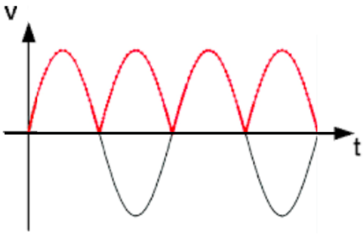


Figure 8: Wave form of the input signal (Black) and the rectified signal (Red).

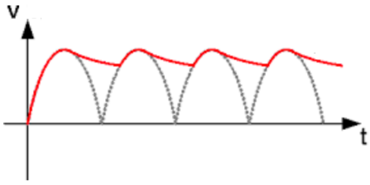


Figure 9: Wave form of the rectified signal (Black) and the Output signal (Red).

Its applications are for systems that demand a continuous source to work, such as the charge of batteries, inverters, power supplies, etc.

4.4.2 DC-DC converter

This converters are a type of PES that with a DC source at their entrance, they convert it into another DC source. It can either convert it to a higher or to a lower level. The most known regulators are the buck, the boost and the buck-boost. There are many systems that work with continuous source but not all of them need the same level of it. This converters are useful for adapting the DC source to the desired level.

4.4.2.1 Buck

A buck is formed by the combination of two electronic switches, normally a transistor controlled by a processor and a diode. It then has a capacitor or an inductance before the output (load) to be possible to have a stabilized level of voltage.

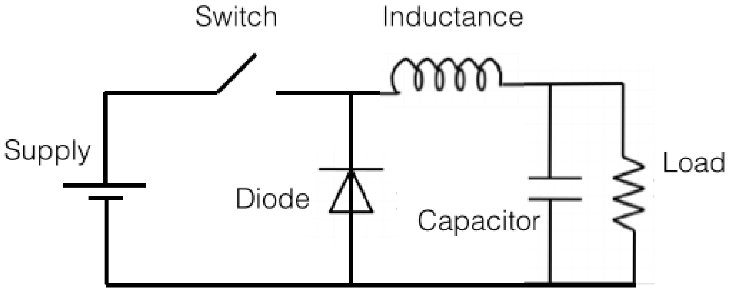


Figure 10: Diagram of a buck.

The transistor commutes at a frequency marked by the control part. The diode has the opposite state of the transistor. When the switch is closed, the inductor is absorbing energy from the input and, therefore, there is an increase in its current from the minimum level to the maximum level.

$$\Delta Ilon = \frac{Vinput - Voutput}{L} * \delta Ton \tag{1}$$

Delta is the percentage of time that the transistor is in an ON state.

When the transistor opens, the inductor works as a generator, and its current decreases from its maximum level to its minimum. As it is proved in equation 1, when the switch is opened, there is no input voltage on the inductor, so Δ Il is negative.

The result is a magnitude of current more or less constant (IL mean) with a slight ripple ($ILmax - ILmin$). When applied on a load, there appears a constant voltage with a lower level than in the input of the system.

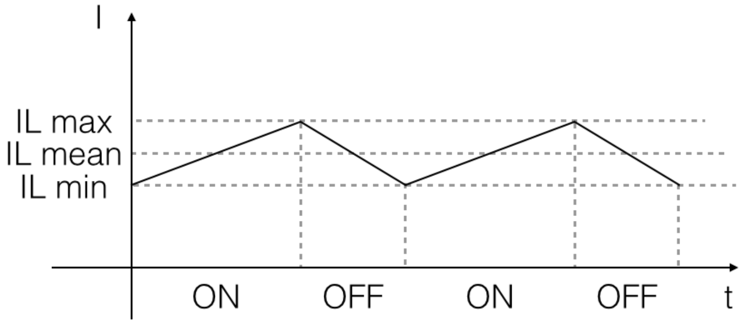


Figure 11: Variation of current in a buck.

4.4.2.2 Boost

The boost system has the same concept of the buck but, in this case, the result is a level-up in its voltage magnitude input. Its circuit diagram has a small variation.

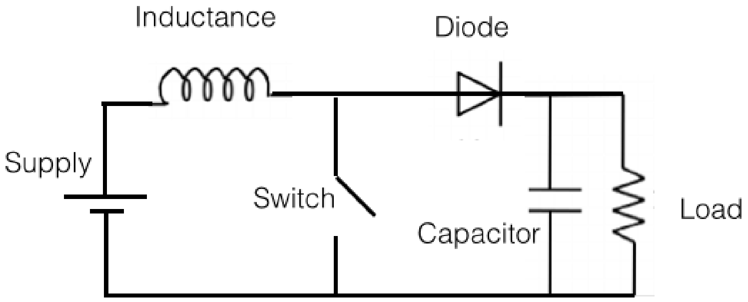


Figure 12: Diagram of a boost.

4.4.2.3 Buck-boost

The final system is the buck-boost. Its function is to either increase or decrease the level of voltage applied. It is combined with a buck and a boost, and depending on the control of the switch it can give a determined output.

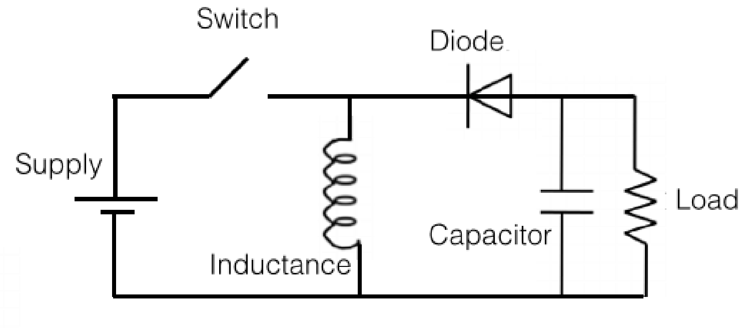


Figure 13: Diagram of a buck-boost.

4.4.3 Inverters

The system that from a DC source in its entrance, converts it and has an AC source in its output is called inverter.

The idea is to grab the energy of a continuous line or bus and transform it. The structure of the system is a bus of continuous power that is commuted by a branch that includes two semiconductors. This semiconductors, normally MOSFET transistors or IGBT, are controlled by the control part. The method used for this control is the Pulse Width Modulation (PWM). It is a method of sending digital information from an emitter to a receptor. This digital information has two ‘possible levels: high level (1) and low level (2).

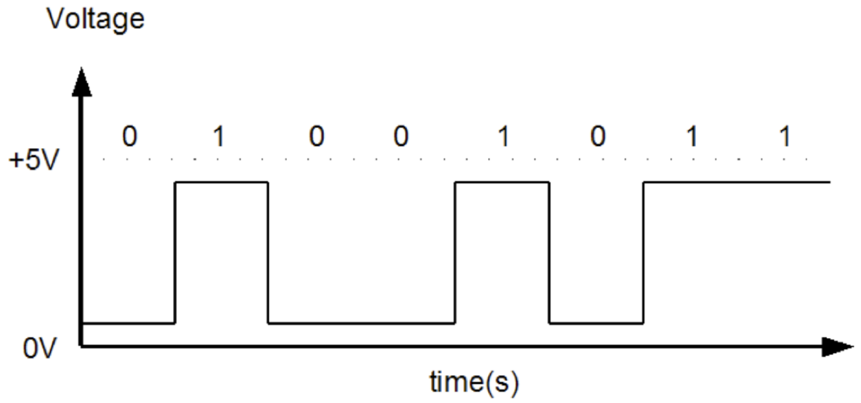


Figure 14: Waveform of a digital signal.

The semiconductor can short circuit or open circuit depending on the signal applied on its gate. In this way, when a high level digital signal is applied, the switch closes becoming a short circuit, whereas when a low level is applied, the opposite state occurs. Since the idea is to have an alternating source at the output of the PES, this semiconductors commutate to acquire it. PWM consists in modifying the duty cycle of the signal sent.

$$DutyCycle = \frac{Timeon}{Totaltime} \tag{2}$$

Depending on the value of the alternating output signal wanted, the width of the duty cycle of the control signal increases or decreases. When the output value is maximum, the duty cycle of the control signal is also maximum. In the other hand, when the output value is minimum, the duty cycle of the control signal is also minimum. The semiconductor will commutate to form a PWM signal that, with the help of a filter that the engines have, it will transform into a sinusoidal signal.

The output line is in the middle of this two semiconductors. The process of conversions is divided in two stages. In the first place, the semiconductor between the positive bus of continuous and the output line, is closed, while the other semiconductor remains opened. During this time, the output of the system is a positive value of energy. The next stage is done with the opposite conditions. The other semiconductor is closed, and the first one is opened again generating a negative value of energy on the output. Commuting this two semiconductor, we obtain a source of AC power. Both switches can't be closed at the same time, it would be a short circuit in teh bus.

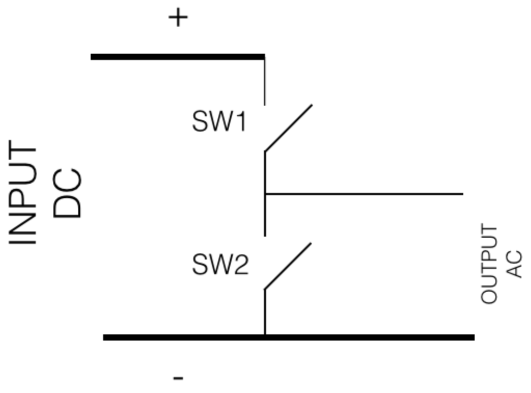


Figure 15: Block diagram of an inverter.

Inverters can be single-phase, or three-phase power energy systems depending on the number of branches that are composed of: one for single-phase and three for three-phase.

Inverters are used for electric engines that need an AC source to power up. Another common use is in solar panels. The energy that the panels generate is a DC source. With an inverter it converts into an AC source. Therefore it becomes a source of electric network. Another common use is in the electrical vehicles as though the energy of the batteries is a DC source and the engine of the wheels is an AC source.

4.4.4 AC-AC converter

There are different typologies of converters when the conversion held is a modification of an AC source to another AC source. There are systems that do the conversion in a singular step, as the cycloconverters, whereas there are systems that combine other converters, known as indirect converters. This indirect converters have an intermediate stage of DC. They convert an AC source to a DC source and then again to another AC source. This project will focus on this type of converter.

4.4.4.1 Indirect AC-AC converter

With an entrance of an AC source, the power part has an AC-DC converter followed by a DC-AC converter. It is composed by a rectifier and an inverter. Its applications are on electrical engines. They are explained in more detail in chapter 6.

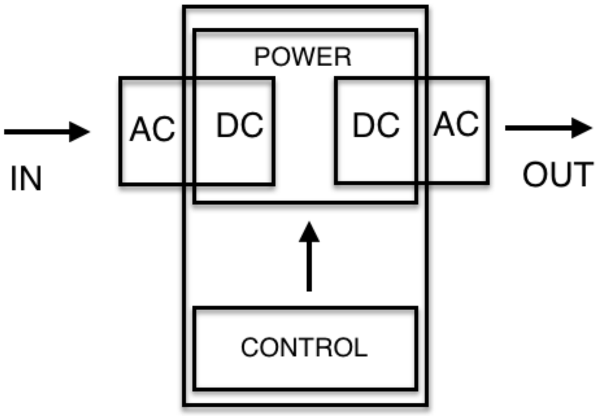


Figure 16: Block diagram of an Indirect AC-AC converter.

4.5 Test of Power Electronic Systems

Power Electronic Systems can be tested in different ways. The main objective is to verify their functionality but the way of doing it is more or less subjective. Through the manufacturing process, many tests are applied as it has been previously explained. There are previous tests done on the different elements. First of all, the PCBs of the control part are tested separately from the rest of the equipment with a functional test. It is more effective to apply it in this form to avoid possible damages over other elements.

After having applied the tests of manufacture, it is here where the verification testing begins. To test the functionality of power electronic systems it is necessary to put them under real conditions. It will be necessary to use high voltage on the power part, and to configure the control part so that it checks if it works correctly.

The first thing required is a source of high voltage to be applied on the power part of the PES so that the PES is under its work conditions.

To proceed with a successful test the optimum option is to have a protocol and follow it. The testing stages on the electronic industries have their own protocol, but the structure of them is practically the same. The study of protocols is explained in more detail in chapter 7.

4.5.1 Value test

The principal functionality test applied on PES is the value test. The idea is to make the PES work as in real conditions and test the output values that it is generating.

The most important thing is to configure the system to generate a specific output with certain characteristics to then be able to revise if the output has a relation with the order done. In the case of an inverter, the action would be to force the PES to give an output with a determine frequency. If the output voltage has a frequency that corresponds to the ordered one, this part would be correct. Depending on the time spent on the testing stage, there can be more measures done. The correct process would be to make the PES work in extreme conditions, applying the maximum and minimum levels of effort. Still in the case of the inverter, the correct test would include a moment where the maximum output frequency would be tested.

If a system generates the desired output it does not necessarily mean that it works correct. It has to be working during a determined time to see if the different parts of it resist to the mentioned levels. It is now where another type of test is realized. The tests that checks the power dissipation of the areas of PES.

4.5.2 Dissipation

According to the Joule effect when a flow of current passes through an electronic device and a variation of voltage appears, there is a transformation of energy. This is based in the power equation.

$$P = I^2 * R \tag{3}$$

This device dissipates part of this energy in a form of heat. There is a maximum dissipation value before it breaks or malfunctions and ,therefore, they have a limit of voltage and current that can be applied on them. An excess of temperature can not only damage the proper device but it can also damage the surrounding devices. It is essential to control the levels of energy dissipated.

An article by the University of Minnesota [10] explains that power dissipation can be used for fault detection.

The fact that a PES may have a fault, directly means that there will be a variation of the energy consumption. In this way, by having the control of the power flow on the PES, there can be an estimation of a fault.

