AC 2010-524: ADAPTATION OF A COMMERCIAL UPS SYSTEM FOR ENERGY SYSTEMS EDUCATION

Christopher Lashway, Pennsylvania State University, Harrisburg

Peter Idowu, Pennsylvania State University, Harrisburg

Adaptation of a Commercial UPS System for Energy Systems Education

Abstract
Uninterruptible Power Supply (UPS) Systems have become a critical component in the monitoring and safeguarding of electrical networks. Having continuous power has been a necessity in data centers for years, but has since extended into protection of businesses and other essential facilities. For this reason, research efforts have focused on the production of large-scale systems capable of handling large quantities of power. In response to this movement, many custom UPS systems have been in production attempting to battle common issues seen with smaller-scale systems and enable support for a growing need for stable and reliable power. In this study, a unique UPS power system is analyzed and retrofitted for use in a university laboratory environment. A fully integrated information system is developed using National Instruments LabView™ to examine the functions of the UPS and its individual subsystems.

I. INTRODUCTION

In the last few decades, power reliability at an acceptable quality has become an important factor in business operations across the world. The first uninterruptible power supply systems appeared in the 1950s, with marketing geared mostly toward protection of defense equipment [1]. These early systems were of rotary design and required a DC motor to power an AC generator in place of an inverter. However, with the development of quality inverters and real-time monitoring solutions, UPS systems became more popular, affordable, and have become a critical link between supply and load to fulfill the increased demand of electrical power and reliability.

While demand for UPS devices has been on the rise, so has focus on research and development of cleaner and stable power systems in the university academic environment. Electrical engineering students have been gaining more exposure to the construction of interacting subsystems involved in a battery backup system [2]. The system can be generalized as the combination of a rectifier and inverter; two power electronic subsystems commonly covered in electrical engineering courses. A software system to study and design ideal UPS systems for power electronics course is featured in [3]. The ideal UPS system is fostered by the creation of an integrated graphical interface calculating the optimal configuration of each component. Though the system has a notable visual interface, it focuses only on the construction aspect, not the monitoring of a system that has already been assembled.

Integration of custom-designed hardware into laboratory and the classroom is growing at a number of universities. Software solutions have even been developed for robotics applications and older devices, which are no longer supported by their manufacturers or contain obsolete components [4]. In [4], the University of Redding, U.K. retrofitted a Puma 560 robot with an enhanced monitoring and torque control system. The project presents an excellent example of how a mechanically sound robot can be revitalized on a modern software platform for experimental research in a classroom.

When selecting a software platform for building interface and user interaction to hardware systems, two programs have been widely used in control system and analysis applications [5]. Many control systems have tested and implemented their commands using Simulink, a powerful add-on to MATLAB allowing for an interactive graphical environment to design, simulate, implement, and test a variety of systems [6]. National Instruments LabView likewise offers a graphical programming environment, as well as the facility to analyze and interpret a variety of live signals [7].

Some power electronics applications implemented both programs, recognizing the most compelling features each has to offer [8]. In [8], a software solution for custom-designed laboratory hardware was implemented using both Simulink and LabView interfaces. Information systems were designed in both programs, using Simulink to model and test the laboratory tools, and LabView to control, capture, and run simultaneous data analysis. In applications such as the UPS system where simulation is not a major focus, LabView appeared to be the more practical choice.

Engineering programs in various places have identified the advantages of using the LabView software. A mechanical engineering department program [9] took full advantage of what the software had to offer and used it as a critical component in converting their student laboratory. Mechanical and thermal science components were retrofitted for the exclusive use of this software for control and monitoring. Although the lab development was a hefty challenge, it was noted that the conversion to electronic instrumentation was a valued asset.

Electrical Engineering labs have also begun to involve the use of the software in custom projects [10]. In [10], an academic unit started a two-year project geared toward developing computer-based laboratory instruments (CLIs) for custom hardware. The program goal was set to have the CLIs integrated into the undergraduate curriculum, giving students a first-hand laboratory experience. The ease of use and flexibility demonstrated in LabView made it a proficient solution.

The unique UPS system that this paper is focused on presents a similar opportunity in the design of electronic instrumentation and control for a custom UPS system. The purpose is to adapt the industrial power unit for educational purposes in power electronics and energy storage areas. Traditionally, undergraduate programs supplement instruction with a series of laboratory experiments in step with power electronic principles and concepts as they are presented in the course. An attractive package is presented in [11], where a circuit board for a flexible electronics laboratory was introduced for custom-designed power-pole boards. The flexible system was used for conducting experiments on standard switch topologies; ac-ac, dc-dc, dc-ac and ac-dc converters.

This UPS system combined with an integrated software interface provides a means to supplement individual laboratory experiments on each power electronic subsystem comprising the UPS system. The UPS integrates three unique modules with their respective properties and specifications.

II. Objective

Small-size UPS systems typically contain the rectifier, battery storage, and inverter all combined in one chassis largely owing to cost and convenience. However the UPS system discussed in this paper is modular, the separate subsystems are assembled to create an integrated 6 kW UPS unit. This industrial power system has a variety of sensors and on-board controllers to ensure its stability and functionality [12].

With the potential to operate and control the UPS presents the idea of extending the hardware into an interactive educational laboratory tool. This would allow undergraduates in electrical engineering to gain a strong perspective on how a UPS functions at the subsystem level, as well as analysis of performance data.

