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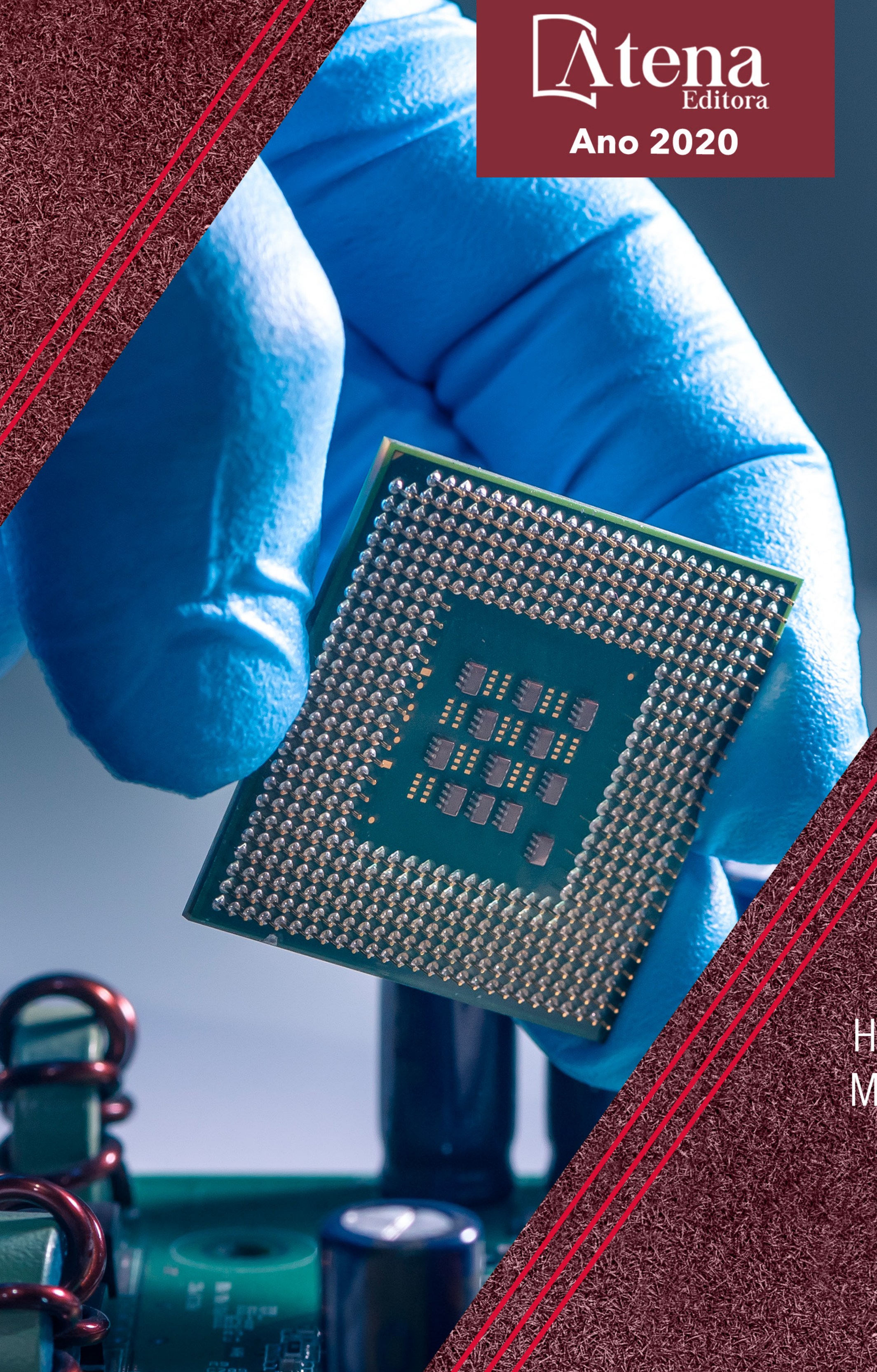

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Engenharia Elétrica e de Computação: Atividades Relacionadas com o Setor Científico e Tecnológico 2

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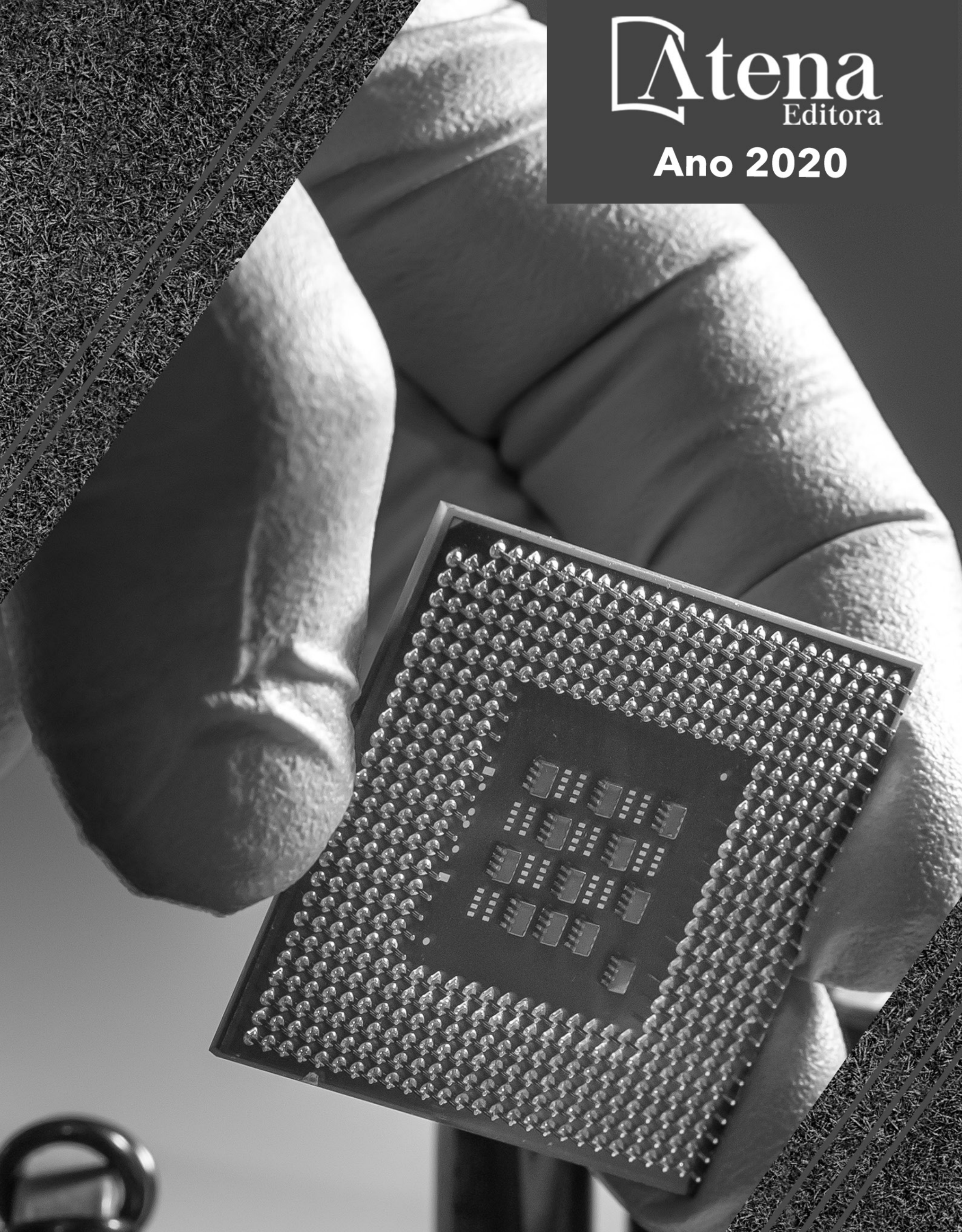

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Engenharia Elétrica e de Computação: Atividades Relacionadas com o Setor Científico e Tecnológico 2

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APRESENTAÇÃO

Não há padrões de desempenho em engenharia elétrica e da computação que sejam duradouros. Desde que Gordon E. Moore fez a sua clássica profecia tecnológica, em meados dos anos 60, a qual o número de transistores em um chip dobraria a cada 18 meses - padrão este válido até hoje – muita coisa mudou. Permanece porem a certeza de que não há tecnologia na neste campo do conhecimento que não possa ser substituída a qualquer momento por uma nova, oriunda de pesquisa científica nesta área.

Produzir conhecimento em engenharia elétrica e da computação é, portanto, atuar em fronteiras de padrões e técnicas de engenharia. Algo desafiador para pesquisadores e engenheiros.

Neste livro temos uma diversidade de temas nas áreas níveis de profundidade e abordagens de pesquisa, envolvendo aspectos técnicos e científicos. Aos autores e editores, agradecemos pela confiança e espirito de parceria.

Boa leitura!

João Dallamuta

Henrique Ajuz Holzmann

Marcelo Henrique Granza

SUMÁRIO

CAPÍTULO 14

OPEN SOURCE MODULAR DIDACTIC PLATFORM FOR POWER ELECTRONICS TEACHING

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ABSTRACT: This work shows the development of a modular platform for power electronics teaching applications. Its importance and the motivations for its conception are presented. The platform consists in several modules that can be interconnected to build different static converter topologies used in power electronics. Through this platform, it is possible to perform studies and experimental classes in technical schools, undergraduate and graduate courses. Several application examples are presented. This allows to improve the teaching of relevant technologies in the present context, with potential to create a positive impact in the society, given that the whole project is freely available under an open source license.