So when a PES is being tested, the idea is to see if there is any device that is consuming a large amount of energy. The best way to do so is to check the current that is consuming, or to check the average temperature that it reaches. For example, if in a PES the frequency of the commutation of semiconductors raises, there should be a proportional raise on the power consumption, because there is a major demand of energy. If instead of being proportional this grow is abrupt , it can be caused by a fault in the system.

4.5.3 Burn-in test

An interesting concept that appears in the test of electronic systems that is also applied in power electronics is the Burn-in-test. It consists on the study of the systems under extreme conditions. It sets high conditions on the DUT. This means that there will be an application of high temperature and high voltage on the systems. It is a good form of reaching the 100% of success in the later launch of the product. Burn-in test results follow the Bath tube curve.

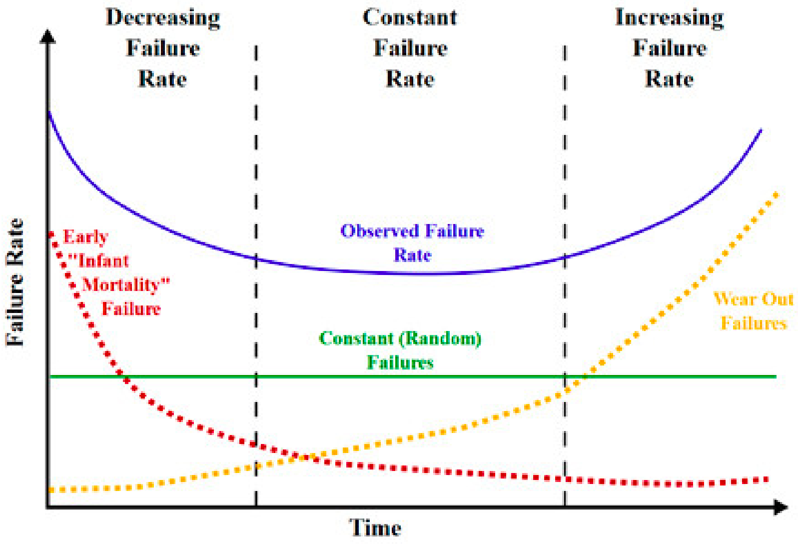


Figure 17: Bath-tube curve of the Burn-in test [11].

It its divided in 3 periods of time. During the first interval of time, the phenomenon known as infant mortality occurs. It is here where the major quantity of products fail, due to the lack of resistance to the extreme conditions applied. This faults can come either from internal issues, as components, PCB, connections; or they can come from a lack of resistance of the packaging of this PES. Many products will be discarded here due to this effect, although the systems that pass the test have a very high chance of success.

The bath tube curve also has two more periods. The second interval of time, is known as the constant area where the rate of failure is constant. It is here where random failures appear due to external factors.

In The last period there is another increase in the curve. It is known as the Wear out or the End of Life of a product. The deterioration of the systems after a lot of years working, is what explains the variation in the curve.

In PES it is useful to apply this type of test. The first stage, the infant mortality period, is the area where the testing of this products occurs. The other stages are not considered in the process because they happen when the product has already been launched.

Applying the infant mortality stage on PES brings advantages. It assures a higher quality of final products with lower chance of failure and with a more examined testing process. It can also give an idea of the modifications needed to avoid the discard of products. Finally, it gives an idea of the lifetime of a product which is a useful information for the client.

There are some problem that Burn-in test have. In the first place, there has to be an extra dedication of time spent on the testing process. The more time spent, the better the final product's rate of failure is. Another important aspect that has to be taken into account is the availability of the specific tools needed to be capable of applying the extreme conditions on the systems. Nevertheless the most important issue is the increase in the cost of the process. The implementation of a Burn-in test needs the utility of specific machines that require a high invest. Another point of high cost is the quantity of products that are discarded due to the extreme process. The application of extreme conditions also makes shorter the Life of the Product and, therefore, makes the product to loose value. [12].

All in all, the use of Burn-in test has very good results and gives an idea of the life-time of a product. The use of it will bring more benefits to the company although a big invest must be made.

4.5.4 Common failures

There are many prototypes of PES each one with its own characteristics and with different blocks depending on the aim of the product. Nevertheless, the failures that appear on them are similar.

With a 90% of rate of failure, electrolytic capacitors and switching transistors are the principal threat of PES. [13]. The problem of capacitors is that they have a short life-time and, as they are responsible of the filtration of the signals, a slight variation of their nominal value due to their life-time can affect on the behaviour of the PES. Another critical factor that affects electrolytic capacitors is that they have a low temperature working zone. PES can reach high temperatures due to the joule effect and it can affect on the electrolytic capacitors.

The other principal cause of failure is the switching transistors. Depending on the command given by the control part this components have to commute at high frequency, which means that they are submitted to high work and, therefore, to high temperatures.

Although this components have radiators to avoid the overheat, sometimes it is not enough and they end up failing. A good calculation of this radiators can prevent later errors.

Transistors are not only affected by their working temperature, they also have other causes of failure. Limitations of voltage and current are fixed depending on the manufacture of a transistor. If their limit characteristics are exceeded, they can fail. They are generally protected with protection circuits that the PES incorporate, such as varistors, or zener diode that limit the voltage and current (respectively) that this devices receive. If there was any higher signal over the limits of this protection, this devices would burn. In this way, the transistor would be protected.

5 Testing equipment at teknoCEA

The author of this project did his university internship at a company called teknoCEA. It is located in Barcelona, and it is in the power electronic production sector as an EMS. Production, and reparation of PES is held in the company. In this project, there will be an analysis of the different testing equipment at teknoCEA to have general concepts of how they are structured.

5.1 Structure of testing equipment

Although there are numerous types of possible testing equipment, they are all designed following the same basic structure. The idea of a testing equipment is to check a specific DUT ans detect its failures. As a generic electronic system, it has the part of hardware and the part of software. The first part is composed by a central CPU and different peripherals, such as input and output connectors that are connected to the DUT, a display, several switches, etc. It also has different multimeters to proceed with the read of the measured values and the supply voltages, to power up the DUT.

The software part is the program that the CPU executes. It has been designed by a programmer and the aim of it is to verify the maximum parts of the equipment. It is the responsible of the different actions that will be applied on the DUT and the connections and disconnection of different parts of the system.

5.2 Examples of test equipment at teknoCEA

To accomplish the testing demand at teknoCEA, there are different testing equipment. Although they are not recent, they are still in use and are practical for solving the problems demanded.

5.2.1 MC I/O

The first testing equipment is from a company A. It is used to test input-output PCB from the industrial machinery.

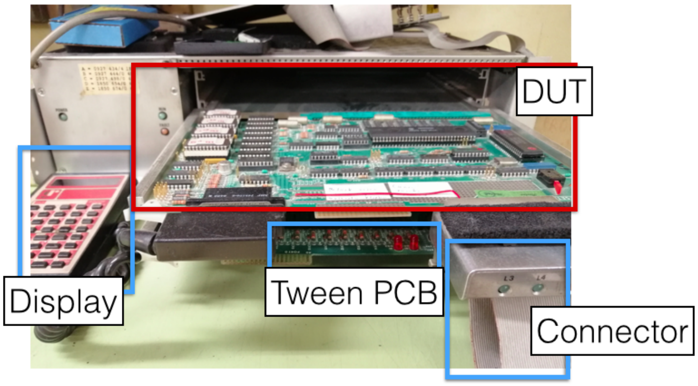


Figure 18: MC I/O Test equipment.

This equipment requires a tween PCB of the DUT. The idea is to send information from one to another. If the information sent matches with the information received, then the testing procedure is correct. It does numerous tests like this and it goes through all the parts of the DUT. It also has a small display where the different tests appear. If there is a failure, it stops testing and it shows the defective test on the screen. There is a testing manual with all the possible tests so when a failure appears, the technician has to look it up in the manual to solve it.

It is a method that requires a long time due to the fact that there are lots of tests done. It has to do all of them so the machine has to be powered up during a long period of time.

5.2.2 Company B's test system

Another example of a testing system in teknoCEA is the company B's system. Its aim is to verify the functionality of PCBs. In this case, it tests PCBs from a machine called UT3. It has the typical structure of a testing equipment, consisting of a CPU that gives the different orders, controlled by the user by a screen and a keyboard. Then there is the tests adapter where the DUT is placed and a test box where the supply voltage and the multimeters are found. The block diagram is explained in the next figure.

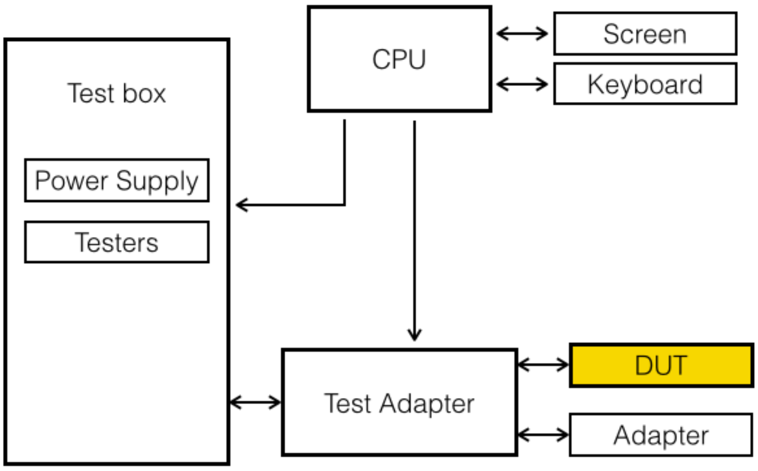


Figure 19: Block diagram of the company B's test system.

The protocol of verification starts with the connection of the different blocks. First the connection of the test box and the test adapter to the PC is done. Then, the PCB is placed on the test adapter with its corresponding adapter. Depending on the DUT there is one or another adapter that matches it. This adapter is formed by different PCB that have been manufactured to satisfy the testing. The test adapter is connected to the test box. When everything is connected, the PC is turned on.

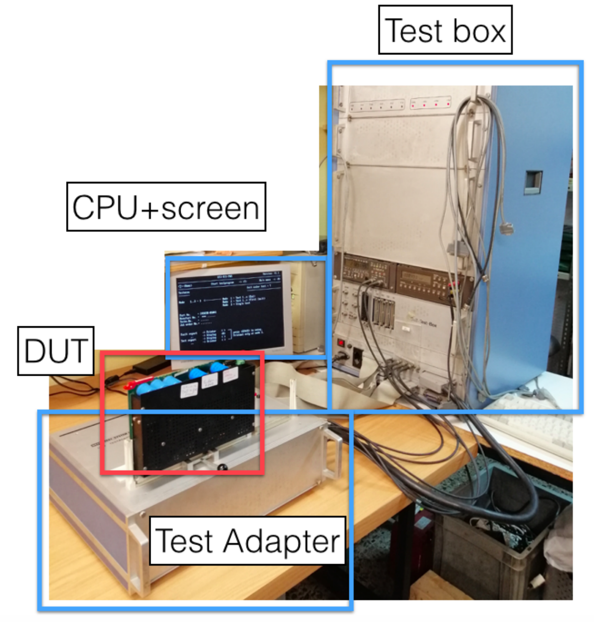


Figure 20: Lay out of the Company B's test system.

When the system has been powered up, in the screen it appears a list of the different PCBs that can be tested and it is here where the corresponding one is chosen. When the analysis was done, the DUT was the PCB Type A.

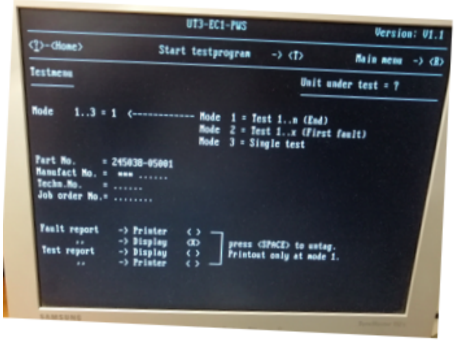
```
Date: 02-16-1999                UT3/UTR3 PCB MENU
Time: 23:56:51                                                   Page 2 of 2
                                                                 Version 1.00

         1. UT3-SP-SPG   STATIC CHECK     PART NO. 245 043-30001
         2. UT3-SP-SPG   FUNCTIONAL CHECK PART NO. 245 043-30001
         3. UT3-SP-IPI   STATIC CHECK     PART NO. 245 043-35000
         4. UT3-SP-IPI   FUNCTIONAL CHECK PART NO. 245 043-35000
         5. UT3-EC1-PWS                   PART NO. 245 030-05001
         6. UT3-EC1-CTT  STATIC CHECK     PART NO. 245 030-10000
         7. UT3-EC1-ITF  STATIC CHECK     PART NO. 245 030-15001
         8. UT3-EC1-MPD  STATIC CHECK     PART NO. 245 030-35000

   ↑ or ↓ point to option  | F1 Help                 Esc  Previous menu
                           | F7 Quit                 PgUp Previous page
   ENTER select option     | F9 Menu Maintenance
```

Figure 21: Principal menu of the Company B's test system.

Then a menu appears with different options to choose. There are 3 possible tests, the complete test, the test until the first fault appears and the single test, where a specific test is chosen. Then it is possible to select whether the system will report the faults in the display or in an auxiliary printer.



```
                         UT3-EC1-PWS                              Version: V1.1
<?>-<Home>          Start testprogram    -> <T>          Main menu  -> <B>
Testmenu
                                                      Unit under test = ?

Mode    1..3 = 1  <----------- Mode  1 = Test 1..n (End)
                               Mode  2 = Test 1..x (First fault)
                               Mode  3 = Single test

Part No.      = 245038-05001
Manufact No. =  *** ......
Techn.No.     = ......
Job order No.= ........

Fault report    -> Printer   < >  ┐
      ..        -> Display   <X>  │ press <SPACE> to untag.
Test report     -> Display   < >  │ Printout only at mode 1.
      ..        -> Printer   < >  ┘
```

Figure 22: Principal menu of the Company B's test system.

