A Flexible Hardware Platform for Applications in Power Electronics Research and Education

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***Abstract*—This work presents the design and development of a three-phase multilevel hardware platform for applications in power electronics. The emphasis of the proposed converter is in its flexibility to allow rapid set-ups of different experiments typically required in power electronics teaching and research. The proposed converter uses a cascaded H-bridge topology whereby multilevel operation with up to 9 voltage levels can be obtained. The selected power stage topology as well as the control, drivers and sensors boards designs, enable the platform to operate in multiple configurations, namely as inverter, controlled rectifier or active power filter, for one, two or three-phase systems.**

***Keywords*-power electronics, multilevel converter, Electronics engineering education, research**

I. Introduction

Development of power electronics solutions involves diverse knowledge areas such as control theory, device modeling, digital signal acquisition and processing, and embedded systems, among others. Main applications for power electronics include energy conversion (dc-ac, ac-ac, dc-dc, ac-dc), harmonic current mitigation in distribution lines, and voltage compensation in transmission lines [1]. Depending on the specific application different topologies are used having, however, some characteristics in common such as: a power stage composed by electronic switches (silicon controlled rectifiers (SCR), insulated gate bipolar transistor (IGBT), etc.), isolated sensing of variables of interest, isolated generation of firing pulses and a processing unit in charge of running the control algorithms.

Research in power electronics applications largely lays in the availability of a hardware platform where the different control techniques to be evaluated can be tested, allowing for the rapid prototyping of the diverse topologies typically used. The same is valid in academic activities where power electronics courses are being developed and it is expected that the students will interact with real power electronic systems. Many papers covering the issue of power electronics researching and teaching have been written, where two main groups can be mentioned: a) those focused in the hardware platform development, and b) those focused in the development of software tools thought to help the researching and teaching process. In the latter group is reference [2] where a geometrical representation of the different blocks composing a power converter is introduced, as well as references [3], [4] and [5] where the use of web-based methods are evaluated versus classic learning process. Also reference [6] whose main contribution is a software tool aimed to ease the design process of ac-dc and dc-dc power converters, and reference [7] where a set of hands-on laboratory experiments are proposed. In the former group are references [8] and [9], where hardware platforms are presented which allow for the study of many topologies of two-level power converters. In [10] a test bench oriented to the implementation of domestic induction heating applications is proposed, while in [11] the authors present a hardware platform for electric vehicle applications including motor drive, DC-DC converter and battery charger. In most cases the hardware platforms are controlled by digital signal processors (DSP) in addition of field programmable gate arrays (FPGA). In [12] and [13] control boards for power electronic converters using DSP and FPGA are presented, while in [14] a board allowing Hardware-In-the-Loop (HIL) simulation with ultralow-latency is presented.

All previous papers are mainly focused in controlling conventional two-level converters which is the most widely used topology in different industrial and domestic applications. In previous works the authors of this paper have developed several versions of a multipurpose two-level hardware platform aimed to test novel control techniques and also used as support of graduate power electronics courses [15][16][17]. In the last decade, however, multilevel converters are increasingly used, and many industrial applications can be found in literature [18]. Advantages of multilevel converters are many as well as the different topologies that have been

978-1-4799-6038-5/14 $31.00 © 2014 IEEE
DOI 10.1109/EPEC.2014.6

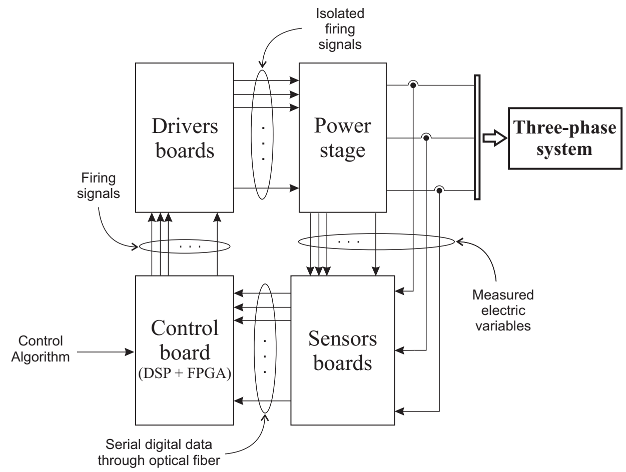


Figure 1: Proposed hardware platform block diagram.