KEYWORDS: Power electronics, static converters, teaching.

PLATAFORMA DIDÁTICA MODULAR ABERTA PARA O ENSINO DE ELETRÔNICA DE POTÊNCIA

RESUMO: Neste trabalho, o desenvolvimento de uma plataforma modular destinada ao ensino de eletrônica de potência é detalhado. A sua importância e as motivações para a sua concepção são apresentadas. Esta plataforma consiste em diversos módulos que podem ser interconectados entre si para formar diversas topologias de conversores estáticos usadas em eletrônica de potência. Através desta plataforma, é possível realizar estudos e aulas experimentais em escolas técnicas, cursos de graduação e pós-graduação. Vários exemplos de aplicação são apresentados. Isso permite melhorar o ensino de tecnologias relevantes no contexto atual, com potencial para criar um impacto positivo na sociedade, dado que todo o projeto está disponível gratuitamente sob uma licença de código aberto.
PALAVRAS-CHAVE: Eletrônica de potência, conversores estáticos, ensino.

1 I INTRODUCTION

1.1 WHAT IS POWER ELECTRONICS?

Power Electronics is the field of Electrical Engineering which studies equipment that convert electrical energy (with a given amplitude, frequency, number of phases) into electrical energy (but with different amplitude, frequency and number of phases) with high energetic efficiency. They are classified in four categories, depending on the type of conversion performed: i) DC (direct current) to DC, ii) DC to AC (alternating current), iii) AC to DC and iv) AC to AC converters. The flow of electric power is controlled by such equipment through semiconductor devices (transistors, diodes, thyristors, etc.) and passive elements (capacitors, inductors, resistors). (MOHAN, ROBBINS, UNDELAND, 2007)

1.2 APPLICATIONS OF POWER ELECTRONICS

The participation of Power Electronics equipment in our lives is increasing day by day. They are presently found in all steps of the energy supply chain, that includes electrical energy production, its transmission, its distribution and its final use. A list of applications, according to the classification of the converters given in Section 1.1 is presented next:

- **AC to DC Converters (Rectifiers)**: generate a Direct Current (DC) output waveform from an Alternating Current (AC) source waveform (with an arbitrary number of phases). They can be used in: i) battery chargers (BOROYEVICH et al., 2010) (electric vehicles, cell phones, notebooks, uninterruptible power supplies-UPS, energy storage systems, etc.), arc soldering machines (CHAE et al., 1998), rectifying substations for railways and subway systems fed by DC (VERDICCHIO et al., 2018); power supplies for electronic equipment (computers, fluorescent and LED lighting systems, cooling systems, communication systems, medical equipment, etc.);

- **DC to DC Converters**: generate one DC voltage level output from another DC voltage source and provides its regulation. Some examples are: i) internal power supply of a cell phone or a notebook (BOROYEVICH et al., 2010) (generates the many required voltage levels from the main battery); ii) speed control in electric vehicles or trains based on DC motors (MOHAN, ROBBINS, UNDELAND, 2007); iii) electronic devices with integrated circuits working with different DC voltage levels (BOROYEVICH et al., 2010); iv) solid-state power transformers in future DC microgrids (RODRIGUES et al., 2016); etc.
- **DC to AC Converters (Inverters):** generate an AC output waveform (with an arbitrary number of phases) from a DC source. Examples include: i) connection of a photovoltaic PV panels to the AC grid (NAIK, MOHAN, 1995); ii) feeding the AC motor of an Electric Vehicle with variable voltage and frequency from its battery (CHAU, 2015); iii) feeding an AC industrial motor from a DC voltage produced by a rectifier (NOVOTNY, LIPO, 1996); iv) providing connection between DC and AC grids (VAN HERTEM, GOMIS-BELLMUNT, LIANG, 2016); v) mitigation of grid disturbances (harmonic voltages, harmonic currents, reactive power, unbalances) (AKAGI, 2005); etc.
- **AC to AC Converters:** generate an AC output waveform (arbitrary voltage level, frequency and number of phases) from an AC supply (with different voltage level, frequency and number of phases) (TRZYNADLOWSKI, 2016). In spite of the possibility of the direct AC/AC conversion (RASHID, 2017), it is usually implemented by an AC/DC converter followed by a DC/AC converter, with common DC bus. They can be used: i) for connecting two power systems with different frequencies (e.g. 60 Hz and 50 Hz) (HORWILL et al., 2011); ii) for high voltage DC transmission systems, where converter stations are connected by a DC transmission line (mainly used in long distance power transmission and for connecting remote renewable sources, such as off-shore wind farms, to the grid) (PADIYAR, 1990); etc.

1.3 MOTIVATION FOR THE STUDY OF POWER ELECTRONICS

According the U.S. Department of Energy, in 2030 80% of the electrical energy is going to be processed by Power Electronics systems (TOLBERT, 2005). This is due to the growing use of Power Electronics in: i) energy generation, transmission and distribution systems (BOROYEVICH et al., 2010) (TOLBERT, 2005) (renewable energy, storage, HVDC, active filters, etc.); ii) transportation electrification (railways (BOORA et al., 2007), electric vehicles (RAJASHEKARA, 2013), hybrid vehicles (EMADI, LEE, RAJASHEKARA, 2008) (RAJASHEKARA, 2014), full electric airplanes (NEUMAN, 2016) and more electric airplanes (RAJASHEKARA, 2014), electric ships (WANG et al., 2015), etc.); iii) industrial motor drives and robot actuators (FINCH, GIAOURIS, 2008) (BOSE, 2009); iv) smart grids (ZHENGYOU, 2017); v) DC grids (JOSEPH et al., 2018); vi) consumer products (MISHRA, 2019); vii) wireless power transfer (HUI, 2013); viii) IoT applications, etc.

Power Electronics is a multidisciplinary area that requires knowledge about electrical circuits analysis, digital and analog electronics, control theory, signal processing, digital simulation, microprocessors, real time processing, programing, switching power devices, electrical energy conversion topologies, electromagnetic devices (transformer and inductors) electromagnetic interference and compatibility (EMI/EMC), etc. (MOHAN, ROBBINS, UNDELAND, 2007).

So, it is a challenging and motivating professional area for the Electrical Engineers, who will be able to engage in projects related to emerging topics. Additionally, they will be able not only to apply almost all the knowledge they learned in the Electrical Engineering Course but will have to learn more during their careers. Undergraduate students, however, don't have this comprehensive view. Power electronics classes are usually restricted to the theory of the open loop operation of power converters, and do not cover all the aspects listed above. Therefore, didactic tools are needed to provide the students more experience in this area. They should provide them with a solid knowledge base, including experimental practices.

1.4 IMPORTANCE OF THE DEVELOPMENT OF A DIDACTIC PLATFORM

The proposal of the didactic kit is the development of a low-cost modular open source didactic platform that allows an easy implementation of different applications used in power electronics, enabling the learning and practical verification of the theoretical concepts needed in this area. This work shows a platform for pulse-width modulated DC-AC, AC-DC and DC-DC converters with digital control (BUSO, MATTAVELLI, 2015).

This kit can be used in experimental and project disciplines in technical schools, undergraduate and graduate courses, as well as in the initial development ("kick-start") of undergraduate research projects, undergraduate final works, master's dissertations and doctoral theses. In addition, it can be used by the "maker" community to achieve functional prototypes with a high chance of success, as well as serving as a training tool for the development of new projects.

Another interesting aspect is that all project files, including schematics, board layouts, bills of materials, tutorial and source code necessary to build and operate the platform are freely available under a public open source/hardware license at (GitHub, 2020). Therefore, interested students can acquire the necessary components for the construction and create their version of the platform at home, being motivated to start the assembly of their own laboratory with the acquisition of the main equipment. This will for sure motivate them, improving their learning during the classes.

1.5 ENTREPRENEURSHIP AND INNOVATION STIMULATION

The dissemination of knowledge linked to the kit allows young people, enthusiasts and other interested parties to know about the existence of this technology and its applications and to be interested in being future innovators and entrepreneurs in activities that use these technologies. Therefore, it is important to have the means to accelerate the growth of this local innovation ecosystem, with such as frameworks (this didactic kit and other (BATISTA et al., 2009) similar developments), which can be freely used by everyone.

In this way, it is possible to accelerate the production of knowledge, since the agents involved have ready and accessible tools available, thus not needing to start the whole process from scratch. Through the knowledge, training, skills and experience acquired, a community of agents is created, being able to participate in the innovation and entrepreneurship processes efficiently.

2 I PLATFORM DESCRIPTION

2.1 DESIGN SPECIFICATION

This modular open source didactic power electronics platform should be able to allow students (either in undergraduate or graduate courses), research assistants and even hobbyists in this area to perform experiments and develop their own projects. It is expected that the users of this platform will have different levels of experience in the field. So, safety and operation easiness are considered priority. According to this concept, the following specifications are outlined:

- Low voltage operation, according to the European Union 2014/35/EU Low Voltage Safety Directive and the Brazilian NR-10 Safety Regulatory Standard, allowing handling and operation without safety equipment.
- Usage of components easily found for immediate purchase in the local market of developing countries, when possible, to avoid expensive shipping costs and import taxes.
- Avoid complicated soldering techniques, using components which are more adequate for amateur soldering (with higher success ratio and easy maintenance).
- Have a modular construction, allowing straightforward and rapid interconnection of the modules. Also, not all modules need to be built at once, they can be produced gradually according to the user demands.
- Be less expensive and more flexible than other commercial teaching platforms found in the market.
- All project files are freely available under a public open source/hardware license.