Then it proceeds to the chosen test. First it revises the supply voltages and then it continues with the different tests guided by the controller. The result will be a report of this measures.

6 Case studies

After doing a research of the aspects related to the test of PES, this project will apply this concepts on teknoCEA. First of all, there will be an explanation of how the repair of the products is done. Then, there will be an implementation of a test system that will be capable to do a functional verification test on a PES from teknoCEA.

6.1 Background

TeknoCEA is a company that works in the power electronics sector. In this technical service department the main activity held is the repair of inverters and indirect AC-AC converters (a rectifier and an inverter) from the industrial sector, although they also repair other electronic systems. They receive them with a problem of malfunctioning , most of the time unknown, and they try to fix them. There is also a department dedicated to the design, development and production of PES. All in all it is a company that works as an EMS, where different types of tests are applied. It is a perfect example to understand how the functional verification of PES is held in the electronic sector.

The testing processes that have been shown are ideal for companies that verify many systems and have a big production demand. TeknoCEA is a company that repairs products that have already been working. This means that the manufacturing tests have already been taken and, therefore, only the functionality tests have to be done. All of the ATE need a big invest to be done and teknoCEA does not produce and repair enough systems for an ATE to be worth it. Instead, manual protocols are done. In this project there will be two systems analyzed to understand how the testing of this repaired products is done.

6.1.1 Inverter A

The first equipment that will be analyzed is the inverter A.

It has the two fundamental parts of a PES, the power part, in this case with a rectifier, an inverter, and the power supply; and the control part. It is an AC-AC indirect converter, but it is popularly known as an inverter. After all, the only difference with a proper inverter is the existence of a rectifier.

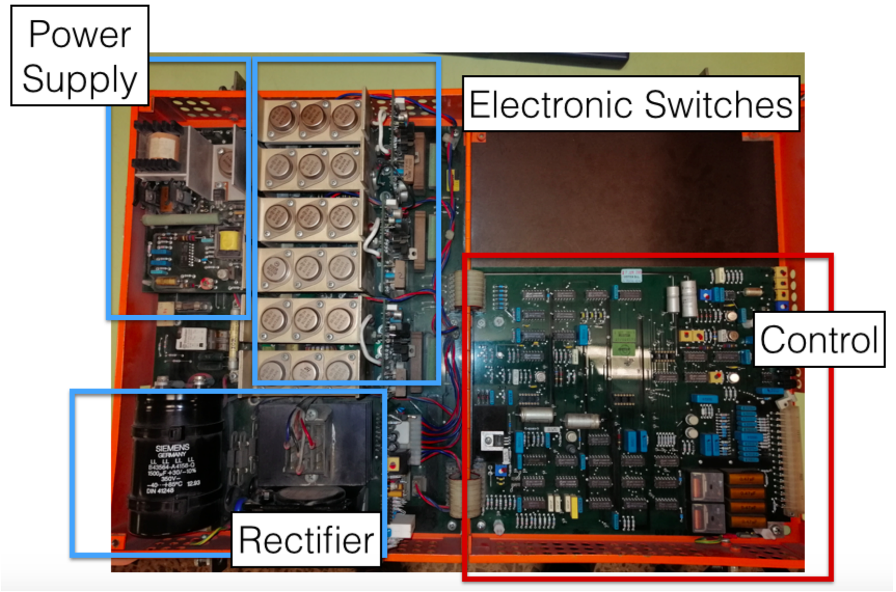


Figure 23: Power part (left) and control part (right) of the inverter A.

This PES arrives with a problem, and it is repaired following a protocol. First of all it is necessary to understand how it works to then know what problems it has.

The aim of this equipment is to adjust the speed of an electrical engine to a desired value. It works with the concept that the speed of electric motors is determined by the frequency of the voltage applied on them.

$$n = \frac{120 * f}{p} \tag{4}$$

n is the speed of the electric engine, f the frequency of its power source and p the number of poles per phase. In this way, the inverters are connected between the power line and the engine and they modify the frequency of the voltage that it receives. To make the repair, we have to check the different parts of the inverter A: the power part and the control part. A protocol has been created to proceed with the testing. First of all a visual check is done, to see if there are any mistakes. In teknoCEA the main errors that are found are the rests of burning in some components. This immediately gives information of what the error can be.

The protocol follows with a revision of short circuits. Before connecting the system to a source of high voltage, it is important to supervise if there exists a short circuit between the positive and the negative of the continuous bus, or, in the case of having an AC entrance, if there is any short circuit between phases. This is checked with a multimeter in the rectifier bridge. In the case of this inverter, the condition of the diodes is first measured. If there was a diode with a problem, the measure would be either a short circuit (zero resistance) or an open circuit (high resistance). In good conditions, a diode has a difference of voltage of 0.6V. The other measure done is the resistance between the positive and the negative of the bus. There has to be no short circuit between the two lines, so when measured, there must not be zero resistance.

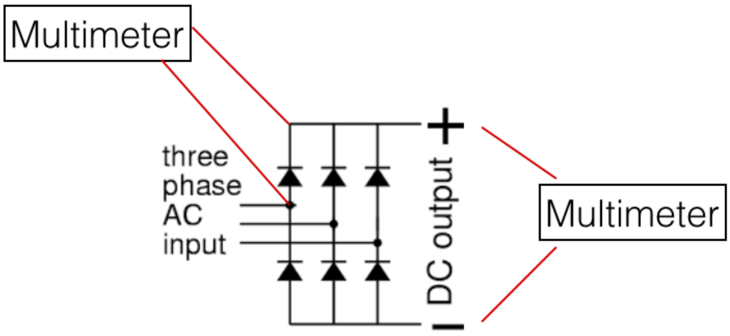


Figure 24: Measurement of the diode bridge in the inverter A.

If the testing is correct, the systems is connected to high voltage. It is important to be aware of any strange circumstances as though the system is not 100% correct and there could be problems. It is here where the testing proceeds. As a manual bed of nails, there is a reading of the values on different test points over the system with a multimeter. The protocol gives an interval of the correct values and, in case of finding some point that does not match, a notification must be written. The most important points checked are the values of the DC bus, the values of the AC output, the ripple of the capacitor at the entrance, and the power supply of the control part.

Depending on the error found, there will be one or other action made. The final part of the protocol is to try the inverter with an electric engine. At teknoCEA there is a machine that consists on a controller of the inverter. It can give different orders to the system. It has different buttons to start-up the system, and is also has different analog multimeters to see the voltage and the current at the input and output of the system. There are also two potenciometers that give the orders of the speed of the engine.

Figure 25: Controller of the inverter A.

This controller is connected to an electric engine and, therefore, the result of the testing can be demonstrated. To solve the problems, there are different schematics of the PCBs of inverter A. To find the problems, there has to be an analysis of them. There are also many spare components that can be substituted in case of having problems. When the protocol is completed, the equipment is ready to work. It is important to save the different failures that appear over the years to have more information, in order to facilitate the repair of the next systems to come.

6.1.2 Inverter B

The other equipment that will be analyzed is the inverter B. It is a more modern model than the previous case but the basis are the same.

In this case, there is no additional controller as it happened in the case of the inverter A so the protocol followed is slightly different. There are different equipment used to do the test: a variable supplier, light bulbs, multimeters and an oscilloscope.

First of all, the normal process of testing is done. The visual check to detect any error and the test of the short circuits with the multimeters. The following step is the application of the he external source to the PES. It is supplied progressively with a variable supplier (variAC). To avoid having a short circuit that has not been detected, there are resistors (light bulbs) connected in series before the PES. If there was any short circuit, this lights that work as resistors would light up and there would be no short circuit. The operator will disconnect the power supply. Two multimeters are also connected to see the level of power voltage and current that the PES is consuming.

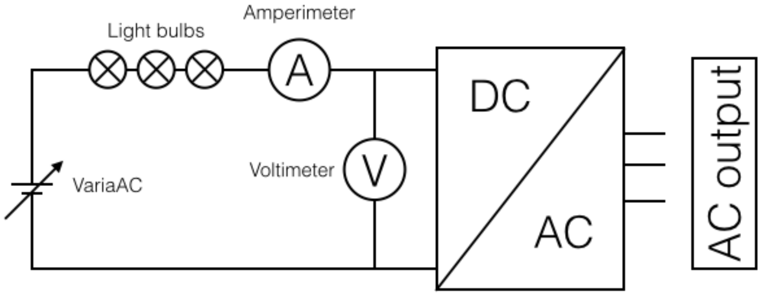


Figure 26: Layout of the connection with the light bulbs protection.

The protocol follows with the measurement of different values. With the help of the schematics of the PES, the signals of the control and the power part are analyzed and studied. Whenever a failure appears, it can generally be resolved by the help of the schematics.

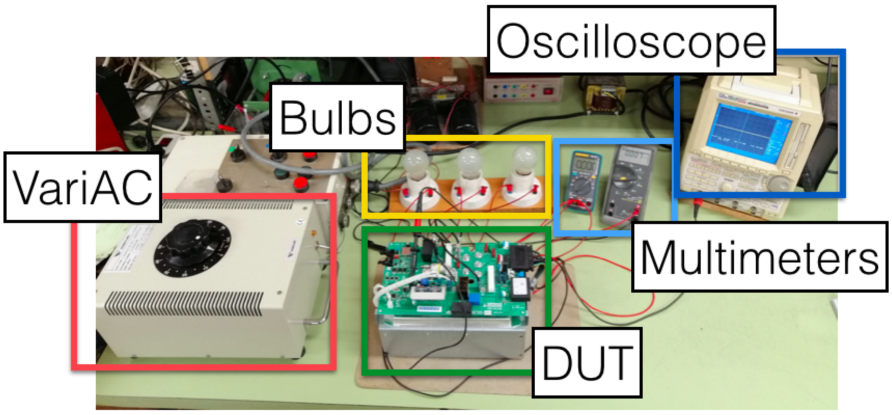


Figure 27: Distribution of the protocol applied on inverter B.

After all, the operations done copy an ATE. Instead of having a microprocessor controlling the measurements, there is an operator doing it.

When the equipment is repaired, it is tested at working conditions as a final inspection. Then it is packed and send to the client.

7 Implementation of a functional verification test on a PES at teknoCEA

7.1 The construction of the protocol

For a testing process to be complete, organized and secure it is essential to have a formal document where the different orders and steps that have to be done are explained. This document is formally called a testing protocol.

7.1.1 Why a protocol?

As it has been seen, there are many tests that can be done on a single system depending on the aim of the test. More over, not all of the systems are tested in the same way. The use of a protocol is needed to organize the information about the testing procedure and to know exactly the steps that have to be taken.

This document has the mission to give the testing orders to the operators with the idea of completing a perfect test and with no possible mistake. It has to have very detailed explanations of how the different stages have to be applied. It has to be written in a language that any testing operator understands. It is the way of transmitting the knowledge acquired by the designer of the test to the other technicians.

A good protocol has to be complete in the way that explains every possible testing stage, as well as it explains the reason of the measures done in order to give an idea of why this actions are being done.

7.1.2 Structure of a protocol

For a protocol to be excellent, it has to have a good structure. The basis structure is based on different points:

First of all it is important to have a space at the beginning of the document with the information about the different modifications that are done in the protocol. These modification can come from mistakes that an operator has found, or new ideas of how to measure a value, etc. It gives an idea of a secure and refreshed document.

It then follows with the list of the different instrumentation that will be needed. It is very important for an operator to begin the protocol with all the material required. It speeds up the process. All of the instruments must be adapted to the circumstances needed. For example, if an oscilloscope is needed, the operator has to calibrate it to the right frequency, amplitude, bandwidth of the signal, etc.

The next point of the protocol is the list of the activities that will be held. This activities have to be very clear and detailed. It is important to explain each activity with no possible confusion. A mistake in a measurement can make a system be wrong without being it. The most important thing is to make sure that the protocol is strict. The objective is that the systems that pass the protocol are a 100% correct. The activities that will be held on the protocol implemented are explained in the chapter 7.2.

The last part of the document is the register of the information. It is normally done with different tables where the values of the measures taken are written, as well as different notes that can be made if any failure appears. It is important to have a register of all the activities done that can be checked with a tick mark or similar. In this way, if there is any stage that has been missed it can be found out in the tables.

When the protocol is finished it is also interesting and important to have a register of all of the systems tested. It can be useful for detecting possible failures that are constantly repeated. This information can then be sent to the design department to see if there can be any modification done to avoid this failures.

In the case of a repair department, this final register is essential because the systems that are tested may have already failed before. With this method, the failures can be detected earlier if they are related to the previous mistakes found.

7.2 Test system of company C's PES

TeknoCEA is a small company that produces and repairs around some hundreds of PES per year. Therefore it is not worth investing in an ATE. This is why the repair of the equipment is done with manual methods where the register of the measurements is done by an operator. The other reason of this fact is that there are numerous types of PES that are produced and repaired and each one has its singular protocol. If automatic methods would be applied, there would have to be several ATE to cover the demand. Nevertheless, there can be improvements done on this manual protocols to speed up and make more efficient the testing of the devices. An example of a new method of test protocol applied in teknoCEA will be developed in this project. It will consist on a test bed platform to test different PCBs from the control part of a PES and the posterior test of the whole PES.