proposed. In general by using a higher number of power electronic switches a multilevel converter can manage higher voltage levels, allowing for a reduction in current levels and also for the direct connection of the converter to distribution or transmission lines without the need of isolation transformers. Also due to the fact of having more available switching states, excellent performances can be obtained if the appropriate control techniques are implemented. The paper main object is the design and development of a flexible multilevel hardware platform capable of being easily reconfigured to work with different number of voltage levels and operated both as an inverter and as a controlled rectifier. Fig. 1 shows the proposed hardware platform block diagram, where the developed control board is based on a DSP and a FPGA. Programming of both chips is made from a PC and, after the download of both codes, the system operates autonomously. The system also includes drivers and sensor boards. The sensor boards measure system voltages and currents by means of Hall effect transducers. The drivers boards are in charge of isolating and amplifying the firing pulses sent to the power switches. The control board also has implemented a port to measure angular position or speed from an optical encoder typically required in motor control applications.

The paper is structured as follows: Section II presents the multilevel power stage structure and its natural voltage space vectors. Section III explains the operation of the control, sensors and drivers boards. Finally in Section IV applications and future works are presented.

II. Multilevel power stage

There are several topologies for multilevel converters. The most popular are the diode clamped (DC), flying capacitor (FC)(also known as capacitor clamped) and cascaded H-bridge (CHB) [19]. While DC and FC structures are easy to construct for low number of voltage levels, they turn

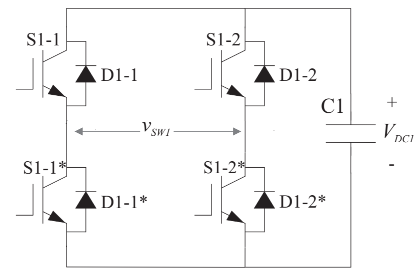


Figure 2: H-bridge block circuit configuration.

Table I: Valid switching states for the H-bridge and the resulting v_{SW} voltages

SS	v_{SW}
"+1"	$+V_{DC}$
"−1"	$-V_{DC}$
"0^u"	0
"0^d"	0

less practical for increasing number of levels. CHB converters instead are highly scalable and can be configured for operation at different number of voltage levels without changing the basic H-bridge building block structure. The basic building block for the CHB converters is an H-bridge composed by 4 electronic switches that switch the voltage of a DC bus. In Fig. 2 a scheme for the H-bridge is presented, and Table I list the valid switching states and the corresponding v_{SW} voltage values produced. The CHB topology uses the H-bridge blocks connecting them in cascade to obtain multilevel operation. Fig. 3 shows the structure for the converter presented in this paper, where each leg is assembled from 4 H-bridge blocks, resulting in 9 available voltage levels from $+4V_{DC}$ to $-4V_{DC}$ with steps of V_{DC}. For three-phase operation the lower ends of each leg are connected together and the upper ends can be connected to the load or the source, depending on the specific application. This converter can be operated with a reduced number of voltage levels just by short circuiting the corresponding H-bridges, giving a high flexibility when comparisons between different hardware topologies have to be established.

For three-phase operation the converter switching states are typically represented by using voltage space vectors (VSV), whereby the voltage amplitude in each leg is combined with the corresponding 120° phase angle displacement. Fig. 4 shows the VSVs generated in a 9-levels converter. The outermost hexagon represents the set of all voltage space vectors available for a three-phase 9-level converter, totalizing 217 different vectors. Concentric to this hexagon the subsets corresponding to 7,5,3 and 2-level converters are shown. The concept of space vectors can be applied to others electric variables resulting in a powerful

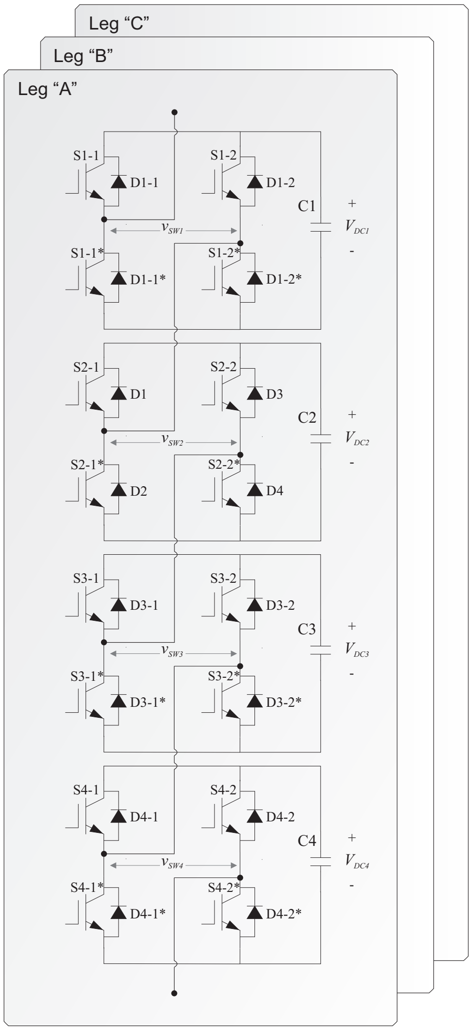


Figure 3: 9-level CHB three legs scheme.

