Abstract—While the past decade has seen a widespread adoption of power electronics curriculum at various university electrical engineering programs, authentic laboratory experiences for students remains to be a challenge for inclusion in the programs. This paper discusses a modular power electronics learning platform called PEGO. PEGO consists of self-contained two terminal modular building blocks for power converters which may be cascaded stage by stage to achieve an overall functional objective. The system has been developed to complement a lecture based design oriented theory course in power electronics. The theory course and the laboratory platform are designed to lead to a system level project experience for the students. A primitive UPS system consisting of a battery charger, high frequency isolated dc-dc converter and a low frequency pulse width modulated inverter is illustrated as a candidate project experience. A detailed description of the system along with sample results from the hardware/software exercises are presented in the paper.

I. INTRODUCTION

A major shift in engineering education is the emphasis on student learning outcomes and integrated approach to course and program design [1]. This is especially true in the case of power electronics which is inherently multidisciplinary and highly design oriented. A well-rounded course structure in power electronics should include both a discussion of the theoretical framework as well as robust practical laboratory environment where the theory is directly observed in action. Such a lab course should not only verify the analytical prediction but also give an insight into the design process. An exemplary system was used for lab instruction at Caltech in the 1980s during the early days of power electronics [2]. More recently, there have been several attempts to incorporate experimental learning techniques in a classroom environment. One of the earliest attempts uses a black-box approach where the converter or the working hardware is encapsulated and a few internal functions are exposed to the student to manipulate and observe [3][4]. The disadvantage here is that the test system is inflexible and there is no real insight into the design process. Later attempts remedied this by including more hands-on student involvement in the design and construction of the various components of a (usually) low power dc-dc converter [5][6]. The introduction of cheap digital controller has had a positive effect in the design of lab courses. Many courses now integrate digital control in the form of microcontrollers or field programmable gate arrays (FPGA) in the test systems [7][8]. Digital control allows the instructor to reconfigure the system and operate the hardware in different modes by just changing the control algorithm. When digital control hardware is coupled with familiar platforms like MATLAB, students are exposed to both simulation and experimentation tools at the same time [9].

This paper discusses a new approach to a power electronics learning platform. The platform is named PEGO (Power Electronics to GO), which consists of interconnecting building blocks that can be configured in different ways to study different power electronics topologies. The PEGO platform that is described here differs from some of the recent efforts in one major aspect, namely modularity, as a concept that goes beyond circuit schematic or a block diagram. It embraces modularity in the geometric and physical aspects of the realizations that have inspired engineered and artistic creations in the past [10-15]. The overall system architecture is detailed in Section II. The digital control architecture is presented in Section III. Section IV shows some experimental results of the converter system. The final concluding section provides a summary of the paper.

II. SYSTEM ARCHITECTURE

A single line diagram enumerating the major components of the PEGO system is shown in Fig 1. The functional topology is a double conversion single-phase uninterruptible power supply (UPS) with battery backup. The source is the single phase 120V, 60Hz AC that is standard in North America for most consumer lighting loads. This system has been carefully selected to provide a broad and integrated experience in the dimensions of power electronics practice. The step-down transformer and the passive rectifier allow a through discussion of design, operation and performance of passive rectifiers in context. It is possible to introduce the concepts of low frequency magnetics, harmonic analysis, passive filtering and power quality using these circuit elements. The battery charger stage provides a forum for discussion of limitations of linear regulators, thermal issues and active control effectively. The presence of battery also provides an ideal avenue for discussion of some aspects of energy storage, charge/discharge dynamics, etc. The battery voltage is used to feed a high frequency single phase bridge inverter. This stage is used to introduce the concepts of high frequency switching, gate drives, losses, etc.
Fig. 1. PEGO powerpack system architecture

Battery Charger PEGO Stages

120VAC Supply → DC Bus → DC-DC converter → Transformer → DC/DC converter → Capacitors → Linear Regulator → Capacitors → Voltage Source → Protection

Battery Charger PEGO Stages

Arctims PWM and ULVO Protection PEGO Stage


External Battery: Lead acid 12V AGM 12V

12V DC-12VDC H-Bridge PEGO Stages


Fig. 2. PEGO power pack system modules
The ac output of the inverter feeds a high frequency step-up transformer, where the design aspects of high frequency magnetics are introduced, along with a discussion of magnetization current, leakage reactance, etc. The secondary of the inverter feeds a high frequency rectifier, where high frequency rectification and the effect of reverse recovery of diodes are introduced. The output of the rectifier feeds a passive filter and develops a high voltage dc. A closed loop regulator is used to control the high frequency inverter and maintain the dc bus voltage with appropriate line and load regulation. The high voltage dc output feeds a low frequency sinusoidally modulated inverter to develop an ac output, which is filtered using an LC filter to obtain a smooth ac output to feed ac loads. The low frequency inverter is operated in an open loop fashion. All of the control, regulation and protection functions are performed using an Arduino Uno microcontroller platform. Thus, powepack, rated at about 180VA output, 18VA input realizes a purposeful function that incorporates all the major aspects of modern power electronics practice. A sample schedule for a semester long course is shown in Table I.