7.2.1 Company C's PES functionality

The PES where this application will be applied corresponds to company C. It is a combination of a rectifier, a DC-DC buck converter and an inverter. Its functionality is to give a determined value of alternating current that is necessary for other applications. It grabs the energy from the electric network, using the three-phase connection. It then has a diode bridge followed by a block of capacitors to establish a continuous signal. The buck system reduces the value of voltage to a lower level. At the exit of this DC-DC converter, there are two inductors connected to form a continuous current source, as it has been seen in the buck converter explanation. The next system, the inverter, is connected after the inductors. It has two branches of semiconductors, therefore the output source is a mono-phase form.

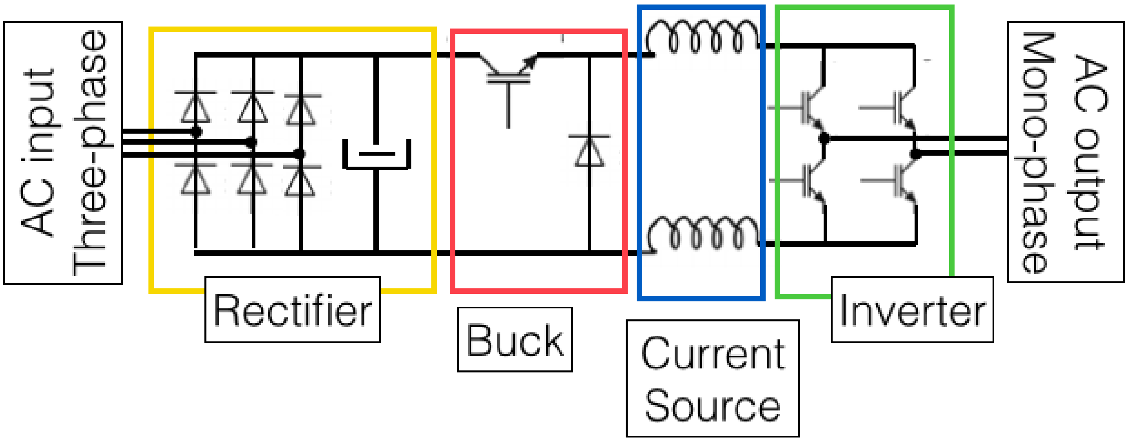


Figure 28: Diagram of company C PES.

The semiconductors of the systems are IGBTs. This is a component with an input and an output that works as an electronic switch controlled by the gate entry. A microprocessor sends a PWM signal to the gate of the IGBT. When this signal is positive the IGBT short circuits, whereas when the signl at the gate is zero, the device opens.

The PES are manufactured in two different modules: the rectifier with the buck and the inverter. They are a combination of PCBs for the control part and other devices for the power part, such as radiators, capacitors, semiconductors, etc. TeknoCEA is the responsible of the manufacture of the equipment and the verification of its functionality.

7.2.2 Test bed platform of the control part of company C's PES

The first step is to test the PCBs of the PES. The client of the PES provides teknoCEA with the boards. They are tested separately from the power part because it is the best way of detecting any failures and to test the functionality of them. A test bed platform will be developed to proceed with the test. It will be a rectangular platform with 4 channels placed on the borders to protect the cables.

The whole system is formed by different PCBs from the control part of the two modules of PES. There are a total of 6 boards:

- The CPU board is based on a microprocessor (it is a digital signal process (DSP)). It is responsible of controlling all of the boards. It is formed basically by a JTAG input, a power supply input, a DAC converter and an I/O connector to send and receive information from other boards.

- The Input/Output board (I/O) is responsible for exchanging the information of the CPU. It has digital and analog inputs, digital outputs and a communication output. It is connected to the other boards, sending them the necessary actions. It receives the information related to the state of the other boards and possible alarms . The information is send with optical fiber.

- The buck driver board is responsible of controlling the electronic switches of the buck. It receives the orders from the CPU and then transforms this information and sends it to the respective switches. This board is necessary because to activate the electronic switch, a signal with high power is required. The signal send form the CPU has low energy and, therefore, an intermediate step is requiredto leevel it up. The driver board has an output for the respective switch. It has a power source to function, and an integrated chip capable of doing the transformation of the small signal from the CPU to the bigger signal needed. It also has different LEDs to show possible alarms.

- There is another driver board for the inverter with the same structure as the buck driver board but in this case, it has 4 outputs, one for each switch of the PES.

- The voltage and current sense board is responsible for detecting when the current and voltage of the inverter is zero. This is needed to control the functionality of the PES. It has a power source to function and a comparator circuit formed by a differential operational amplifier.

- The auxiliary board is designed for the protocol purpose to be capable of applying external signal on the Voltage and Current sense board.

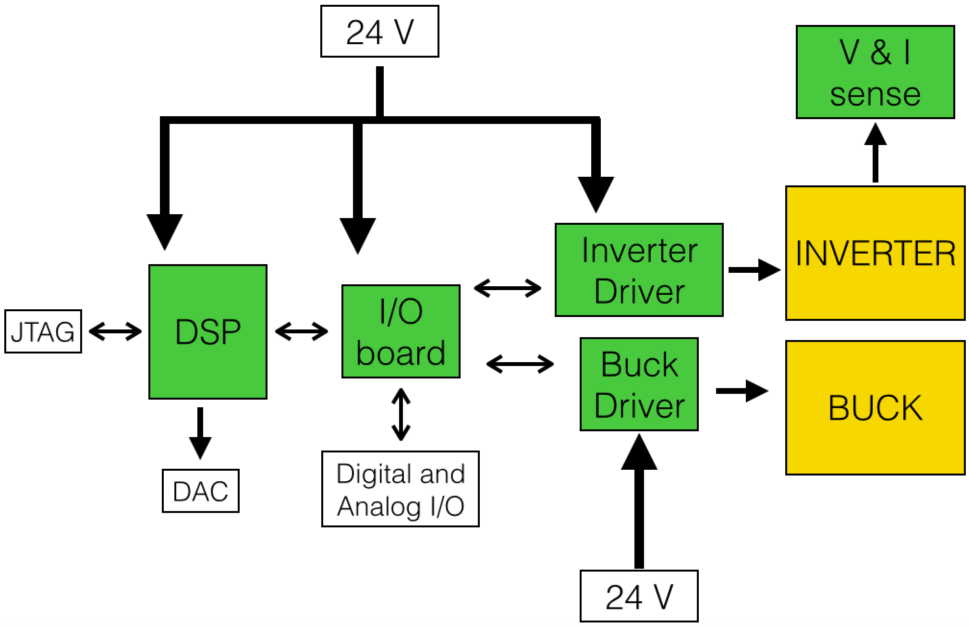


Figure 29: Block diagram of the test bed platform.

7.2.2.1 Distribution of the boards on the test bed platform

In the test bed platform created there is the combination of all this boards simulating the original PES's control part. They are connected as if they were functioning normally. They are placed over a platform and connected with different optical fiber cables.

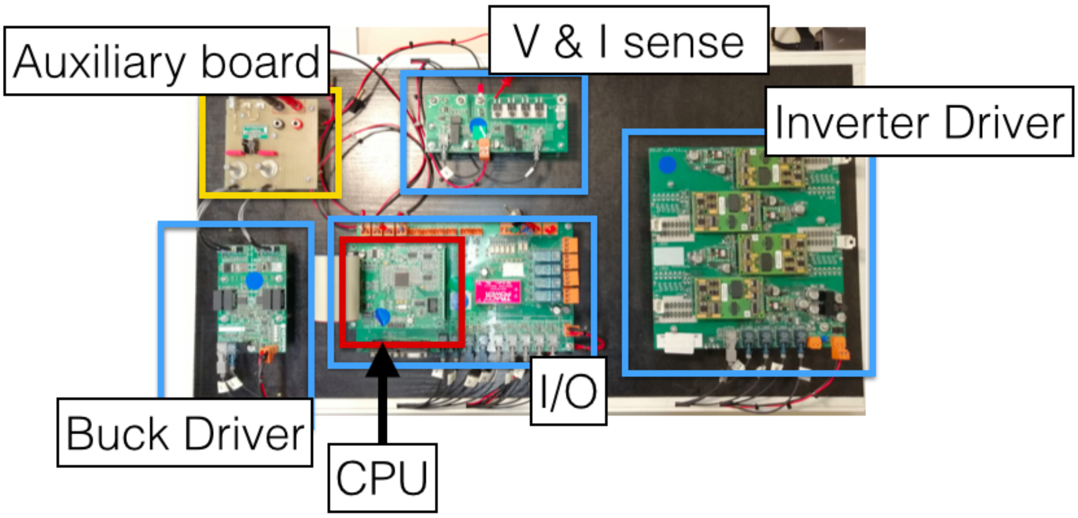


Figure 30: Distribution of the test bed platform.

Every board is powered up by an external source of 24 volts. There are some complementary devices connected to do the test. There are different LEDs and switches placed on the I/O board to analyze the state of the inputs and outputs. There are also different test points around the board. It is important to have an easy access to this points. There are also different oscilloscopes, power sources and multimeters around the platform. Finally the platform is connected to an external computer with the JTAG protocol.

7.2.2.2 Testing protocol of the boards of company C's PES on the test bed platform

As it has been studied, the first important stage of a protocol is to have the equipment ready. In this case, an oscilloscope, a multimeter and a power supply will be needed. It will also be necessary to have a computer. The list of activities that will be done begins when the instruments needed are placed around the platform.

1. The first step of the protocol is to do the visual test. Every board has to be revised to see if there are any mistakes found out. It is important to check them to avoid later problems.

2. After having analyzed the boards visually and having checked its correctness, it is time to power them up, connect all of the peripherals and follow with the protocol. The aim of this protocol is to do a functional verification test of the DUT, in this case, the boards. The idea is to apply different orders to the microprocessor to verify the functionality of the systems. With the JTAG protocol, the manufacture state of the boards is tested, as well as the possible short circuits. It is also the form of communicating with the controller. It is necessary to have a special software in the computer to be able to send information to the microprocessor. This software is explained in Chapter 8.

   When the program has been created, the test bed platform is powered up and the program is loaded to the DSP.

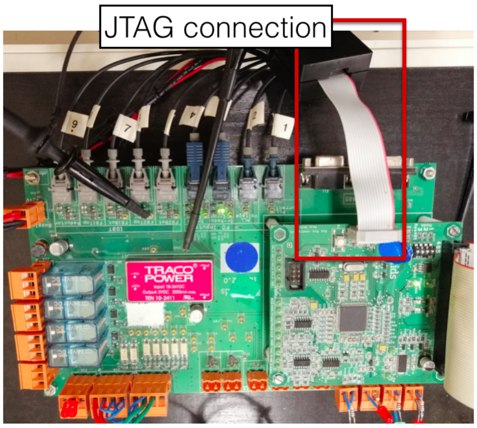


Figure 31: JTAG connection with the CPU board.

3. The next step of the protocol is to measure the power supply level on the boards using a multimeter and the test points. It is recommended to write down the different values of the measured points to have a register of the test.

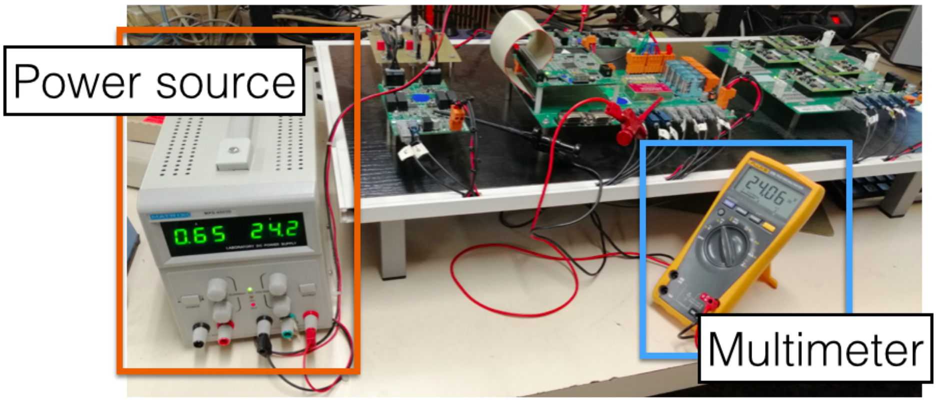


Figure 32: Supply voltage test done with a multimeter.

The current shown in the power source supply gives us a reference of the consumption of the systems. In this case, 0,65 A is a reasonable level of current. If it had a level over 1 A, it could indicate a possible short circuit or a failure in a device, as it has been studied in the detection of failures based on the power consumption.

When the power supply level is correct, the test of the boards begins.

- CPU board

    1. To test the CPU board, the DAC test is done. The idea is to sent a determined information to the DAC, configuring it with the program. This device will then give a determined signal in its output. The value of this signal is known. Therefore it is tested with an oscilloscope to see if it is correct.

2. The program is configured to generate a ramp function of 50 Hz of frequency and 4 V pick to pick level of voltage. The 4 outputs of the DAC are measured.

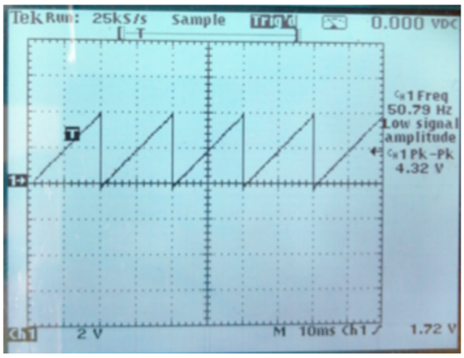


Figure 33: CH1: Ramp function generated by the DAC on the CPU board. (2 V/div, 10 ms/div).

The measured taken by the oscilloscope shows a perfectly marked ramp function. The indicators of frequency an voltage confirm the good result: 50,79 Hz of frequency and 4,32 V pick to pick level of voltage

The rest of the boards are also tested with the CPU board, afterall it is the one that gives the orders.