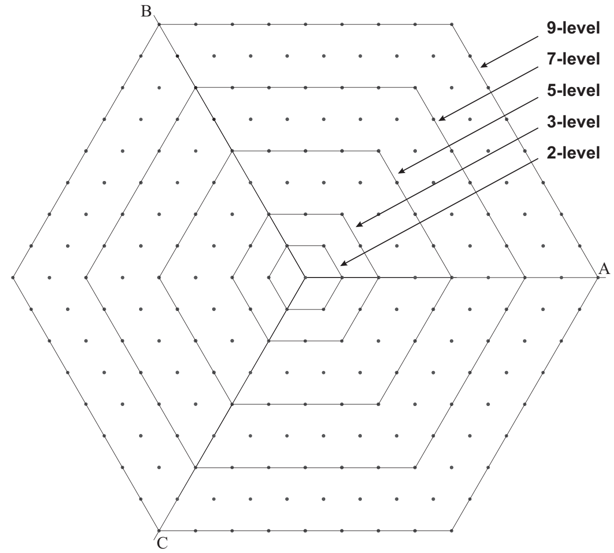


Figure 4: Voltage Space Vectors (VSV) available in converters with different number of voltage levels.

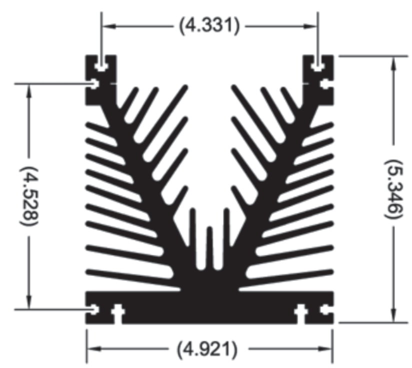


Figure 5: Transverse section of the MM12878 aluminum extrusion profile used as heatsink.

tool which leads to an extensive set of control algorithms.

The selected switch was the IGBT SKM150GB12T4 from Semikron, which can block 1200V collector-emitter voltage, supporting up to 150A collector current and a switching frequency up to 20kHz. These IGBTs are packaged in SEMITRANS® 2 dual modules intended to be attached to a heatsink by means of nuts and bolts. Fig. 5 shows the selected heatsink profile [20]. The IGBT modules will be fixed to the heatsink flat side, and the sensor and drives boards will be attached to the grooves in the heatsink sides. This heatsink has a thermal resistance $R_{th_{sa}}$ of 0.96°C/W. The maximum power dissipation in each IGBT can be calculated using the thermal resistances as [21]

$$P_{jmax} = \frac{T_{jmax} - T_a}{R_{th_{jc}} + R_{th_{cs}} + R_{th_{sa}}} = \\ = \frac{150 - 25}{0.19 + 0.2 + 0.96} = 92.59W \quad (1)$$

where $R_{th_{jc}}$, $R_{th_{cs}}$ and $R_{th_{sa}}$ are, respectively, the junction-to-case, case-to-sink, and sink-to-air thermal resistances. The DC bus for each H-bridge was connected to a 2200 μF, 450V electrolytic capacitor, ensuring a wide operation range, allowing for the testing of different configurations. The power stage completely mounted is shown in Fig. 6, where it can be seen that the power modules are connected by copper bars to form each H-bridge. The capacitors are directly attached to the bars, ensuring a significant reduction of parasitic inductances.

III. Control, sensors and drivers boards

A. Control board

The control board is in charge of executing the user control program, which is downloaded from a PC through a USB connection. The processing unit is the SHARC®