**TABLE I**

<table>
<thead>
<tr>
<th>Session</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low frequency rectifier</td>
</tr>
<tr>
<td>2</td>
<td>Battery charger</td>
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<tr>
<td>3</td>
<td>State machine and digital PWM</td>
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<tr>
<td>4</td>
<td>Gate drivers</td>
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<tr>
<td>5</td>
<td>Choppers</td>
</tr>
<tr>
<td>6</td>
<td>High frequency inverter/transformer</td>
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<tr>
<td>7</td>
<td>Open loop bridge dc-dc converter</td>
</tr>
<tr>
<td>8</td>
<td>A/D conversion and signal conditioning</td>
</tr>
<tr>
<td>9</td>
<td>Closed loop dc-dc converter</td>
</tr>
<tr>
<td>10</td>
<td>Sine wave PWM</td>
</tr>
<tr>
<td>11</td>
<td>Low frequency inverter</td>
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<tr>
<td>12</td>
<td>Fault handling and protection</td>
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<tr>
<td>13</td>
<td>Housekeeping</td>
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<tr>
<td>14</td>
<td>Overall system integration</td>
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</tbody>
</table>

This experimental laboratory platform was used at UW-Madison as a course experience for about 4 years with a fully analog controller. Students purchased all the components in the form of a kit, soldered and tested the system step-by-step, and owned the system at the end of the semester. The course was popular and it realized a broad set of instructional objectives. But the hardware platform was too expensive in terms of consumables. Furthermore, TA support for debugging poor soldering and wrong interconnections in the lab was time consuming. Therefore, a system of reusable building blocks and solderless interconnections were recently developed as described further to make the PEGO system.

A quick overview of the system block diagram in Fig. 1 illustrates that the entire power converter is composed of a cascade connection of devices that have an input port and an output power, each consisting of two terminals. Thus, if each of the component modules are made on a separate printed circuit board (PCB) that conform to a geometric rule, they can all be placed next each other in a system of rails, and interconnected appropriately. A schematic illustration of the system cascade is shown in Fig. 2. A photograph of a fully assembly PEGO Powerpack rack is shown in Fig. 3. As a comparison, a photograph of the powerpack assembled on a single PCB is illustrated in Fig. 4. Details of the sliding rail for the PCB modules are shown in the expanded view in Fig. 5.

![Fig. 3. A photograph of the PEGO Powerpack rack](image1)

![Fig. 4. A photograph of the fully assembled UPS Powerpack](image2)

### III. CONTROL SYSTEM

The digital controller used is ATmega328p, an 8-bit microcontroller used in the popular Arduino Uno development board. The control platform is written in C and compiled using the open source compiler AVR-GCC. The code emulates
some characteristics of a real time operating system with a state machine that transitions from READY to RUN or FAULT states depending on the condition of various state flags. The microcontroller monitors the battery voltage and sets the battery under-voltage flag during fault condition. The microcontroller has three hardware timers, each of which drives a set of three pulse-width modulated (PWM) outputs. Timer1 PWM outputs control the high frequency inverter and Timer2 PWM outputs control the 60Hz sinusoidal inverter. The controller also senses the AC line voltage and switches the AC relay from direct pass-through to UPS when AC line fails. A block diagram of the controller interconnection to the PEGO power circuit is shown in Fig. 6.

### IV. Sample experimental results

The PEGO Powerpack has been used in a semester-long lab course in the past, and is currently being used during a 3 week summer session. Fig. 7-10 show a set of selected results from student experiments. The current waveforms were captured using a sense resistor. Differential voltage measurements were conducted by using both channels of a DSO and subtracting the channel outputs mathematically in the scope interface. The hardware experiments do not require any differential probe or current probe for conduct of the laboratory course, and can be readily conducted in a general purpose electronics lab with a scope and a multimeter.

![Fig. 6. A block diagram of the microcontroller system interface with PEGO](image6)

![Fig. 7. Secondary voltage and current waveform of 60Hz transformer](image7)

![Fig. 8. High frequency inverter output waveform with differential measurement CH2-CH1.](image8)

### V. Conclusion

Power electronics is a multidisciplinary subject with emphasis on both analytical modeling and practical design. The PEGO system is designed to maximize the learning experience by separating the various components of the power electronics system, which allows students to learn the system stage by stage in a series of cascaded modules. The digital controller platform implemented by open source Arduino platform is inexpensive, which makes the system compatible with a huge number of existing Arduino shield boards. The experimental
components as follow: The PEGO system is about US $1000, with a break up of major (15 stations), the total cost of the material components per conditions to verify the design.

results show some of the waveforms during normal operating

At the pilot prototyping stage, with small number of stations (15 stations), the total cost of the material components per PEGO system is about US $1000, with a break up of major components as follow:

- Mechanical parts including heat-sinks, fasteners, rack, rail and interconnects: $500
- Printed circuit boards: $100
- Battery: $30
- Arduino: $30
- Magnetics: $30
- Capacitors: $25
- Gate drivers: $25
- Power semiconductors: $25
- Miscellaneous low-power electronics hardware (including resistors, cables, LEDs, etc.): $135

When labor costs for assembly are included, the cost per system would reach about $1200 per station. Since all the components are reusable, and replaceable, this investment in this is similar to that of a laptop computer, or an low-end oscilloscope. This expense needs to be balanced against the number of users that can be served per station over its lifetime, and the learning outcomes of these students.

The PEGO platform permits the adaptation of new modules, new power devices, new reactive components, new drive circuits, new digital or analog control platforms, as long as they conform to the specified interconnection and mechanical layout geometries. In the future, a more advanced digital control platform interface, wireless interconnection interface are being planned. The design details of the entire platform is available for replication by other university campuses, engineers and hobbyists on an open-source licensing basis. It is the conjecture of the instructors and initial cohort of students who have taken the course that the learning outcomes of the laboratory using PEGO is vastly superior to conventional courses. It is the hope of the hardware platform developers to collaborate with a broader academic community to initiate a formal educational/curricular research project and conduct a definitive study. Broad availability of such an authenticated platform will enable our discipline to grow further among the academic, professional and hobbyist community.

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