- CPU board + I/O board
    1. The first test done on the I/O board is the ADC converter test. An external analog source from a signal generator is connected to the analog inputs of the board.
    2. The ADC is configured to read this values and write them on a variable.
    3. The computer software has a table where the list of variables is showed, as well as their respective value. It changes in real time, so the values variate depending on the level of analog source applied.

4. The next test is the digital I/O. All of the digital inputs and outputs of the board are saved as a variable. With a simple program based on the *if* command, it is easy to read or write on this inputs and outputs.
5. There are leds connected to the outputs that light up when the respective variable is modified.
6. The inputs are connected to a switch. Modifying the state of it can modify the value of the variable associated to this inputs.

The rest of the boards are also tested with both the CPU and the I/O boards.

- CPU board + I/O board + buck driver board

    1. The buck driver board has the function of sending information to the IGBTs. It receives it form the CPU in the form of PWM and applies it on the gate of the switch. The program is configured so that the CPU sends a signal between 0V and 3,3V of 5 kHz of frequency. The first step is to measure if this signal is correct.

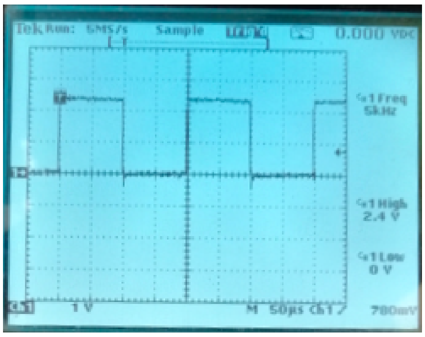


Figure 34: CH1: PWM signal sent by the CPU board to the buck driver board. (1 V/div, 50 us/div).

The frequency of the signal is 5 kHz. The maximum point is 2,4 V and the minimum point is 0V. Te signal is inside the limits marked by the test protocol (between 3,3 V and 0 V). The test is correct.

2. When it arrives to the driver, it modifies it to a signal between -10V and 15V. This has to be measured in the outputs of the board, where the gate of the IGBT would be connected.

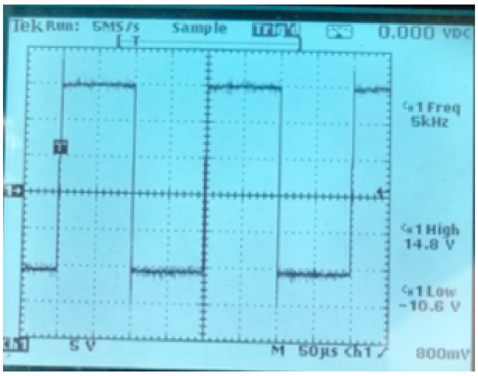


Figure 35: CH1: PWM signal sent to the gate of the buck's IGBT. (5 V/div, 50 us/div).

The frequency of the signal is 5 kHz. The maximum point is 14,8 V and the minimum point is -10,6V. It is a square sign with correct characteristics. The test is correct.

- CPU board + I/O board + inverter driver board

  The same test is done on the inverter driver board. In this case the commuting frequency is 250 kHz. The program is modified to send information to the 4 IGBTs on the inverter. To test it, first the signal from the CPU is measured and then the signal at the output of the board, where the gates of the IGBTs of the inverter would go. The 4 gates have to be checked.

1. First the CPU signal

Figure 36: CH1: PWM signal sent by the CPU board to the inverter driver board. (1 V/div, 2 us/div).

The frequency of the signal is 250 kHz. The maximum point is 2,8V, which is under 3,3 V, the maximum limit. The minimum point is -0,48 mV which is accepted as 0 V. The signal is approximately a square function and the measured values are inside the limits. The test is correct.

2. Then the gate signal

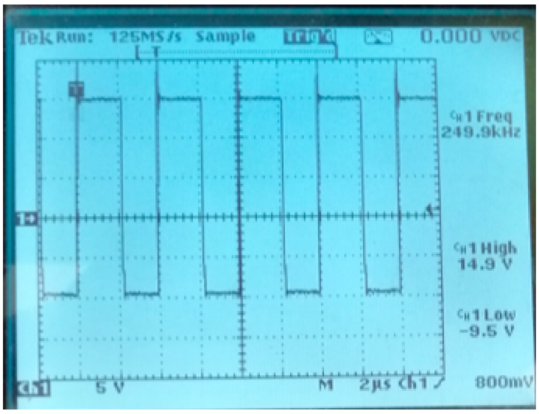


Figure 37: CH1: PWM signal sent to the gate of the inverter's IGBT. (5 V/div, 10 ms/div).

   The frequency of the signal is 249,9 kHz. The maximum point is 14,9 V and the minimum point is -9,5 V. It is a perfect square signal within the limits. The test is correct.

- CPU board + I/O board + Voltage and Current sense board

  The final test is done on the voltage and current sense board. A signal generator (AC supplier) is needed. To proceed with the test an extra board that enables the connection between this board and an the AC supplier is required. The DSP program has a variable associated to the output of the comparator in the board. When the level of the signal generator applied on the board is modified, the value of the variable changes.

7.2.3 Functional verification test of company C's PES

The implementation of the protocol seen assures the functionality of the boards, but it does not assure the functionality of the PES. When the final manufacture is done (where this boards are placed with the power part to become the final PES) another test protocol must be done. Now it is not necessary to test again the functionality of the boards, but it is necessary to test the whole block. Principally because it is important to assure that the power part matches with the control part. Different tests are applied to assure the functionality of it.

7.2.3.1 Description of company C's PES manufacture

The company C's PES is also manufactured at teknoCEA. When the control boards are verified, they are introduced in the manufacture stage. The result is a pair of systems, an inverter and a buck converter with a rectifier.

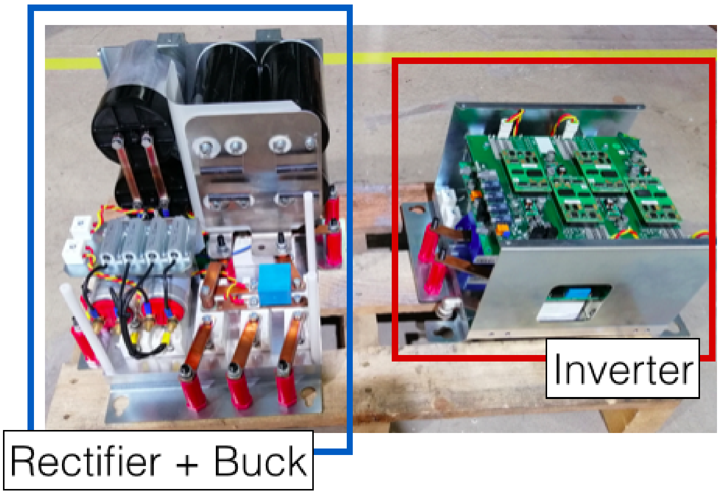


Figure 38: Company C's PES.

The manufacture stage begins with the placement of the semiconductors on the radiators that assure a good refrigeration. This radiators are previously calculated taking into account the maximum temperature of the semiconductors and the characteristics of their packaging. Between the package and the radiator a thermal paste is spread to have better thermal dissipation.

Afterwards, there are copper plates placed between the semiconductors and the input and output points of the system. They are responsible of carrying the high energy sources. They are transmitted from the capacitors to the inductance and to the semiconductors.

The posterior step is to place the block of the capacitors. They are mounted perpendicularly on the radiator. They are fixed on a metallic board and are connected to the plates.

The boards are also placed in the systems. They are fixed with specific screws.

Finally, the connection of the power part to the control part is done with different cables.

7.2.3.2 Testing protocol of company C's PES

When the systems are manufactured it is necessary to test their functionality with a functional verification test before launching them to the market . A protocol has been done to proceed with the test.

Taking into account that the boards have been previously tested with the other protocol, the aim of this test is to check the functionality of the both modules connected. The important measures that have to be done are: the DC bus after the rectifier, the commutation of the IGBT on the buck, the output value of the buck, the current applied on the inverter and the commutation of the IGBT on the inverter.

1. The preparation of the instruments needed.

   The first thing to do before starting the protocol is to organize the instruments needed. In this case, an oscilloscope is needed as a measure equipment. There are also diverse power supplies required and a platform where the CPU and I/O board, protection switches and the input of the electric network will be. It also has an emergency stop button. There is a contactor before the rectifier that is controlled by the CPU. Writting a '1' in the comand *switchK1* at the variable list displayed on the computer this switch is closed. Between the input and the rectifier there is a magnetothermic switch. It has a block of resistors in paralel. It is used to do a preload. It is important to do this because a capacitor has to have a progressive connection to the power supply, it can't be connected directly to it. The preload regulates the consumption of power so a block of resistors is placed before the systems and the input source and are then extracted when the capacitors are ready. A switch is placed in paralel with the resistors so when it is closed, the resistors are not connected to the circuit.

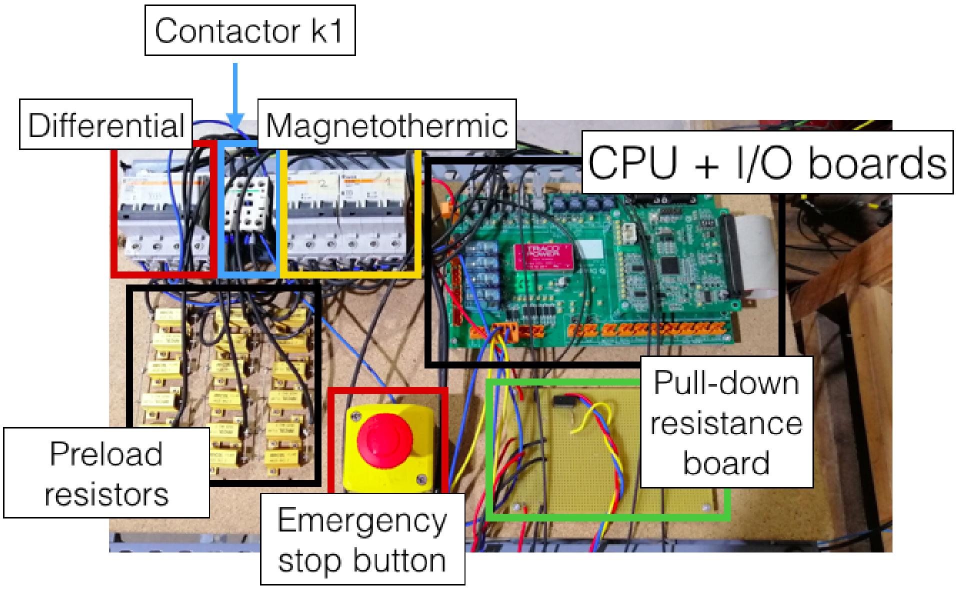


Figure 39: Platform of the testing protocol of the company C's PES.

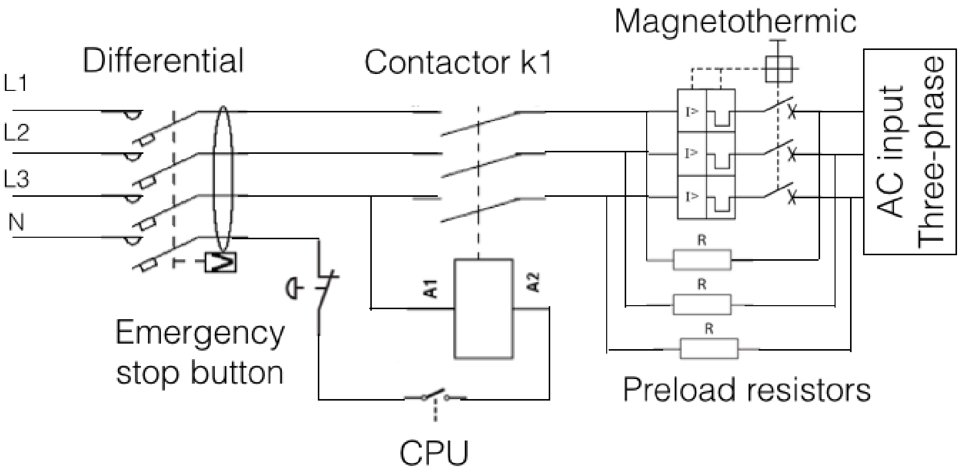


Figure 40: Electric circuit of the platform of the testing protocol of the Company C's PES.

2. Visual check.

   The buck converter is connected in series with the inductors and with the inverter as it has been seen in the schematic. When the connection is done, the visual check and the short circuit test is done. It is important to assure that the connection between the control part and the power part is correct. The driver board has to bee correctly connected to the IGBTs gate. It is also important to analyze if the capacitors are well placed (some capacitors have polarity). The other important aspect to check is the possible short circuits. With a multimeter, the connection between the positive and the negative of the DC bus is checked. It must not be connected. The connection between the input phases is checked, as well as the connection of the output points. There must not be any connection.+

3. Low voltage test.

   The next point is the test of the modules. First, it is done at low voltage because trying high voltage directly can be risky.

   (a) The CPU and the I/O boards are placed in the external platform with the entrance of the electric network, the diverse switches to protect the supply, a source of 24 Vdc for the boards and a variable DC source of 30 Vdc for the low voltage test. It is here from where the both systems are controlled and supplied.

   (b) A resistor simulating a load is placed at the exit of the inverter. For this case, it is a resistor of 55 Ω.

   (c) A variable DC source of 30 Vdc is connected to the preload resistors switch that is connected in series with the input points of the buck converter. As a continuous signal is applied, the diode bridge of the rectifier is not tested in this test so the level of the DC bus is approximately the same as the level of the source supply.

(d) The boards are supplied with the 24 Vdc source. The testing program, previously done with CCS sofware as the board testing protocol, is loaded to the CPU board with the JTAG protocol. The software is explained in chapter 8.