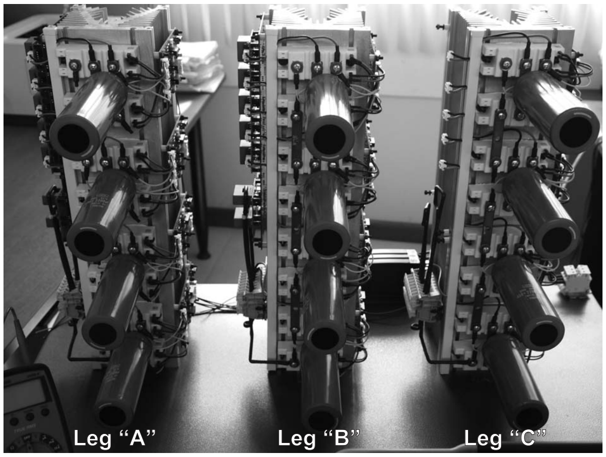
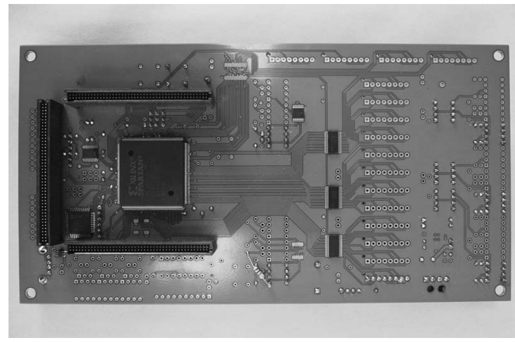
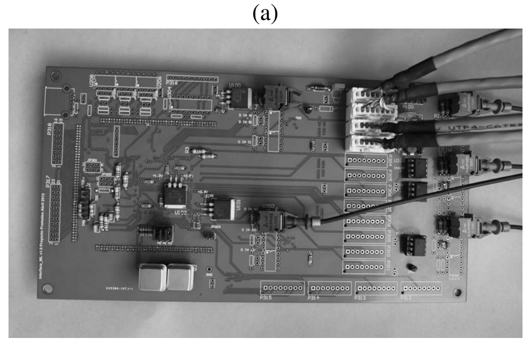


Figure 6: Frontal view of the three converter legs.



(a)



(b)

Figure 7: (a) Bottom side of the control board showing the FPGA and the expansion connectors. (b) Top side of the control board showing optical fiber transmitters and receivers, voltage regulators and PWM ports

ADSP-21369 from Analog Devices which is included in the development board EZ-KIT Lite®. This DSP has a 400MHz operating frequency, and can perform 2.4 GFLOPS, supporting 40 bits floating point arithmetic format. The time-consuming tasks, such as serial to parallel data conversion, width modulated pulse generation, input/output port memory mapping, etc., are delegated to a FPGA where specific hardware structures were embedded to perform them, giving the DSP more free time to execute the control algorithm. The EZ-KIT Lite® board has three expansion connectors where the developed FPGA board was attached. Fig.7a shows the bottom side of the developed board where the expansion connectors and FPGA chip can be seen and, in Fig.7b, the top side for the FPGA board shows the optical fiber receivers and emitters, some of the PWM ports and the voltage regulators. The selected FPGA model was the Spartan® XC3S500E-4PQ208C from Xilinx, which has 500000 gates and 208 pins, allowing to allocate 12 4-bits PWM output ports required to turn on and off the 48 IGBTs [22]. The FPGA was also programmed to manage up to 3 sensors boards, sending the control signals (clocks, conversion start) and receiving multiplexed serial data.

B. Sensors boards

All closed loop controls require the measuring of a set of electric variables which will be used by the DSP to calculate the next control action. The developed sensor boards use Hall effect transducers to obtain scaled versions of the measured variables, providing, at the same time, galvanic isolation between platform high and low voltage zones. Each sensor board has 8 channels which can be independently configured to measure either voltage or current by changing the corresponding transducer, depending on the specific application requirements. Fig. 8 shoes a sensor board configured to measure 5 voltages and 2 currents. The voltage transducer is a LEM LV 20-P, configured to measure voltages up to 500V and the current transducer is a LEM LA 55-P able to measure up to 50A. The isolated measures are sent to an AD7607 8-channel analog-to-digital converter (ADC) with 14 bits resolution and bipolar inputs. This ADC is able to output digital converted data for the 8 channels in serial format, minimizing the number of optical fibers to be used between the control and sensors boards.

C. Drivers boards

These boards were designed with modularity as a main goal. Each driver board controls one H-bridge and 4 boards are required for each leg. Every firing signal coming from the control board is fed to an HCPL-316J gate drive optocoupler where is amplified and isolated. Voltage source for the high voltage side of the driver board is obtained by means of a dc-dc converter VESD1-SIP, which provides isolated outputs of $\pm$15V when its input is fed with 15V. The gate drive include desaturation detection, inhibiting further firing pulses and returning an optocoupled fault signal when this condition is detected in any of the power switches. The fault signal is sent to the control board allowing for the activation of different fault management strategies in the control program. Fig. 9 shows the 4 drivers boards attached to the converter leg "C".