2.2 FUNCTIONAL DESCRIPTION

Using this platform, it is possible to build several static converters topologies, including:

a) Voltage Source Inverters

The voltage source inverters use electrical switches (such as power transistors) to be able to convert (or exchange) energy between a DC source and an AC source (MOHAN, ROBBINS, UNDELAND, 2007). In order to perform this conversion in a controlled fashion, current and voltage measurements are needed at the inputs/outputs of the inverters. Those measurements are used by a central controller (or processing unit) to control the switches adequately. However, the switches generate unwanted harmonic components that compromise the stable operation of the inverter and the compliance with the harmonic emission standards (ERICKSON, MAKSIMOVIĆ, 2001). Thereafter, proper filtering of such harmonics must be performed. Possible applications of voltage source inverters are shown in Section 4.1, 4.2 and 4.4.

b) DC-DC Converters

Again, electrical switches (such as power transistors) are used, but now to convert (or exchange) energy between two DC sources (BASSO, 2014). This is useful when conversion between different DC voltage levels is needed. Energy storage elements such as inductors and capacitors are used as energy storage elements in DC-DC converters (MAMMANO, 2017). Once more, to perform this energy conversion in a controlled fashion, current and voltage measurements are needed at the inputs/outputs of the converters. Those measurements are used by a central controller (or processing unit) to control the switches adequately. Possible applications of DC-DC inverters are shown in Section 4.3.

Modern approaches for education in power electronics use both simulations and experiments to facilitate the learning process. Through the usage of this platform, for the topologies being studied, it is possible to:

- Study the theoretical background of a given power converter and develop the necessary control strategies for their operation (including their numerical simulation).
- Build the studied converter topologies using the modules available.
- Verify their operation experimentally, validating the theories and simulations involved.
- Evaluate the designed controllers, raising eventual opportunities for improvements.

2.3 OVERVIEW OF THE MODULES FROM THE PLATFORM

This platform consists in the following separate modules:

- **Processing Module**: routes signals (including power supply pins) between the microcontroller board, which is responsible for the operation of the platform, and the other modules.
- **Voltage Sensor Module:** uses four isolated Hall effect sensors to measure voltage signals needed for the converter control.
- **Current Sensor Module:** uses three isolated Hall effect sensors to measure current signals needed for the converter control.
- **Inverter Module:** incorporates four independent inverter half-bridges, opto-couplers, an isolated DC-DC converter and the DC link capacitance.
- **Filter Module:** comprises an inductor and a capacitor board, which are combined

to build different harmonic filter topologies.

- **Resistive Load and Transformer Module:** provide means to test the converters connected to passive loads and to the grid.
- In Section 3, the modules of the platform are specifically detailed and in Section 4 their interconnection in different topologies and applications is presented.

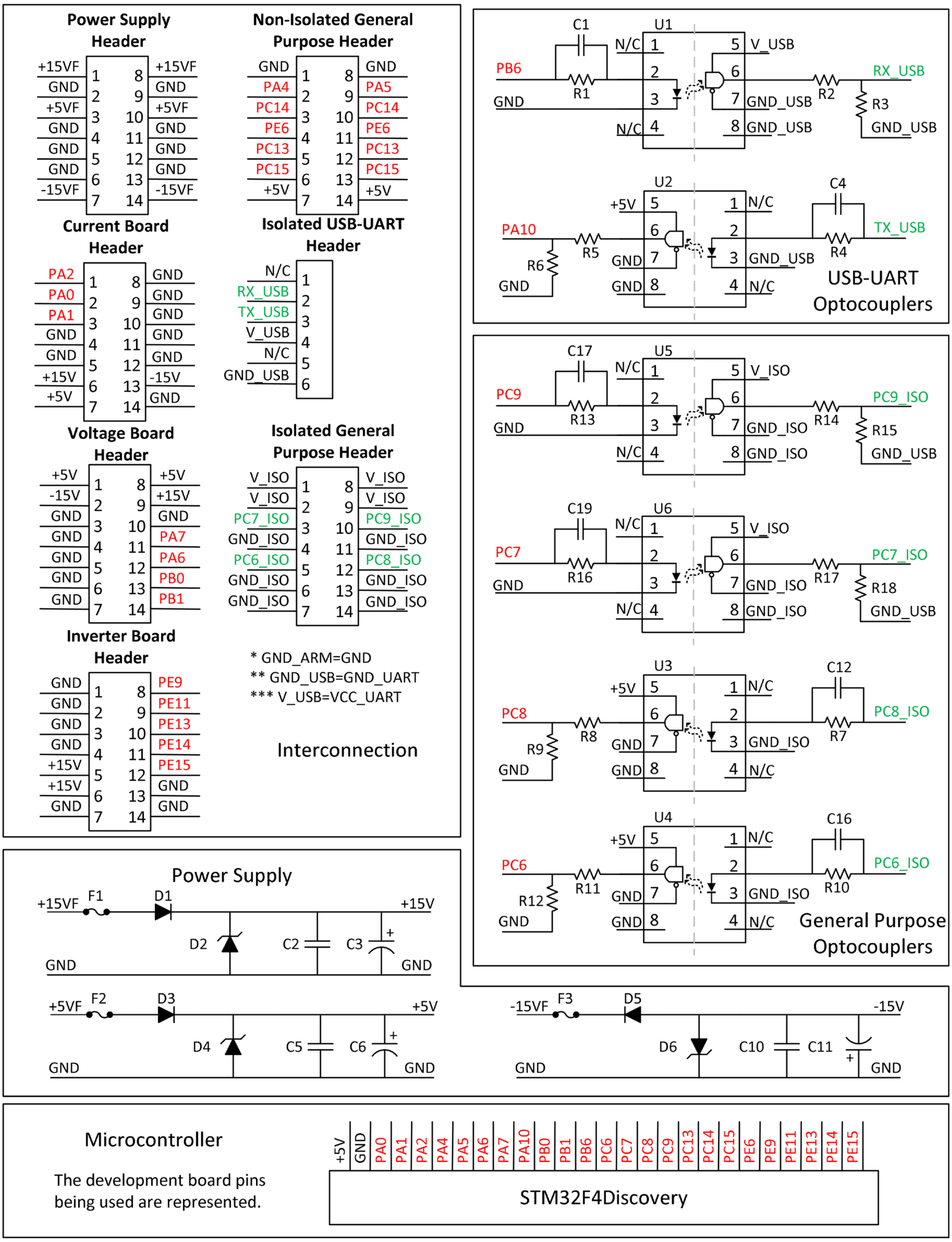
3 I DESCRIPTION OF THE MODULES

This item will describe each of the Modules by using simplified schematic diagrams. This approach presents easy to understand figures, but still showing enough details for the comprehension of the board's operation based on their internal electronic components, including the power supply and signals interconnections. The complete schematics and their corresponding bills of materials are available under a public open source/hardware license in (GitHub, 2020). Photographs and some initial experimental results using this platform were previously reported in (KOLEFF et al., 2019). A complete description of the Modules is presented in this paper.

3.1 PROCESSING MODULE

The **Processing Module** schematic is shown in Figure 1. The **Processing Module** is responsible for connecting the pins of the **STM32F4DISCOVERY** microcontroller development kit to the pins the pins of six board-to-board (**B2B**) connectors.

Those connections are described next. The B2B connectors "**Current Board Header**" and "**Voltage Board Header**" receive measurement signals coming from the **Current Sensor Module** (pins "**TC_OUT1, 2, 3**") and the **Voltage Sensor Module** (pins "**TP_OUT1, 2, 3, 4**"), respectively. The **Processing Module** routes the analog measurements (voltage level between 0 to 3,3V) to the **STM32F4DISCOVERY**, so that they can be processed. Once those signals are processed, the **STM32F4DISCOVERY** generates digital trigger signals (voltage levels of 0 to 3,3 V) transmitted to the **Inverter Module** (pins "**IN_A, B, C, N**" and "**IN_EN**") though the "**Inverter Board Header**" B2B connector. These four signals will command the switching of the eight inverter transistors. The signal on the inverter pins "**IN_A, B, C, N**" command the switching of the inverter transistors, while the signal on the "**IN_EN**" pin enables the inverter operation.



Note: all microcontroller pins are indicated in **red**, and all isolated pins are indicated in **green**

Figure 1 –Processing Module Schematic

The correspondence between the B2B connector pins of the processing module and the other modules is presented in Table 1.

Header Name	Processing Module		Target Module		
	Pin Name	in/out	Pin Name	in/out	Module
Current Board Header	1 - PA2	in	1 - TC_OUT1	out	**Current Sensor Module**
	2 - PA0	in	2 - TC_OUT2	out	
	3 - PA1	in	3 - TC_OUT3	out	
Voltage Board Header	11 - PA7	in	11 - TP_OUT1	out	**Voltage Sensor Module**
	12 - PA6	in	12 - TP_OUT2	out	
	13 - PB0	in	13 - TP_OUT3	out	
	14 - PB1	in	14 - TP_OUT4	out	
Inverter Board Header	8- PE9	out	8- IN_A	in	**Inverter Module**
	9 - PE11	out	9- IN_B	in	
	10 -PE13	out	10- IN_C	in	
	11 - PE14	out	11- IN_N	in	
	12- PE15	out	12- IN_EN	in	

Table 1 – Correspondence of the Pin Connections

The **Processing Module** allows the optically isolated serial communication between a computer and the **STM32F4DISCOVERY**. This communication is done by **USB/UART** converter module board (powered by the computer), connected to the "**Isolated USB-UART Header**" B2B connectors. This feature is useful for implementing Human-Machine Interfaces, facilitating the sage of this platform during experimental classes, freeing students from learning system hardware and software details and focusing on the power electronics topic under study.