(e) Test of the DC bus.

  i. To check the DC bus an oscilloscope probe is placed on the positive and negative points of it.
  ii. The input source is gradually increased as the signal in the oscilloscope follows this increment.
  iii. When it is stable, the preload resistors are disconnected manually.
  iv. When the input source is fixed at 30 V, if the DC bus level of voltage is approximately 30 V, the test is correct.

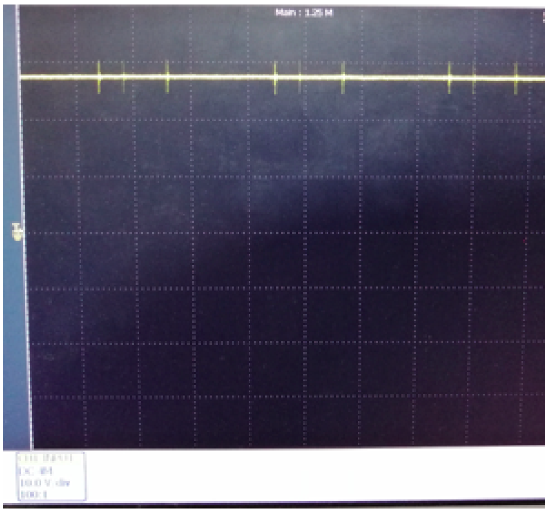


Figure 41: CH1: bus DC signal in the low voltage test. (10 V/div, 50 us/div).

The bus has a stable value of **27 V**. There are small picks that are negligible. The test is correct.

(f) Test of the buck's output.

   i. If the buck is working correctly, the output value is tested. The oscilloscope is placed on the buck's output.
   ii. The CPU is programmed to give a PWM signal to the IGBT of the converter and ensure a square output signal with a duty cycle of 30% and a frequency of 6,5 kHz. The company C uses this equipment at 5 kHz but a higher value has been fixed to make it work in harder conditions.
   iii. The signal at the output point of the buck has to be a square signal, with the mentioned characteristics.

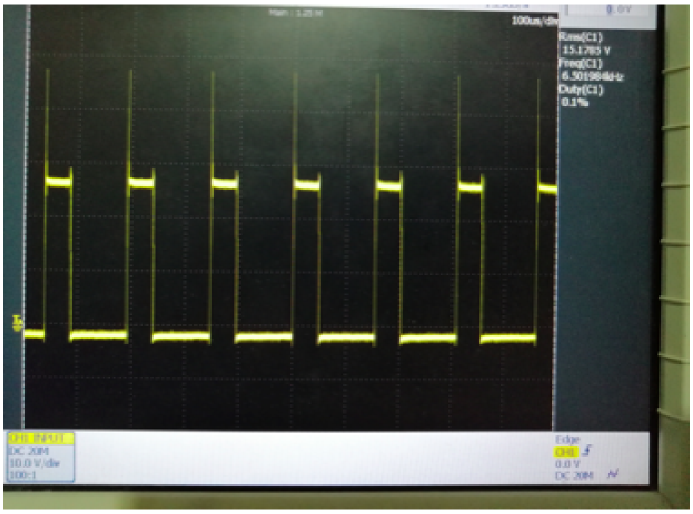


Figure 42: CH1: Buck's output signal in the low voltage test. (2 V/div, 100 us/div).

It is a square signal with a pick value of **27 V**, a frequency of **6,5 kHz** and a duty cycle of **30%** approximately. There are some picks in the signal due to the commutation of the IGBTs. The duty cycle is not registered correctly with the measurements of the oscilloscope. It has done manually.

(g) Test of the inverter's functionality.

  i. The test of the inverter is done analyzing the current on the load resistor. The two branches of the inverter commute at a constant frequency of 10kHz that is fixed at the CPU program. The next step is to measure the current through the load resistor. The output of the buck converter is a square sign that, when applied on an inductor, it generates a constant current source. The value of current measured is around 150 mA. It is measured with a hall probe connected to the oscilloscope.

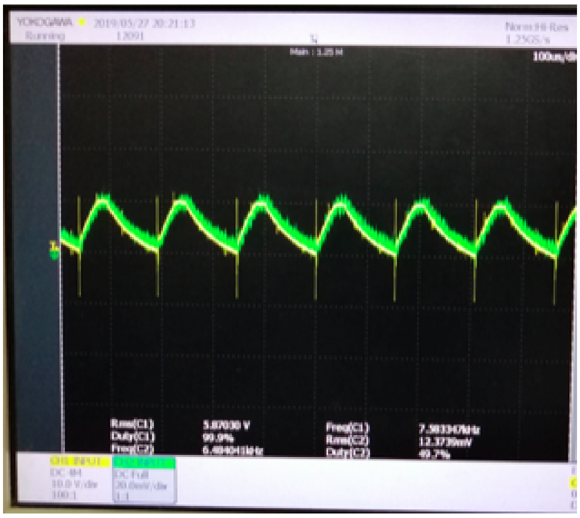


Figure 43: CH1 (yellow): Load resistance voltage signal in the low voltage test. (2 V/div, 100 us/div). CH2 (green): Load resistance current signal in the low voltage test. (20 mV/div, 100 us/div).

The current through the load resistance is measured with the hall probe. It transforms the current read to a voltage signal with a factor of 100 mV/A. The current through the load resistance is a more or less constant signal with a mean value of 12,37 mV. The current of the system is **123,7 mA**.

        ii. As the two branches of the inverter are commuting periodically, the current of the resistor passes in the first period of time through the top IGBT of the first branch and through the bottom IGBT of the second branch and then it passes through the other two. The output current must remain with the same level. If the current through the resistor doesn't change it means that the inverter is commuting correctly.

4. High voltage test.

   When the low voltage test has been done successfully and there is no risk of failure in the PES the high voltage test is applied.

   (a) The electric network is connected to the three switches in series: the differential switch, the magnetohtermic switch in paralel with the preload resistors and the switch that is controlled by the CPU. Then it is connected to the three inputs of the buck converter, one for each phase.
   (b) The oscilloscope is connected to the DC bus of the buck converter with a probe.
   (c) The control boards are supplied with the 24 Vdc power source. The program is loaded to the CPU and the connection of the load resistor remains as in the low voltage test, at 55Ω.
   (d) The differential switch is closed manually and the K1 contactor is closed with the CPU program. The systems are now powered up.
   (e) DC bus test.
        i. The level of voltage measured at the DC bus should be approximately 430 V. It is the level of voltage that has been rectified form the input. When it has a stabilized value the preload switch is connected, canceling the effect of the preload resistances.
        ii. The voltage that the resistors had is now given to the buck converter. This effect makes the voltage level at the DC bus increase to 545 V. This value is measured with the oscilloscope to proceed with the test.

(f) Continuous bus ripple test.

When a rectifier is powered up at around 500 V, the quality of the continuous bus that is generated is lower than in cases where smaller levels of voltage are applied. This quality is measured by a factor named ripple. It is the triangular wave of the charge and discharge of the capacitor but at high voltage it appears with more emphasis. Its mean level is the level of continuous bus but if the maximum or minimum level of it is too big it can cause failures. It is fundamental to analyze the ripple of the DC bus (maximum level minus minimum level) to see if the capacitors of the rectifier are stabilizing the voltage to a correct level. The limit has been fixed to 1 V pick to pick (from the higher level to the lower level).

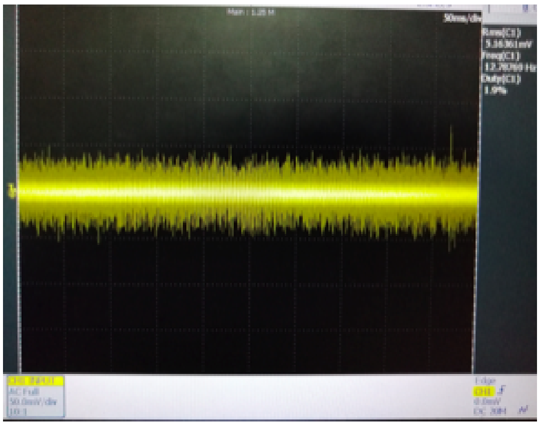


Figure 44: CH1 (AC): Ripple of the DC bus signal in the high voltage test. (50 mV/div, 50 ms/div).

The DC bus is measured in the AC mode to see the ripple that it has. It has a value of ripple of around **100 mV**. It is correct.

(g) Buck's output test.

As in the previous test, it is also important to check the output of the buck converter at high voltage. With the same program as before, the buck commutes to give an output signal. It is a square wave with a pick value of 545 V, a duty cycle of 30% and a frequency of 6,5 kHz.

(h) Load resistor measures.

  i. To test the final step of the system, the functionality of the inverter, the same process as before is followed. With the oscilloscope, the voltage of the load resistor is measured. It has to be around 3,7 A.

  ii. The current that passes through the resistor is also measured with the hall probe. When the inverter commutes, this value must not change or it would directly mean that a branch of the inverter is not working properly.

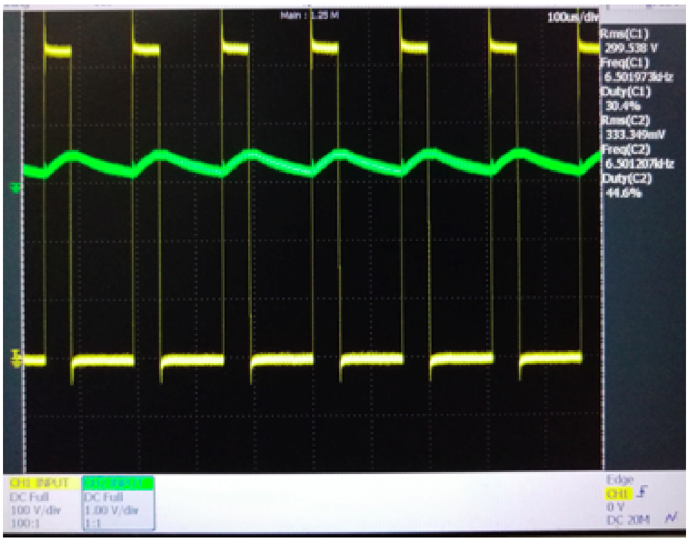


Figure 45: CH1 (yellow): Buck's output signal (100 V/div, 100 us/div). CH2 (green): Load resistance current signal in the high voltage test. (1 V/div, 100 us/div).

    The buck's output is a square signal with a pick value of approximately **540 V** with a duty cycle of **30,4%** and a frequency of **6,5 kHz**. The current through the load resistance is measured with the hall probe. It transforms the current read to a voltage signal with a factor of 100 mV/A. The current through the load resistance is a more or less constant signal with a mean value of 333,3 mV. The current of the system is **3,33 A**

    (i) Current sensor test.

    The inverter is equipped with a current sensor that is placed in the output of the system. It is a hall sensor that sends the information to the CPU board. To finish the test it is essential to compare the value of the current that the sensor is measuring with the current measured in the load resistor. An additional board has been created with a power source of +15V and -15V to supply the hall sensor. A pull-down resistor is connected to the output signal of the current sensor to have the possibility to measure it. The voltage is measured in this resistor and compared with the level of current measured before.

5. Temperature test.

   The two converters are equipped with a temperature sensor. It is a bimetallic sensor configured at 40ºC. When the working temperature of the converters reaches this value, the sensors send a signal to the microprocessor. This test has the aim of checking if the temperature detector works correctly. It is essential to revise the final temperature of the semiconductors and the time they take to reach to 40ºC.

   (a) The connection of the system to the electric network is done as in the high voltage test. The only different aspect is that the load resistor is changed to a value of 7,5 Ω.

   (b) The program has the configuration of the temperature test. Writting a '1' in the comand *termverif* at the variable list displayed on the computer the program is enabled and a counter starts.

   (c) The two converters commute to give a current through the resistor of 20 A. It is measured with the hall sensor.

(d) As in the high voltage test, the current through the current sensor in the inverter is checked. It has to be the same value as in the load resistor.

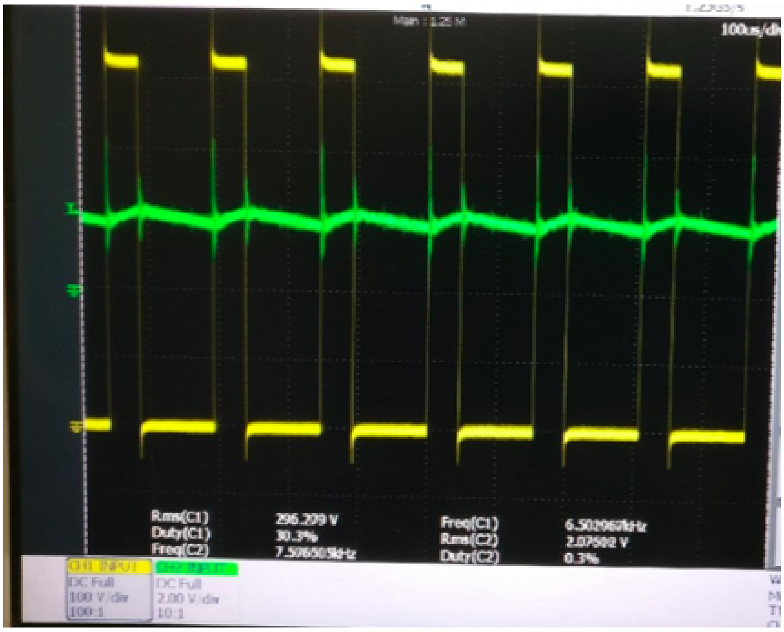


Figure 46: CH1 (yellow): Buck's output signal.(100 V/div, 100 us/div) CH2 (green): Load resistance current signal in the temperature test. (2 V/div, 100 us/div)

The buck's output is a square signal with a pick value of approximately **545 V** with a duty cycle of **30,3%** and a frequency of **7,5 kHz**. The current through the load resistance is measured with the hall probe. It transforms the current read to a voltage signal with a factor of 100 mV/A. The current through the load resistance is a more or less constant signal with a mean value of 2,02 V. The current of the system is **20,2 A**.