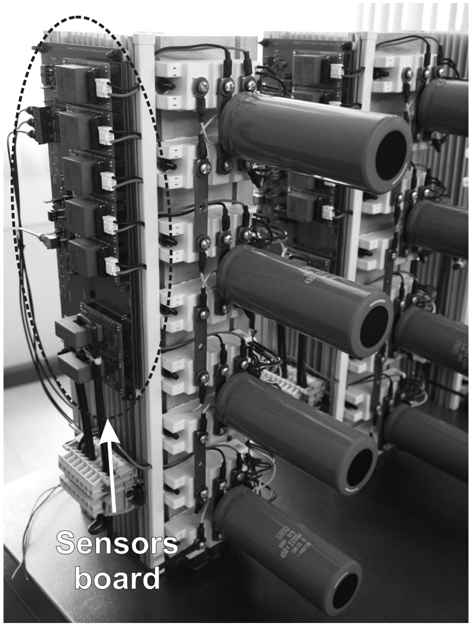


Figure 8: Sensors board attached to converter leg "A".

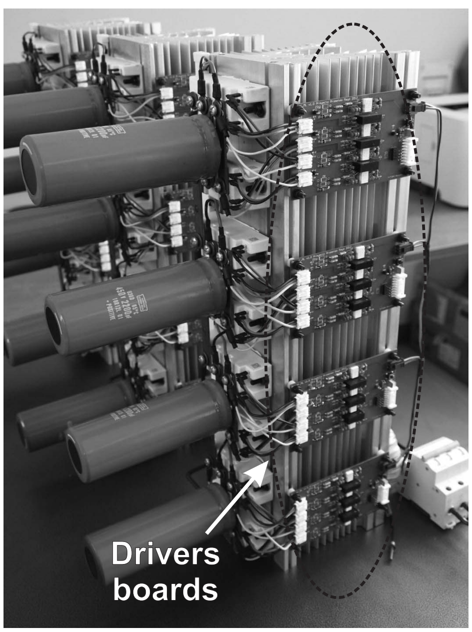


Figure 9: Drivers boards for the IGBTs of converter leg "C".

IV. Applications and Future Works

In previous works the authors have addressed different power electronics control problems by using two-level hardware platform also controlled by DSP [15], [16], [17]. Applications varied from torque control in three-phase induction machines [23] [24] [25],where the two-level converter was used as an inverter, to active power filter design and control in one-phase and three-phase systems [26] [27], where the converter was used as a controlled rectifier. Many theoretical concepts, however, cannot be tested with the previous versions of the hardware platform due to a reduced number of available sensors, the limited computation power of the DSP, and the operation with two-level voltages. The hardware platform proposed in this paper is flexible enough to be used as an inverter or as a controlled rectifier, in both cases with different number of voltage levels since it is straightforward to inhibit the operation of any H-bridge block, resulting in a lesser number of available voltage levels. This characteristic is particularly useful when comparisons need to be established between control algorithms operating with different number of voltage levels. Some works recently developed or in progress include:

- Current loop control with estimation of DC bus voltages [28], where two different methods of capacitor voltage estimation are developed and compared allowing for a reduction of the number of required voltage transducers.
- Predictive control applied to active power filtering in three-phase systems, where a model of the nonlinear load connected to the mains is identified to be used afterwards in predicting the best control action to apply in the next control cycle.
- Direct torque control of induction machines by selection of natural voltage space vectors, where a novel strategy to choose the best available voltage space vector is developed.
- Development and comparison of different pulse width modulation techniques which can be embedded directly in the FPGA.

V. Conclusion

The present paper address the design and development of a multilevel hardware platform for power electronics research and education. The central idea of the proposed design is flexibility in both hardware and software. The former is assured by using a multilevel converter topology that easily allows for a reduction in the number of voltage levels to be used in each application. The latter is achieved by basing the control board design on a powerful DSP with floating point capabilities, which allows the student or researcher to test new control techniques, which is a distinctive characteristic not available in commercial power converters. Additionally, by using a FPGA, different input/output ports and protocols can be programmed and adapted to be used with different configurations of the sensor and driver boards. Safe operation of the whole system is guaranteed by means of galvanic isolation between high and low voltages areas, and immunity to electromagnetic interference is reduced by using optical fiber as serial data links between control and sensors boards.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of Prometeo Project, Secretaría de Educación Superior, Ciencia, Tecnología e Innovación, and Universidad Politécnica Salesiana, both in República del Ecuador, as well as the Dean's Office for Research and Development of Universidad Simón Bolívar and FONACIT Research Project ♯ 2011000970 both in Venezuela.

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