There are six optocouplers in the **Processing Module**, named U1 to U6. They provide the galvanic isolation between the B2B connectors and the Processing Module, necessary to avoid damages to this Module and to the external computer in the case of inadvertent operation. The pair U1 and U2 isolates the computer from the **Processing Module**. The other optocouplers are used to isolate the "**Isolated General-Purpose Header**" B2B connector. They provided optically isolated access to further input-output pins of the **STM32DISCOVERY**.

The "**Non-Isolated General-Purpose Header**" is not optically isolated by optocouplers and provides access to further **STM32F4DISCOVERY** pins. Three from its six pins can be only used as digital signals, while the other can be used either as digital or as analog signals.

A single external DC source, with voltage levels +15 V, +5 V, -15 V and GND feeds the processor board by the "**Power Supply Header**" B2B connector. These voltage levels are distributed through the **Processing Module** to the other modules. It also powers the +5V supply pins from the **STM32F4DISCOVERY** board and the optocouplers.

3.2 CURRENT SENSOR MODULE

The **Current Sensor Module** consists of three Hall effect current transducers, LEM LTS 6NP, capable of measuring DC, AC and pulsed currents, with full galvanic isolation.

They are represented as U2, U3 and U5 in the board schematic shown in Figure 2.

The output signal of the LEM sensors has a voltage ranging between 0 to 5V, which is higher than the 3.3V range tolerated by the microcontroller. Therefore, each signal is processed by a conditioning circuit.

At the output of the LEMs, the resistor pairs R2-R4, R6-R8 and R10-R12 form voltage dividers to attenuate the signals. The capacitors C2, C4 and C5 are used to create low-pass filters for the signals. A TL074 operational amplifier, represented as U4x (x=A, B, C) in the schematics, is used as buffer for the output signal to prevent over- and undervoltages that can damage the microcontroller. The resistors R1, R5 and R9 are adjusted to compensate for the input impedance of the amplifier circuit. to adjust the signal amplitude. R15, R17 and R11 are used to load the output of the amplifiers and finally R3, R7 and R11 serve to limit the amplifier output current. The diodes D1, D2, D4, D5, D6 and D7 are used to clamp the output signal.

The output signals (”**TC_OUT1**”,” **TC_OUT2**” and “**TC_OUT3**”) go to the “**Current Board Header**” B2B connector. This connector also receives the power supply inputs +15V and -15V used to power the amplifier and 5V to power the current transducers. The 5V input is regulated to 3.3V through the voltage regulator U1 for use in the signal clamping circuit.

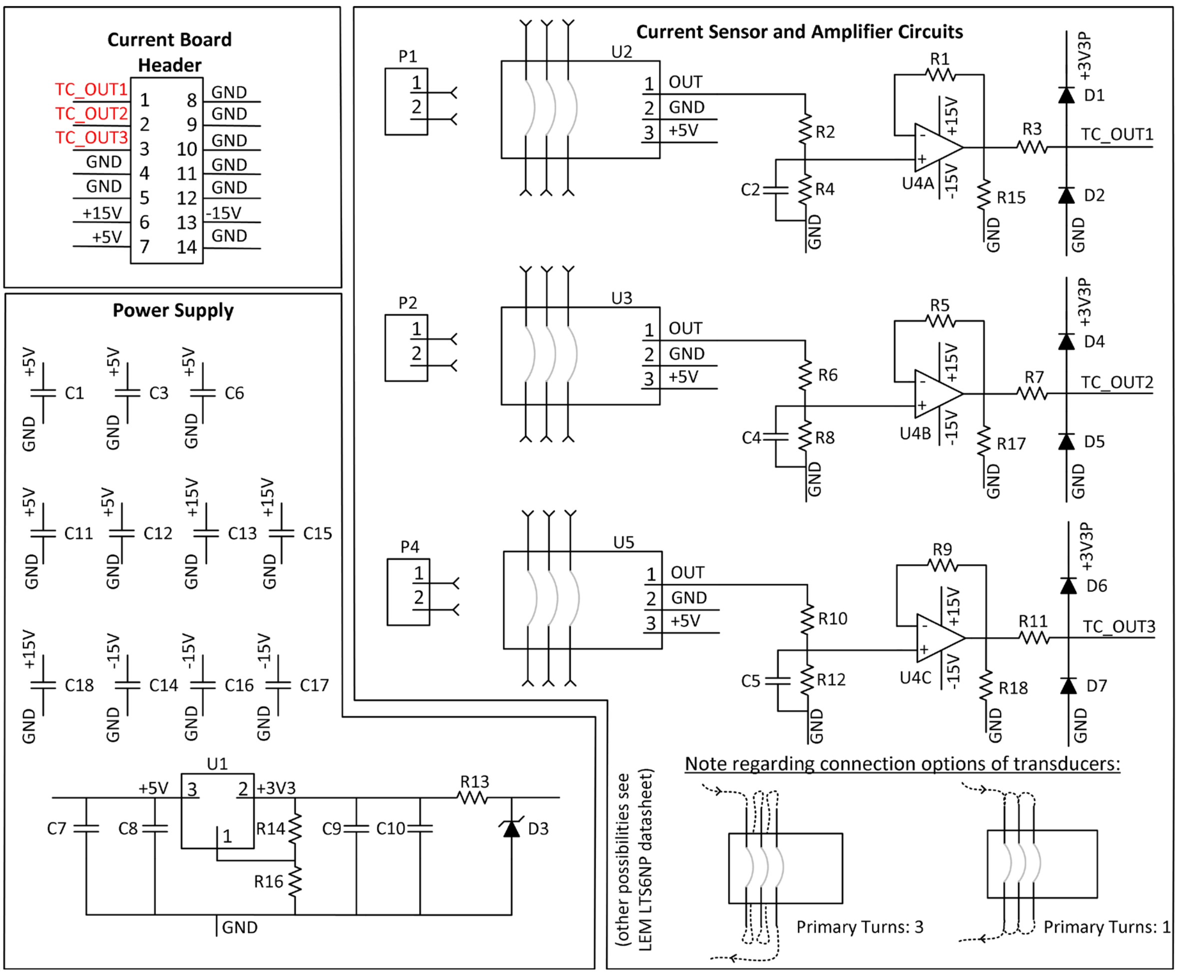


Figure 2 -Current Sensor Module Schematic

3.3 VOLTAGE SENSOR MODULE

The **Voltage Sensor Module** uses 4 Hall effect transducers, LEM LV25-P, with full galvanic isolation. In the schematic of Figure 3, each Voltage Sensor Unit (VSUx with x=1, 2, 3, 4) features one transducer that measures the difference of potential between the input pins "**+Vx**" and "**-Vx**" of the P2x connectors. In the primary side of the LV25-P, the proper choice of the shunt resistors R8x, R9x, R11x, R17x, R20x and R21x allows to adjust the voltage measurement range. In the secondary side, R16x is the burden resistor.