(e) Due to the fact that the inverter commutes at a higher frequency and that there are more semiconductors, it will reach the temperature of 40ºC earlier. When this happens, the inverter counter at the program stops and the inverter's commutation too. The final value of time has to be registered. It has to be around 20 minuts.

(f) The temperature of the buck converter will carry on increasing until it reaches the desired temperature. When it is reached, the buck counter at the program stops. The final value of time has to be registered. It has to be around 30 minuts.

(g) The commutation of the converters stops automatically when the both systems reach 40ºC.

(h) The temperature of all of the semiconductors is now measured with a digital thermometer. It will be lower than 40ºC because it is measured in the encapsulation of the semiconductors, not in the proper device. It has to be around 30ºC.

8 Software of the functional verification test protocol of company C's PES

During this project, there has been many information about the testing procedure and how to measure and collect the information needed. When the test done is to measure different values of voltage on different points of a board or a system it is not necessary to program a microprocessor. The only necessary thing is to supply the system with a source and check weather or not the values of voltage are correct. When the aim of the test is to see if the system works correctly in its normal conditions (a functional verification test) it is necessary to program the microprocessor. It is done with a software in a computer and then it is sent to the device with a communication method. In this project the JTAG protocol has been studied and used as a communication method.

If the system to test has to be repaired, it may have the program saved in the microprocessor. It is no necessary to create a new program because the system can already work in normal condition. In cases where the test is done in the production stage, before launching the product into the market, it is necessary to create a program for the microprocessor.

For example, in the implementation of the functional verification test made in this project, there are two programs needed to do the protocol. This programs are an integrated development interface to communicate with the device.

The software that has been used in this project to do the program is the *Code Composer Studio*. It converts the information given by the operator, in C/C++ language, to the JTAG language. The microprocessor that company C's PES uses is a DSP (digital signal processor) from a known company. Each microprocessor needs a specific configuration. It is explained in the technical manuals of the devices that are exposed in the website of the manufacturer.

The structure of this programs are based on a principal file where the main instructions will be written down. There will then be other files with the subprograms that will be called from the main file.

8.1 Software of the control part of the Company C's PES

The first program that will be created is for the control test on the test bed platform. This tests has been explained and detailed in chapter 7.2.2. It consists on a distribution of 6 boards from the control part of the PES on a platform. They are connected with optical fiber cables. The CPU board that controls the rest of the has to have a program that contains information for all of the boards. The idea is to send information to the microprocessor and test the main devices on the boards. It is not necessary to use real condition values as though the main objective of the test is to find out the state of the functionality of the boards.

The main file of the program will have the orders of the program. Different instructions will be written down. The first lines are destined to the initial configuration, then the proper program with the orders for the functionality test will be written.

8.1.1 Initial configuration

The creation of the program starts with the configuration that the microprocessor needs. This configuration sets the system on and ready to function. The lines of the program destined to the initial configuration are orders that call sub functions from other files.

The lines of the program are common for other microprocessors because the parameters that are programmed are most of the time the same. The list of instructions for this application is enumerated:

1. The initial configuration begins with the initialization of the interruptions. An interruption is an action that temporally stops the program of the microprocessor acts. There are pins of the DSP that are configured to be interruption. For example, a pin can be connected to a specific point and when it reaches a determined value, the microprocessor has to stop. It is done with an interruption. In this DSP there are a lot of interruptions. There is a Peripheral interrupt expansion (PIE) formed by a block of multiplexors that selects the interruption needed. This interruptions are defined in the registers. They first have to be cleared writing a 0 in the instruction. Then they are enabled.

2. The DSP works with a system of clock. This parameter regulates the number of instructions that the microprocessor does in a period of time. The value of the desired level of clocking must be established.

   For this test, the clock has been established at 100 MHz

3. The DSP incorporates diverse timers. There are fixed structures that configure the design of the timers. Depending on the test, this parameters are modified. For this example, the Timer 0 is used. The instructions needed to configure the timer have to be enabled.

4. Input and Output pins.

   The DSP has many pins that can be either an input or an output. There is a multiplexor that selects the state of the pin. In case of having an input, the order will be the number of the pin with a '1'. For an output, the order will be the same but with a '0'. If it is an output, the information goes outside and it can proceed from many intern peripherals. It is necessary to indicate the state of the pins. This is done with the instruction *GPIO.Mux*.

5. Finally, the variables that will be used in the program have to be created. There is a file where all of the variables used are defined. They can be long, short, positive, negative integers, etc. The initial value, generally 0, has to be defined too. as well as the type of variable used.

8.1.2 Main program

The following step is to write the orders that correspond to the desired test. Depending on the results wanted, the program has to have a determined value for the parameters and for the instructions given.

1. DAC

   The first test done is the DAC test. The microprocessor has to give a determined information to the DAC. The instructions for this device have a determined structure that can be found in the DSP manual guide. The parameters are selected depending on the application done.

2. ADC

   For the ADC test, the idea is the same. The ADC is configured as desired with the instructions *ADC.registers*.

3. Digital I/O

   For the outputs test, it is necessary to join the pins that have the LEDs connected with the program. A variable for this test is created *LED*. When it is enabled (turned to '1') the microprocessor gives the instructions. Or it sets the output pin ('1') or it clears it ('0').

   The same protocol has to be done for the inputs test. Different variables are created for every possible input that is connected to the switch. Every pin is associated to a variable. When the variable SW is enabled and the switch is actioned, the pins change their state and the microprocessor gives the orders to the variable. It either sets the variable or it clears it. The result is displayed in the variable list on the variable $INPUTx$.

4. Buck PWM

   To test the buck driver the microprocessor sends a PWM sign to the driver board when the variable *buckPWM* is enabled. The creation of this order is done with the PWM peripheral that the DSP has.

   It is a module that is controlled by the CPU and the clock and has two outputs for the PWM signals. For the buck driver only one output is needed. This instructions have a fixed structure with variable parameters depending on the conditions of the signal send. There are many possible ways of generating a PWM signal. It has the parameter of the frequency, the period, the duty cycle, the rising-edge delay etc. Each one is selected with a determined structure in the program. Configuring the respective registers of the module to '1' or '0' and adding the parameters.

   The program adapts the parameters to the demand and selects the output pin of the microprocessor from where to send it. If the variable for this test is enabled, the PWM pin is set.

5. Inverter PWM

   It happens the same for the inverter driver test. In this case the two PWM signals have to be send at the same time. The parameters are the same as in the previous case. The only difference is that now there are more instructions that have to be modified. The microprocessor gives the option to send the two PWM signals at the same time with toggled commutation. There are different possibilities of combinations. There can be a delay of 0 seconds where one of the signals becomes positive at the time that the other becomes negative. They can also have negative or positive delays. If it is negative, the two PWM signal are overlapped. If it is positive, they are separated.

   The program adapts the parameters to the demand and selects the output pins of the microprocessor from where to send them. When the variable *inverterPWM* is enabled, the pins are set.

8.1.3 Flowchart of the algorithm of the software

The program is written in C, but the best way to understand it is by using a flowchart of the algorithm.

In this first image, there is an explanation of the different blocks used in the algorithm. It is a legend useful for the rest of the diagram.

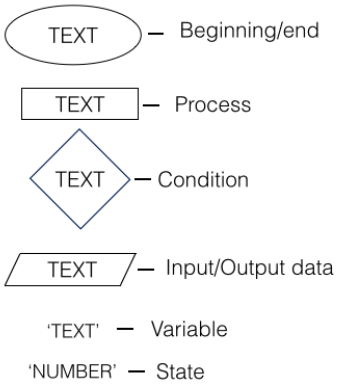


Figure 47: Legend of the algorithm of the software of the control part of the Company C's PES.

The algorithm begins with the initial configuration as we have seen. It is the beginning of the main file.

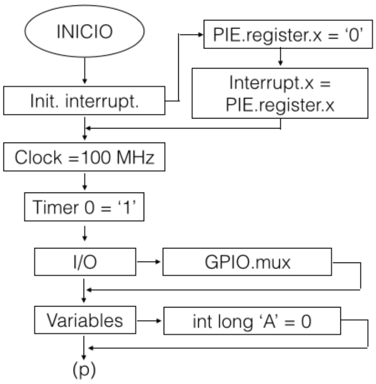


Figure 48: Algorithm of the initial configuration.

The rest of the program is written after the initial configuration. It is divided in sub functions and depending on the test, one or other will be applied.

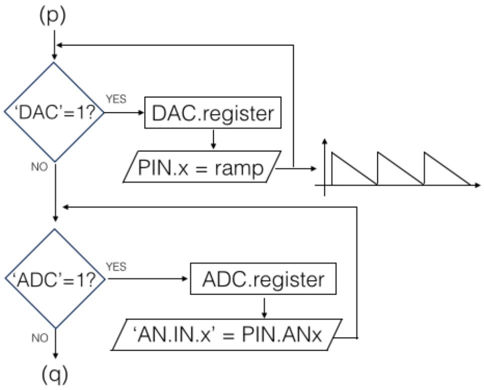


Figure 49: Algorithm of the DAC and ADC configuration.

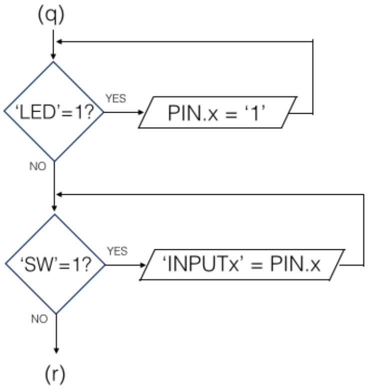


Figure 50: Algorithm of the Digital Inputs and Outputs configuration.

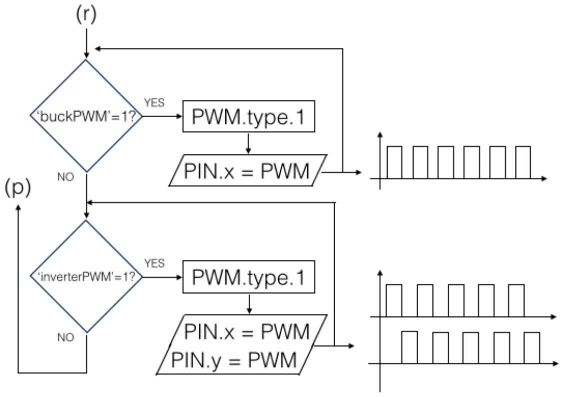


Figure 51: Algorithm of the buck's driver and the inverter's driver.

8.2 Software of company C's PES

The other program created is for the final test of the complete PES. When the boards have tested, they are manufactured with the power part to form the complete PES. The CPU board is the same so it has the same microprocessor. The only thing that changes in this test is the finality of the program. In this case, it is necessary to test the functionality of the two systems as though they were working in real conditions. Knowing that the previous test has been done, it is not necessary to focus in the functionality of the boards.

8.2.1 Initial configuration

The initial configuration is the same as the one determined in the control test because the micro processor is the same. The configuration of the clock and the timer has the same structure and values. The difference with the previous software is the declaration of variables. For this example, there has been different variables created. Another big difference is the use of the contactor K1 as showed in the electric circuit of the testing protocol in chapter 7.2.3. It is controlled by the CPU

8.2.2 Main program

The following step is to give the orders that correspond to the test. In this case, it focuses in the commutation of the semiconductors so the main program will be based in the PWM structure.

1. contactor K1

   The program starts with the configuration of the input contactor K1. The switch that is connected at the input of the electric network is a CPU controlled contactor. When the microprocessor activates the relay of the I/O board that is connected to the contactor it activates the relay on the contactor and it closes. For the program, the respective pin is configured as an output with the GPIO instruction. When the variable *switchK1* is set to '1', the output value changes to '1' and the switch is closed.

2. Low voltage test

   The low voltage test is enabled with the variable *commute*. The buck and the inverter start commuting when it is active.

   (a) Buck's commutation

   As it happened in the control part test, for the buck to commute a PWM sign has to be send from the microprocessor. This is done with the PWM structure that has been seen. In this case, the parameters are a frequency of 6,5 kHz and a duty cycle of 30%. The buck has been design to commute at 5 kHz but a higher frequency has been established to force it to the limits. With a duty cycle of the 30% we obtain an output signal with a mean value that, when applied to the inductors, it will give the current that we are aiming 20 A.

   (b) Inverter's commutation

   For the inverter, the PWM signal is configured as in the control test. For this example, the frequency is the same, 6,5 kHz and the duty cycle is 50% because the objective is to have the both branches commuting the same period of time to make no variations in the value of current on the load resistor.

3. High voltage test

   The only difference in this test is the value of input voltage. The software program is exactly the same as the low voltage test because the two systems commute at the same frequency.

4. Temperature test

   The temperature test is based on two counters, one for the buck converter and one for the inverter converter. When the microprocessor receives a signal form the sensor, it stops the counters.

   (a) Sensor signal

   The pins of the microprocessor that correspond to the signal of the temperature sensor are declared as an input with the configuration structure seen.

(b) Counters

The test starts when the variable *termverif* is enabled in the displayed variable list. At this precise moment two counters are enabled.

Knowing the time that the DSP takes to do an instruction (clock), a counter can easily be done with the *while a¡n, i++* instruction. A variable for the minuts and a variable for the seconds is created. When the temperature of the inverter reaches 40°C, the inverter counter stops and the converter stops commuting. The buck counter carries on. When the buck reaches the 40°C, his counter stop and the program stops sending the PWM signal and, therefore, the systems stop commuting. The contactor K1 is opened so no power supply is reaching to the converters. The program is done like this to protect the systems and to make them work on

8.2.3 Block diagram of the algorithm of the software

As in the previous example, the algorithm of the software is explained in the following images:

The initial configuration has the same structure as the control test program.