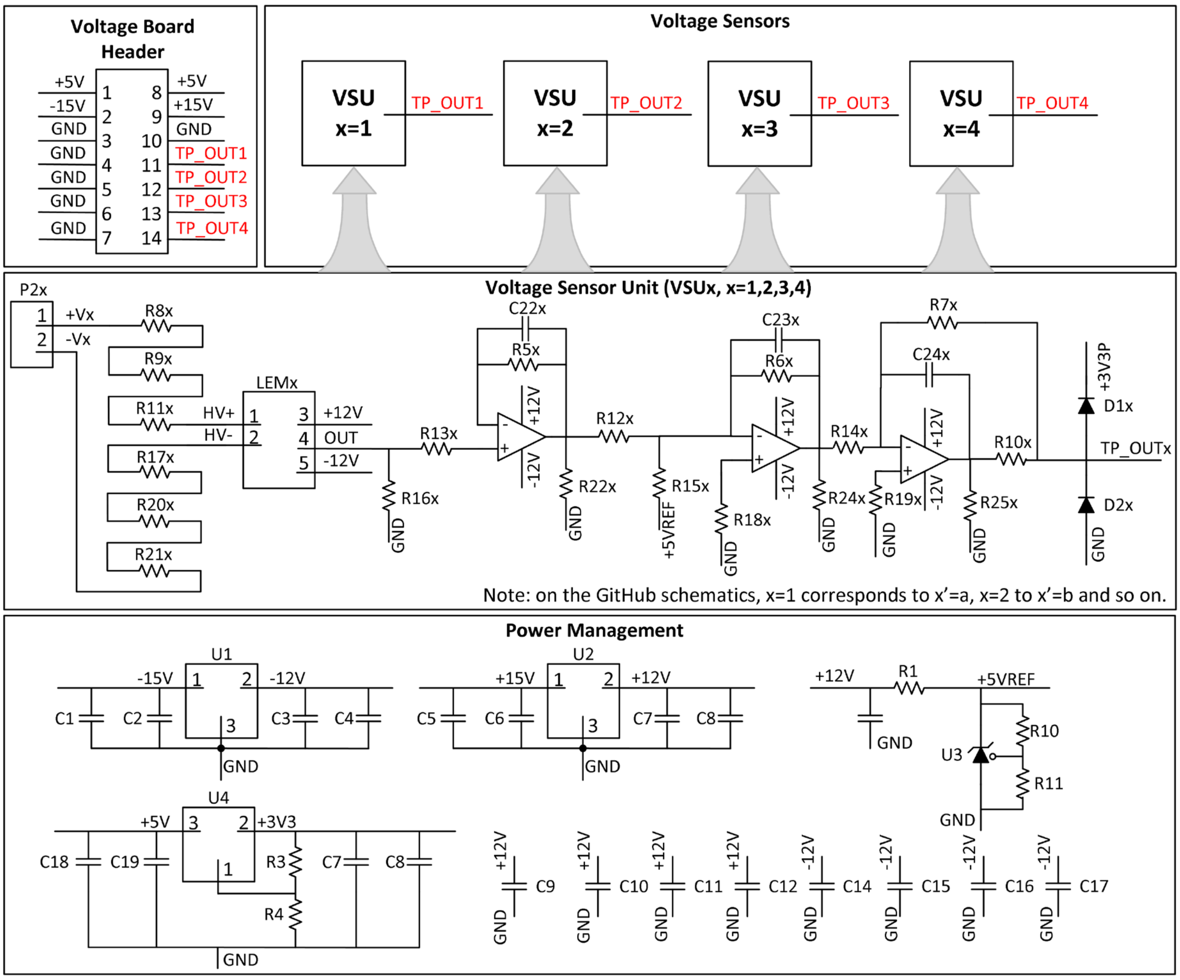


Figure 3 – Voltage Sensor Module Schematic

The output signal of the transducer ranges between -12V and +12V, therefore it needs to be adjusted to the voltage range tolerated by the microcontroller. This is done by the three stage of amplifier circuit described next:

I. The first stage is a unitary gain non-inverting circuit, with R13x equal to R5x connected to the non-inverting input. The capacitor C22x is used for low-pass filtering in this stage. R22x is used to load the amplifier output.

II. The second stage is an inverting adder circuit, with R12x connected to the output of the first stage and R15x connected to the +5V reference. In the feedback loop, R6x is in parallel with the capacitor C22x is used for low-pass filtering in this stage. R18x is adjusted to compensate for the input bias current and R24x to load the amplifier output.

III. The third stage is in the inverting configuration. An attenuation is provided by the resistor pair R14x-R7x. The resistor R10x is used to protect the output of the amplifier from overcurrents. The capacitor C24x is used for low-pass filtering in this stage. R25x is used to load the amplifier output and R19x is adjusted to compensate for the input bias current. D1x and D2x are used to clamp the output signal between 0V and 3.3V for protection.

The outputs signals "**TP_OUTx**" go to the "**Voltage Board Header**" B2B connector, which includes inputs from the +15V, -15V e +5V supply voltages. This board also has three voltage regulators for the +12V and -12V supplies to feed the operational amplifiers and the LV-25P and for the 3.3V supply that is used in the signal clamping circuit. These are represented as U1, U2 e U4 respectively. At last, a precision shunt regulator, represented as U3, provides the +5V voltage reference for the amplifier circuits.

3.4 INVERTER MODULE

The **Inverter Module** (see schematic shown in Figure 4) features the four transistor pairs (half-bridges) responsible for converting DC input voltage into AC output voltages, resulting in a three phase, four wire, four legs converter. Each of the integrated circuits U1 and U2 (L6203 Full-Bridge Driver) contain 2 half-bridges and the corresponding gate driver circuits. Each pair of transistors (half-bridge) operates complementarily, producing two level output voltages on the output pins "**OUT_A, B, C, N**". They are commanded by the gating signals provided by the **Processing Module**, which are inputted in the "**Inverter Board Header**" through the "**IN_A**", "**IN_B**", "**IN_C**" and "**IN_N**" pins. The "**IN_EN**" enables the inverter operation. These control signals are all referred to the same ground ("**GND**") and connected to five different optocoupler units (OcU). Each of those units contains an HCPL 2200 optocoupler (named U3, U4, U5, U6 and U7) with a speed-up capacitor (C1, C2, C3, C4, C5) and a resistor (R1, R2, R2, R4, R5) connected to its input. The OcUs provide optical insulation between the input signals environment (**Processing Module** and **Sensor Modules**) and the power circuit.

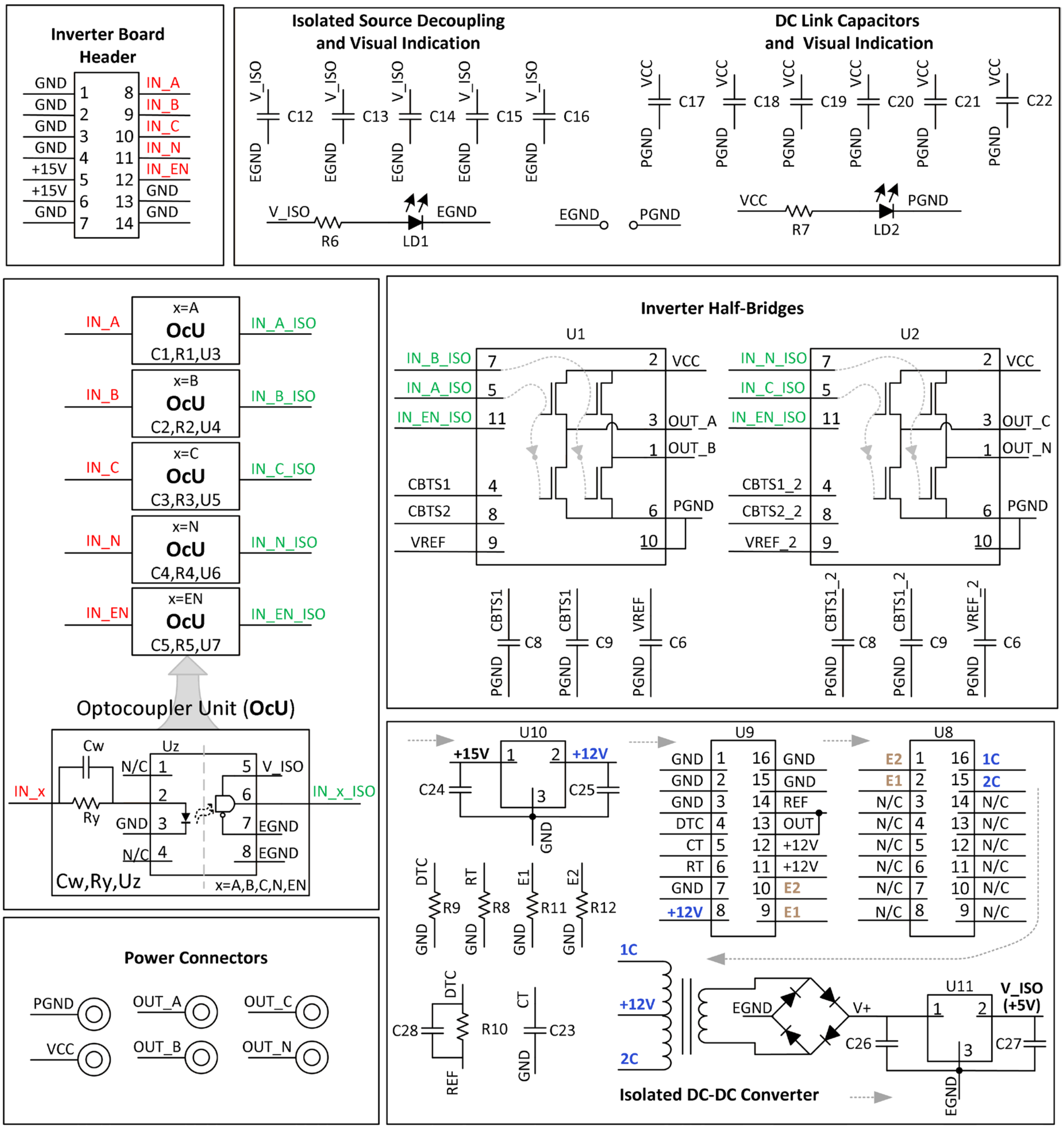


Figure 4 – Inverter Module Schematic

The output side of the optocouplers is powered by an isolated DC-DC converter unit. This unit is used to convert the +15V voltage supplied by the Processing Module to a +5V isolated DC voltage, which is then used to power the optocouplers. The DC-DC converter consists internally in a voltage regulator 7812 (U10), a PWM generator TL494 (U9), a current buffer ULN2004A (U8), a 12V:9V transformer, a rectifier circuit and a voltage regulator 7805 (U11). The voltage regulator U10 ensures a regulated input voltage of 12V for the DC-DC converter. The PWM generator together with the current buffer constitutes an inverter with square wave output voltage that is applied to a 12V:9V transformer. Its output is then rectified and finally adjusted to 5V by the regulator U11. The input pins share the reference pin “**GND**” (same potential as the Processing Module). The inverter circuit has as reference pins: “**EGND**” (ground pin for the electronic part of the **Inverter Module**) and “**PGND**” (ground pin for the power processing part of the Module). “**EGND**” and “**PGND**” must be interconnected (see jumper point at figure 4) but are isolated from the “**GND**” pin by the optocouplers.

The output signals from the optocoupler units (“**IN_A_ISO**”, “**IN_B_ISO**”, “**IN_C_ISO**”, “**IN_N_ISO**” and “**IN_EN_ISO**”) are directly connected to the L6203 Inverter Half-Bridges (U1 and U2).

On the power circuit of the board, it is possible to see the Inverter Half Bridges U1 and U2, the Isolated Source Decoupling capacitors (C12, C13, C14, C15 and C16) and the DC Link Capacitors (C17, C18, C19, C20, C21 and C22). The L6203 Half Bridges operate at a nominal voltage (VCC) of 30V. Their output signals (“**OUT_A**”, “**OUT_B**”, “**OUT_C**” and “**OUT_N**”) are connected to the **Filter Module** of the educational platform.

3.5 FILTER MODULE

This **Filter Module** is composed by three separate boards: two identical **Inductors Boards** and one **Capacitor Board**. These boards can be connected to build the following filter topologies: L, LC, LCL, 2L and 2LC. Their schematics are shown in Figure 5.

Each **Inductor Board** contains four identical inductors (one for each phase A, B, C and one for the neutral wire, which can be short-circuited by a switch). Their nominal inductance is of 3.315 mH, while their nominal peak current is of 1 A and their quality factor Q is of 4.96.

The **Capacitor Board** is made of six capacitors and three resistors (one capacitor in parallel to a capacitor and a resistor in series for each phase to neutral). The resistor can be short-circuited to perform experiments related to active damping. The individual capacitance is C=4.7µF/100V (film) and the resistance 39 Ω/2 W.

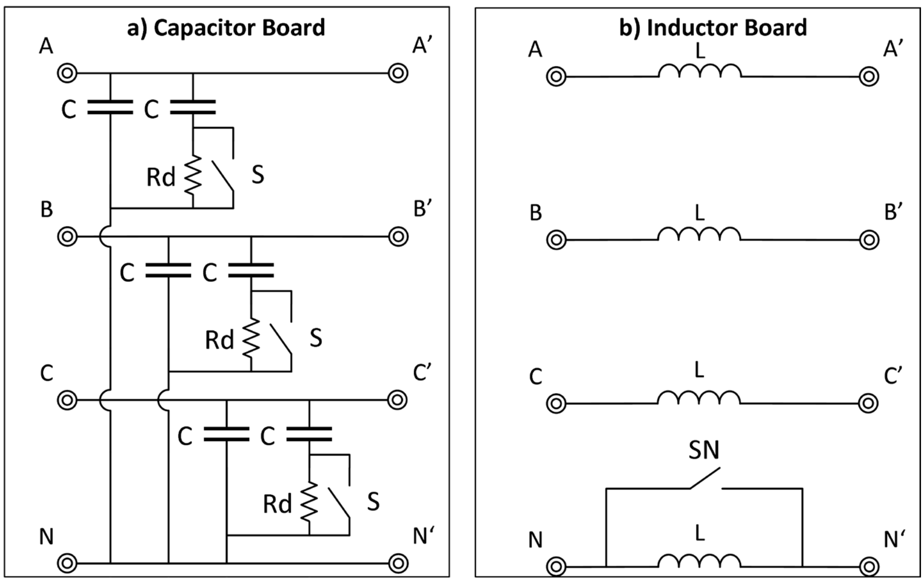


Figure 5 – Filter Module Schematics: a) Capacitor Board, b) Inductor Board

3.6 LOAD AND TRANSFORMER MODULES

The resistive **Load Module** is of very simple construction and comprises three wye-connected power resistors, identified as R in the schematics shown in Figure 6. It is also possible to see the banana plugs used for interconnection with other boards. The resistors can be connected to perform experiments where an electrical load needs to be simulated, as they convert energy into heat (which is then dissipated).

Conversely, the **Transformer Module** allows the platform to exchange energy with the electric grid. However, as the usual RMS grid voltage is of 127V/220V, and the didactic platform operates at low-voltage, transformers need to be used to step-down the grid voltage for adequate operation of the system. Also, the transformers can also ensure complete galvanic isolation of the platform from the grid if the neutral switch (identified as SN in the schematics) is set to be opened. A three-phase switch SG allows for complete connection/disconnection of the grid phases.

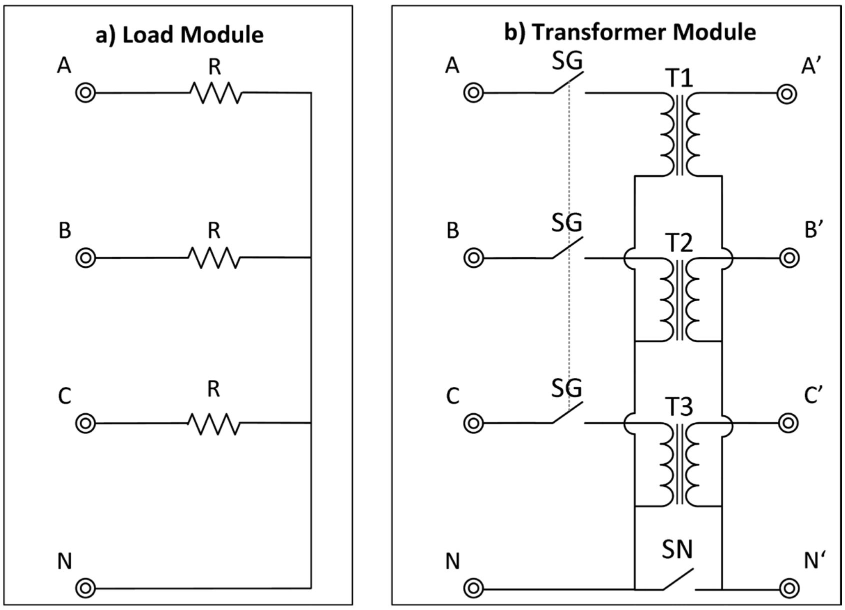


Figure 6 – Schematics: a) Load Module, b) Transformer Module

4 I SOME APPLICATIONS FOR THE DIDACTIC PLATFORM

This section lists some experiments that can be performed using the Didactic Platform. Current applications in renewable energy systems and electrical vehicles are emphasized to motivate students. Each case is briefly explained, showing how the modules are interconnected to perform the experiment. Possibilities of variations in the basic setup are discussed for each case. In all schematics shown in this section, the cables that interconnect the B2B connectors are shown in blue. The wires for the voltage measurements are shown in red, green and orange. Additionally, the wires used in power stage are represented in black.

4.1 GRID CONNECTED CONVERTERS

4.1.1 CONNECTING A PHOTOVOLTAIC PANEL TO THE AC GRID

The connection of Photovoltaic (PV) panels to the AC grid is not a straightforward task. A DC/AC conversion is required (RASHID, 2017) to interface the DC voltage produced by the PV cell and the grid AC voltage. The controller will be responsible for injecting AC side currents with sinusoidal waveform and keep them with the same phase angle of the grid voltage (NAIK, MOHAN, 1995) for active power injection. Figure 7 presents the schematic of the power stage, identifying each of the platform modules and their interconnection to implement a single-phase case. This is the most used configuration for residential PV systems.

For experimental classes it is more convenient to substitute the photovoltaic panel by a DC power supply. The description of the existing control strategies (WALLBANK, SINGH, WALTERS, 2017) and their implementation in a microcontroller is out of the scope of this work.

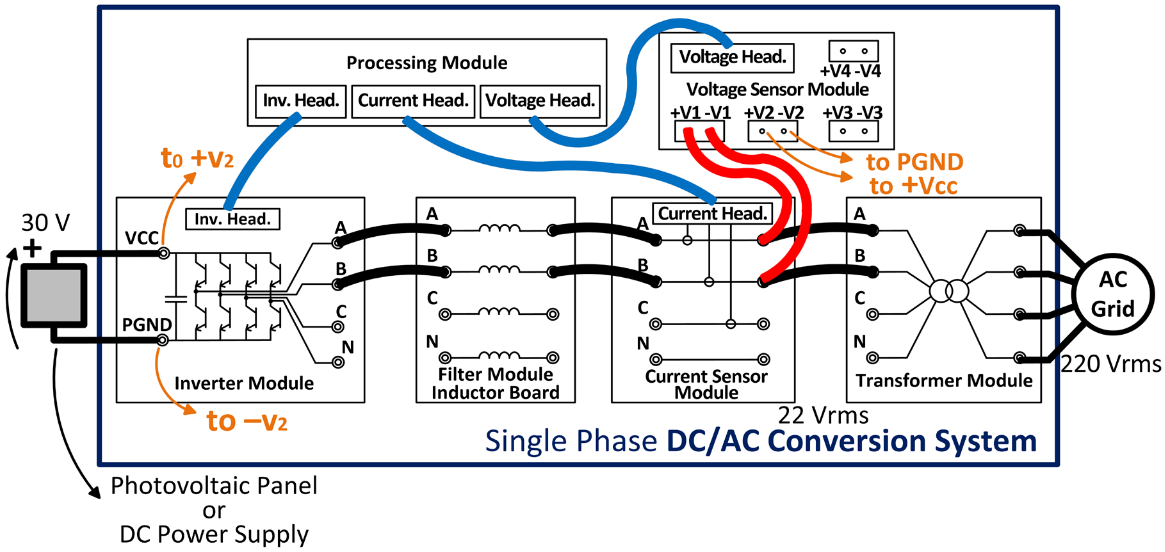


Figure 7 - Photovoltaic Panel connected to the single-phase AC Grid

Some variations can be easily achieved with this experimental set up:

- - A three-phase converter is easily achieved by connecting the phase C pin of the **Inverter Module** to the phase C pin of the **Transformer Board**, requiring changes in the controller strategy (RASHID, 2017).
- - The series inductive "L" filter can be substituted by a "LCL" filter (CHANNEGOWDA, JOHN, 2010), which is utilized in real applications to cope with Power Quality Standards (DUGAN et al., 2012), but presents a more complex model, requiring learning of improved controllers (PARKER, MCGRATH, HOLMES, 2014).