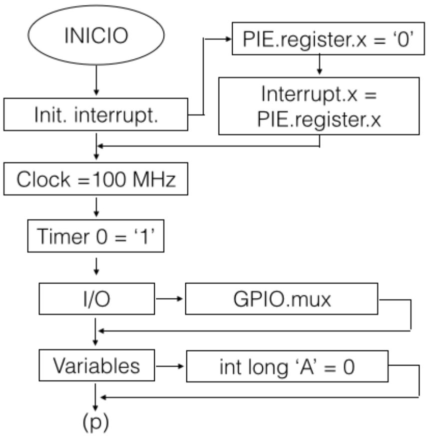


Figure 52: Algorithm of the initial configuration.

The rest of the program is written after the initial configuration.

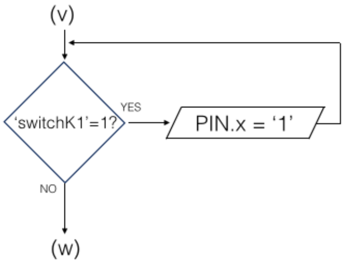


Figure 53: Algorithm of contactor K1's configuration.

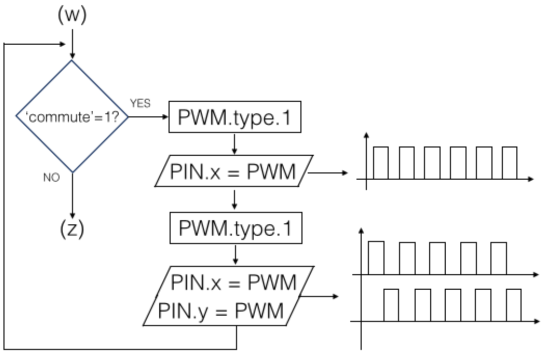


Figure 54: Algorithm of the system's commutation.

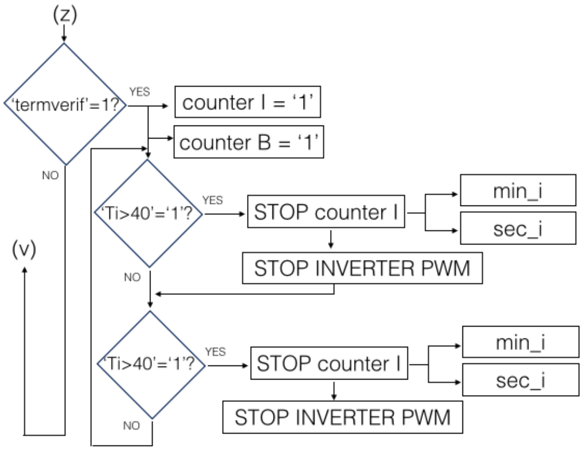


Figure 55: Algorithm of the Temperature test.

9 Validation results

To validate the test system and the testing protocol created and see if it is successful there has to be some tests performed. There will be the implementation of the tests on a group on the complete company C's PES. The idea is to validate some PES with the system and then force an error on the PES and see if the system is capable of detecting it. With the error known it is easy to see where the tests system should detect it. Without this actions, there is no certainty that the system acts correctly. The only way of finding it out is by forcing error on these 3 devices and seeing if the testing system detects the errors.

3 pairs of PES have been selected to be the sample of the test. Knowing what the results have to be and following the protocol created the 3 pairs are verified. When they are correct, an error for each one of them has been forced as explained in table 1. The protocol has been followed until the detection of the failures.

Validation test table		
Device	Error forced	Test result
1	Disconnection of the buck's IGBT	No commutation
2	Copper plate removed	No voltage in the DC bus
3	Modification of the load resistor	Wrong current value

Table 1: Results of the validation test.

The first device had no connection between the buck's driver and the IGBT. With the test system, it has been detected. In the low voltage test, when the commutation of the buck was testes, there was no commutation. The oscilloscope showed a continuous signal instead of showing a square signal.

For the second device, the copper plate that connects the input voltage with the rectifier has been removed. In the low voltage test, when the 30 V power supply has been connected and the DC bus did not increase, the test has been stopped. The failure has been detected: the input source was not reaching the system.

In the third device there has been a modification done in the load resistor. The value of it has been changed to 100 Ω. The current measured in the low voltage test had a lower value. The error has been detected. As it is seen, the system detected the 3 errors and, therefore, the system is successful in the validation test with a 100% of error detection.

To give more reliability to the system, a production test has been done. A sample of 12 pairs of PES have been taken. The functional verification tests has been applied to each one of them after their manufacture. The results are shown in the table 2.

Production test table		
Device	Test result 1	Test result 2
1	OK	–
2	OK	–
3	OK	–
4	FAILURE	OK
5	OK	–
6	OK	–
7	OK	–
8	OK	–
9	OK	–
10	OK	–
11	OK	–
12	OK	–

Table 2: Results of the production test.

There has been 12 tests done on company C's PES. There has been a rate of success of 91,7%. Only one pair of PES have been defective. The failure was due to a manufacture error. There was a wrong connection between the driver board and an the buck's IGBT. When the protocol has been done, the failure has been detected in the the low voltage test. The system was not commuting. The connection has been revised.

10 Environmental impact

This project belongs to the electric and electronic ambit. It is an area where the environmental impact is very low compared to others due to the high efficiency of the systems. The protocol of functional verification test that has been designed uses electrical energy from the electric network and it is applied on a load resistor. The output power is dissipated through the load resistor in the form of heat and there are also some losses in the two converters

The power absorbed from the electric network is calculated following the next equation:

$$Pin = 1,732 * Vin * Iin = 1,732 * 400V * 6,8A \tag{5}$$

It has a value of **4.711,17 W**. It is the power that the system is consuming. The output power is the consume of the load resistance analyzing the worst case, where the output current is 20 A.

$$Pout = Iout^2 * Rload = 20^2 * 7,5 \tag{6}$$

The output power is **3.000 W**.

The difference between this two powers is the dissipated power in the converters. The rectifier and the semiconductors are dissipating an amount of energy in the form of heat.

$$Pdis = Pin - Pout \tag{7}$$

The power dissipated is **1.711,17 W**. This power is not considerably big but it reduces the system's efficiency.

The impact caused by any possible failure is also very low. If there was any failure in the system created, there has been protections implemented, such as magnetothermic and differential switches, that would act, protecting the devices tested. This switches can be used again when the problem is fixed.

There is no waste generated and when the life time of the products is over, the recycling of the PES is responsibility of the client that has ordered the production and verification.

11 Budget

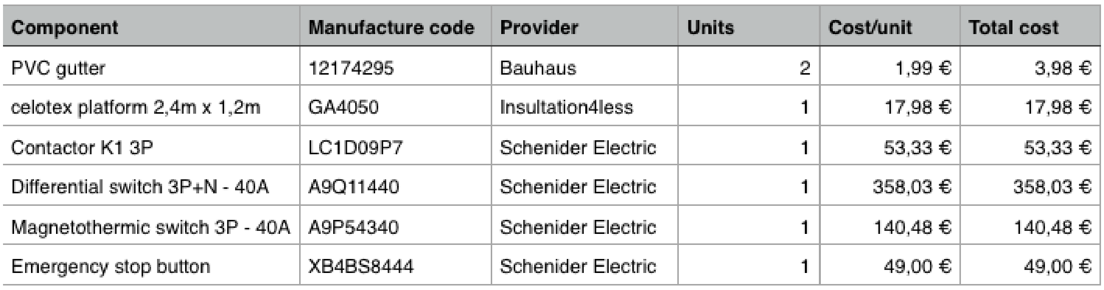
A study of the budget that would be needed to create the testing system in this project has been done. The different points that form it will be analyzed.

- Design

  The design of the two platforms and their respective software created for this project an has taken a period of time of 2 months. In the company where it has been produced, there is a price per hour established for an engineering work. In this case it is 70 euros per hour. A total of 320 hours approximately have been dedicated to the creation of the platforms. The design cost is **22.400 €**.

- Construction

  When the idea has been created, the following step is to manufacture the platform. The materials that have been as well as the information related to them is exposed in the next figure.



Component	Manufacture code	Provider	Units	Cost/unit	Total cost
PVC gutter	12174295	Bauhaus	2	1,99 €	3,98 €
celotex platform 2,4m x 1,2m	GA4050	Insultation4less	1	17,98 €	17,98 €
Contactor K1 3P	LC1D09P7	Schenider Electric	1	53,33 €	53,33 €
Differential switch 3P+N - 40A	A9Q11440	Schenider Electric	1	358,03 €	358,03 €
Magnetothermic switch 3P - 40A	A9P54340	Schenider Electric	1	140,48 €	140,48 €
Emergency stop button	XB4BS8444	Schenider Electric	1	49,00 €	49,00 €

Figure 56: Material cost.

The boards and the converters that were tested belonged to the client. They have no additional cost because they are borrowed. The cost of the auxiliary multimeters, oscilloscopes and power supplies is not considered.

The hours dedicated to manufacture the platforms have a cost of 40 euros per hours. The operators have taken 40 hours to build it. The cost of manufacture is 1.600 €.

Adding up all of the construction costs, the total value is **2.223 €**.

- Confection of the protocol

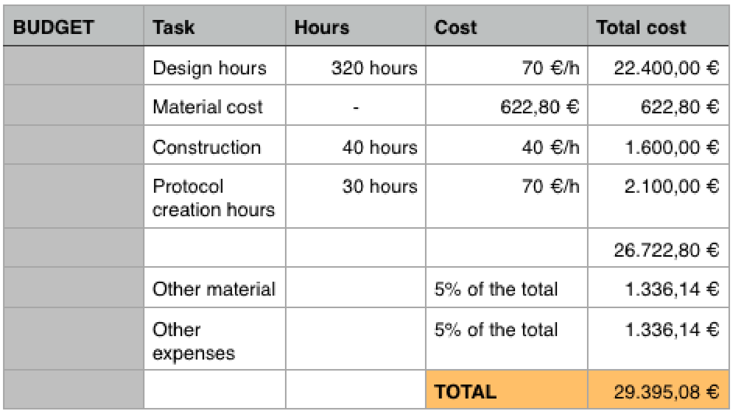
  The time dedicated to write the protocol of the two systems is also taken into account. 30 hours were required to generate the protocol. The cost of this hour is 70 euros. The total cost destined to write the protocol is **2.100 €**.

- Other material

  The use of other material such as cable or connectors has been stipulated at 5% of the total cost

- Other expenses

  Another 5% of the total cost has been added to cover other expenses.



BUDGET	Task	Hours	Cost	Total cost
	Design hours	320 hours	70 €/h	22.400,00 €
	Material cost	-	622,80 €	622,80 €
	Construction	40 hours	40 €/h	1.600,00 €
	Protocol creation hours	30 hours	70 €/h	2.100,00 €
				26.722,80 €
	Other material		5% of the total	1.336,14 €
	Other expenses		5% of the total	1.336,14 €
			TOTAL	29.395,08 €

Figure 57: Budget of the project.

The budget required for the implementation of a functional verification test on a PES is **29.395,08 €**.

12 Discussion of future improvements

The tests system has several aspects that could be improved to accomplish better results and more efficiency.

The temperature test done in the test of company C's PES is one of the most problematic aspects of the protocol. The main problem is that the measurement of the temperature is a very sophisticated action and no good method has been thought. The principal problem that has been noticed is that the digital thermometer has lots of interferences when the measure is done while the commutation of the systems is being held. This makes bad results and, therefore, the measures have to be done when the systems stop commuting. The temperature at the exact moment is not registered so there is a small error. There is already a variation from the real value due to the fact that the measure is done in the encapsulation of the devices. The access to the proper device is not possible because it is covered by its package. With the problem of the digital thermometer, this variation increases. It would be perfect to have the value of temperature at every moment.

A possible improvement done could be the incorporation of another type of thermometer with less interference vulnerability. The same thermometer could also be used with a protection to improve the results. It could be covered with an insulating material and the sensor would be shield. An example would be to protect the system with a type of elastomer.

The other possible improvement proposed is also related to the temperature test. It is the test that takes more time because there is a time destined to the increase of the temperature. During the time that it is being executed there can't be any other tests done. Another platform of the test of company C's PES could be produced to optimize the duration of the test. It could be destined to the temperature test. While the temperature of the PES would be increasing, another PES could be tested in the new platform.

Another proposal for the system could be to reduce to the minimum the dissipation losses. All of the output power is dissipated in the form of heat and it is lost. This energy could be used to power up other systems or it could be introduced to the electric network or a DC bus again.

13 Conclusion

The reliability of test systems as well as the necessity for them to be adapted to the new products is an important issue to solve. The aim of this project was to design a test system that was capable of doing a functional verification test on company C's PES.

The designed test system is reliable. The validation results show that the test has detected the 100% of the failures that were forced.

The system can be used in the production process. It was able to detect 1 failure on 12 products manufactured.

The system shows a good cost-benefit balance. The most amount of money has been destined to the design of the system but the cost of construction is low, so once it is designed, it can be manufactured with low costs. In addition, the system has a low environmental impact.

Following this results, it can be confirmed that the system is useful for a new product and it is reliable due to the fact that it has done a perfect failure detection of the tests.

Some improvements have been suggested that could increase even more the quality of the test system. If the implementation of a system to recover the energy is done, it could reduce the low environmental impact that is generated due to the lost dissipated energy.

All in all, with the design of this test system the correct functional verification of company C's PES has been achieved and the aim of the project has been accomplished. The system can now be implemented in the electronic industry.

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