4.1.2 CHARGING OF ELECTRIC VEHICLE (EV) BATTERIES AND BATTERY

ENERGY STORAGE (BES)

The increasing usage of Electric Vehicles (EV) makes the battery charging process an important topic, addressing aspects like: i) duration of the charging; ii) implementation, energetic efficiency and cost of the charger and iii) impact of the charger on the battery life and on the grid power quality (JIANG et al., 2014). Among many possibilities of circuits used for battery charging, the “DC-AC conversion system” presented in Figure 7 can be employed. In this case the PV panel is substituted by the vehicle battery pack. It is important to emphasize that this converter enables bidirectional power flow. For higher power ratings, the three-phase converter will be a preferred option.

The capacity to implement bidirectional power flow makes it a good candidate for the implementation of Battery Energy Systems (BES) (ATCITTY, GRAY-FENNER, RANADE, 1998). Soon, those will be necessary in substations to provide the required power levelling to cope with the increasing use of renewable energy, which are power sources inherently with intermittent generated power.

One can notice that the electrical vehicle with a bidirectional charger is itself a small BES (TANG, ZHANG, 2017). In the future, when a dynamic energy pricing system will be available, vehicle owners will be able to buy energy in periods of low price and sell in convenient periods (WANG, ZHANG, SHEN, 2016). They will also be able to feed their homes during energy system blackouts (BOLLEN, 2000).

4.1.3 HIGH VOLTAGE TRANSMISSION SYSTEM (HVDC LIGHT)

The usage of DC transmission (HVDC - High Voltage DC Transmission Systems) is an adequate option for carrying high amounts of electrical energy for long distances. The reasons are the lower costs of the transmission line and the possibility of interconnecting two power systems with different operating frequencies (PADIYAR, 1990). HVDC systems can also be used to send energy produced by offshore wind farms, through a DC submarine cable, to onshore AC consumers (VAN HERTEM, GOMIS-BELLMUNT, LIANG, 2016).

Two experimental setups identical to the “DC-AC Conversion System” shown in Figure 7 can be interconnected according to Figure 8 to implement a small scale HVDC system. The real system DC transmission line is substituted by two short wires in this small-scale setup. Considering the bidirectional behavior of both converters, energy can be drawn from grid 1, converted to DC by using the conversion system 1 and sent to grid 2, by the conversion system 2, and vice versa.

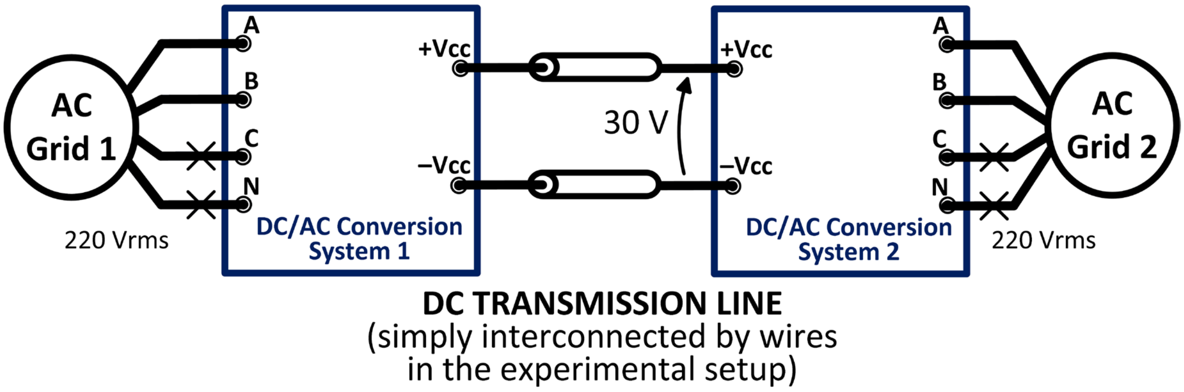


Figure 8 - HVDC and Back to Back system (single phase)

The system shown in Figure 8 is too complex, requiring many modules. Another possibility, that uses half of the number of modules is to use the circuit of Figure 7, where converter phases A and B are used as the conversion system connected to grid 1 (phases A and B or the transformer board) and converter phases C and N are considered as the conversion system 2 (connected to phases A and B of the transformer board). The interconnection of both conversion systems is done through the common DC link (Vcc).

4.2 VARIATION OF THE SPEED OF AN AC ELECTRIC MOTOR

The AC three-phase motors are nowadays the main choice for electric and hybrid vehicles (CHAU, 2015). The DC voltage supplied by the vehicle battery must be converted to a three phase, variable amplitude, variable frequency set of voltages that feed the AC motor, resulting in variable speed and torque (MOHAN, 2012). Figure 9 presents the basic setup for obtaining motor speed variation. A conventional DC power supply is connected to the CC/CA converter. A low power induction motor can be rewound to be able to operate with the low amplitude voltages produced by the **Inverter Module** (<30V peak).

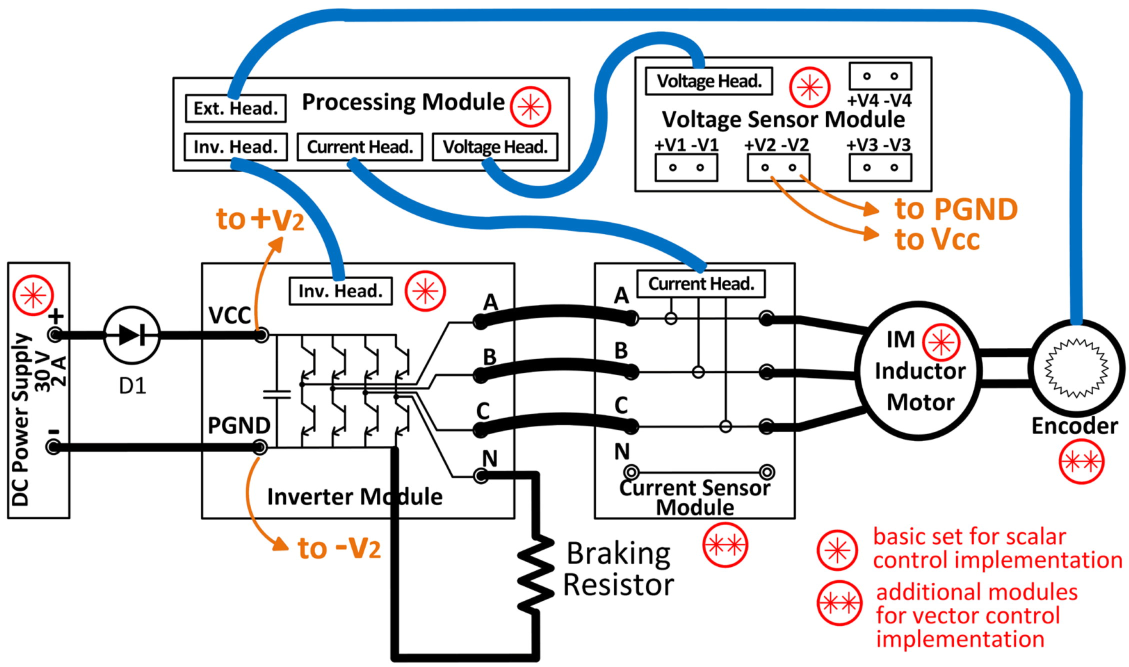


Figure 9 - Three Phase AC Drive

It is suggested to include the diode D1, to avoid power supply damage during motor deceleration, when DC side capacitor voltage will increase, due to the inability of the conventional power supply to absorb the motor and mechanical load kinetic energy. Additionally, a braking resistor must be connected to the phase N of the converter, to adequately dissipate this energy. Many control strategies can be employed for this motor drive, including the scalar and vector ones (NOVOTNY, LIPO, 1996). For the scalar control the parts indicated by the symbol (*) are needed. For the vector control the parts with a (**) symbol are included.

An industrial AC drive would require a AC/DC stage, which can be a simple and low cost diode bridge without regeneration capacity, or a full AC/DC like the one presented in Figure 7, where braking energy can be returned to the power grid.

4.3 DC-DC CONVERSION

4.3.1 MATCHING PV CELL AND PV INVERTER DIFFERENT VOLTAGES

The circuit presented in Figure 7 is not the most adequate solution for connecting a photovoltaic panel, whose output voltage depends on incident light, to the grid. The DC/AC converter works well for small variation of the DC voltage amplitude, that must be kept slightly above the peak value of the AC grid voltage. The matching of the two different voltages can be achieved by intercalating the DC/DC buck-boost converter (Figure 10) between the photovoltaic cell and the DC/AC converter (Figure 7).

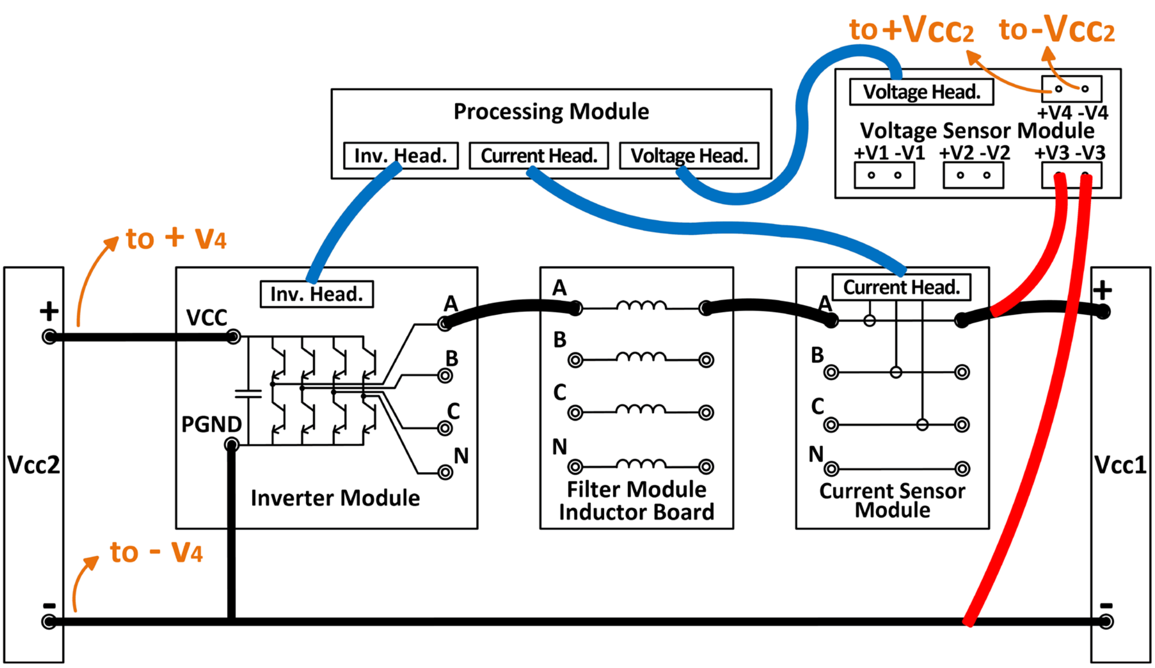


Figure 10 - Experimental Setup for DC-DC Converter Experiments

The block Vcc1 in Figure 10 is the PV panel, that can be substituted by a DC power supply for laboratory experiments. The block Vcc2 is the DC side of the DC/AC converter and can be substituted by a resistor for a simpler experiment.

The buck boost converter operates in boost mode, because the DC bus voltage of the DC/AC converter is always kept higher than the PV panel voltage. The DC-DC converter must be controlled so as to match both DC voltages (LI, HE, 2011) and to drain the maximum possible power from the PV panel for any level of incident light (MPPT-maximum power point tracking control) (NARENDIRAN, 2013). The controller of the DC/AC converter has two main tasks (OBI, BASS, 2016): i) to regulate the DC bus voltage and ii) to inject sinusoidal currents into the grid, with unitary power factor.

4.3.2 CHARGING THE AUXILIARY BATTERY OF ELECTRIC VEHICLES

Electric and Hybrid Electric Vehicles have a main high voltage battery package for traction and a 12V auxiliary battery for supplying control circuits, lights, small motors, etc. The setup of Figure 10 can be used for experiments regarding the charging of such auxiliary battery from the main battery. In this experiment, Vcc2 is the high voltage battery (a 24V battery or a DC power supply can be used) and Vcc1 is the auxiliary battery (a 12V battery can be used). If two batteries are used in the experiment, bidirectional power flow can be imposed.

4.3.3 VARIATION OF THE SPEED OF A DC MOTOR (DC SERVO MOTOR)

The DC servo motor drives are composed by a brushed DC motor and a bidirectional DC/DC converter. They are used in applications that require speed, position or torque control with low cost and simplicity. (MOHAN, 2012) In its most simple topology, the setup of Figure 10 can be used, where Vcc2 will be a 12 or 24V battery and Vcc1 will be the DC brushed motor. Two quadrant operation can be achieved, that means, rotation direction cannot be reversed but regenerative braking (negative torque) can be imposed. If the negative terminal of the DC motor is connected to terminal B of the converter module, four quadrant operation is obtained. Then, the motor can rotate in both directions with regenerative braking.

4.4 AC UNINTERRUPTIBLE POWER SUPPLY (UPS)

The AC Uninterruptible Power Supplies are required in events of energy supply shortage, where AC loads can be fed by an DC/AC converter supplied by a battery. A three phase four wire UPS is presented in Figure 11. The converter output voltage waveforms are filtered by a LC filter and a resistive load is used.

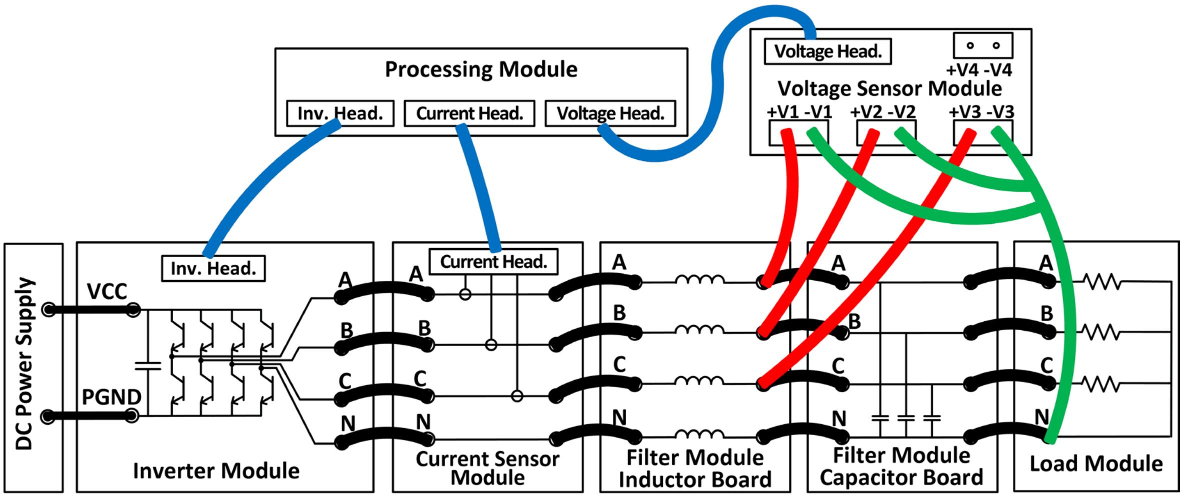


Figure 11 - DC-AC Stage of an Uninterruptible Power Supply

5 I BENEFITS OF THIS PLATFORM FOR THE SOCIETY

Having presented the structure of this educational platform and some of its possible applications, it is imperative to notice the social benefits of developing this platform and making it openly available.

The first possible benefit is enabling its users to learn advanced technology of energy conversion by providing a low-cost kit with easy usage. A similar phenomenon can be seen in the usage of popular boards such as Arduino and Raspberry Pi. The low cost of such boards made possible to a high number of students to get in touch with robotics, internet of things and other technologies. It is expected that this platform will obtain a similar result in the field of electrical energy conversion. We also believe that students will be stimulated to learn and develop themselves in more advanced concepts after using this boards for different projects.

Therefore, this development has a great impact in public education. Initiatives like this empowers professors from Brazilian technical schools and universities to create or improve their laboratories, which has a direct impact in scientific and technological productivity inside the country. Students that work in such laboratories or take specific practical classes in which this product may be used will certainly benefit from it.

The usage of such devices also encourages entrepreneurship and innovation in key sections of high technology, which are essential for the economic and scientific development of a country. Using this kit could inspire professional engineers, students and amateurs to build products and businesses, whether by starting with a low cost minimum product value or by making them get in touch with the earlier cited fields (robotics, internet of things, mechanics, energy and others). This consequently enables the development of more advanced hardware and software that can be used in many other fields, and also creates more job positions for specialists in the longer term.

At last, the open source/hardware concept of this project is to make it highly available for every possible interested person in the field, professional or amateur. In addition to it, open source/hardware also implies collaborative development. We are open and hope to receive contributions from other enthusiasts of the project, and to inspire other similar initiatives to broaden the open source hardware community inside Brazil.

6 I SUMMARY

In this work, the concept and importance of power electronics is discussed first. This contextualizes the motivation for the development of the didactic platform presented. It is composed of seven modules: Processing Module, Voltage Sensor Module, Current Sensor Module, Inverter Module, Filter Module, Load Module and Transformer Module. Each module is briefly described, and its schematic is shown right after its description.

Following the presentation of the didactic platform, the interconnection of its modules for the study of several applications is presented. Those applications include, but are not limited to: Connecting a Photovoltaic Panel to the AC Grid, Charging Of Electric Vehicle (EV) Battery and Battery Energy Storage (BES), High Voltage Transmission System (HVDC Light), Variation of the Speed of an AC Electric Motor (e.g. for hybrid and electric vehicles), DC-DC Conversion, Charging the Auxiliary Battery of an Electric Vehicle - EV, Variation of the speed of a DC motor (DC Servo Motor), AC Uninterruptible Power Supply (UPS).

If the reader is interested, then more information about this didactic platform can be found in the following URL: *github.com/LEP-PEA-EPUSP*. All design files, including schematics, board layouts and source code files are available under a public open source/hardware license.

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