In order to achieve such a tool, a convertible software solution must be developed to bridge the physical apparatus to the computer (shown in Fig. 1). Through the use of effective graphical interfaces and visual objects, a control center can be created to mirror each facet of the UPS. Once the system has been replicated in a software model, signals, indicators, and controls can be interpreted on screen. Each module can have its own respective section containing all the available inputs and outputs associated with it. A student can then view several graphs and indicators simultaneously, as well as see how altering the controls modify the output sequences.

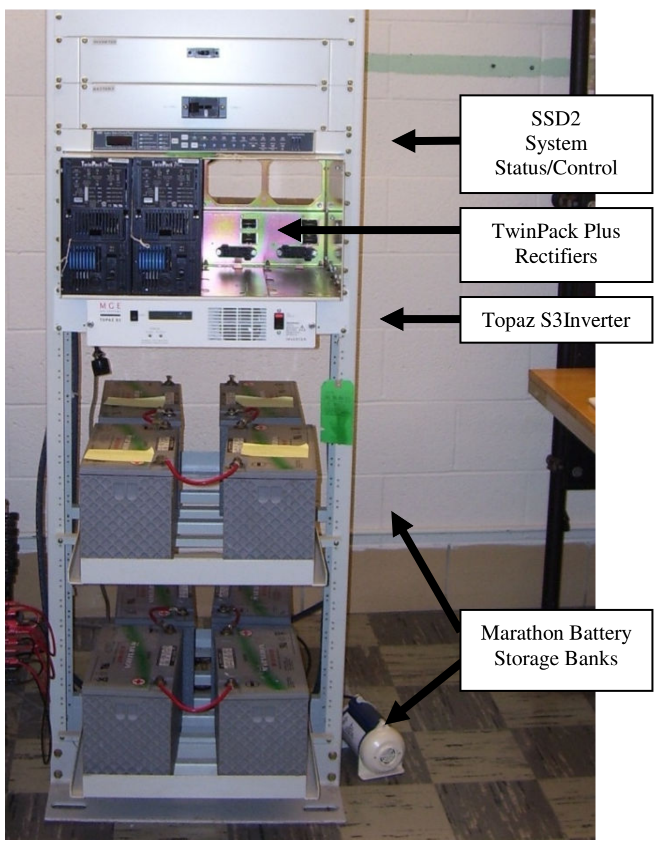

Fig. 1. UPS System showing System Status/Control Panel, Rectifiers, Inverter, and Battery Storage Banks

III. Uninterruptible Power Supply

Uninterruptible power supply systems provide reliable and high-quality power for many types of loads [13]. These systems have been designed to protect sensitive loads against various irregular power conditions. These can range from common overvoltage, under voltage, and power surge conditions to line disturbances and harmonics. In general, an ideal UPS system should be able to handle constant power flow while simultaneously providing power conditioning. The subsystems of the UPS are explained in detail in the following sections as well as the features and ratings of each used.

To ensure stability and control power flow across all three modules, a status panel is typically installed and wired in parallel to each component. In this system, the Power Conversion Products SSD2 System Status/Control Panel is used to monitor the operation of all modules [14]. The SSD2 provides the operator with system voltages, currents, and an emergency shutdown sequence. Connections to each of the modules also provide for a summary of all faults across the system and are indicated by visual and audible alarms. A flowchart showing these components and the connections made on this UPS system is shown in Fig. 2.

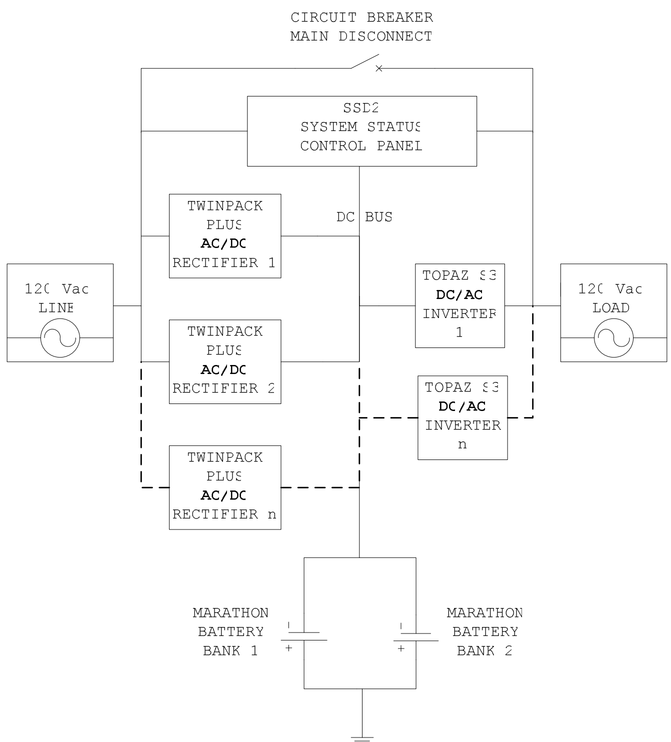

Fig. 2. UPS Flow Diagram

A. Rectifier

Two interconnected TwinPack Plus rectifiers are used for the operation of this UPS. The TwinPack Plus modules contain circuitry that monitor incoming and outgoing power and stabilizes the voltages [12]. Each rectifier module has a 3 kW capacity (6 kW total) and produces a -48 VDC output from a single phase AC input ranging from 176 to 264 Vac and operate between 45 and 65 Hz. It is important to note that operation of these rectifiers is not jeopardized by line voltages below the minimum. Each module contains its own controls and indicators including an on/off toggle switch, a DC output circuit breaker, and a rectifier test button. In addition, DIP switches are provided on the front of each module to adjust high voltage shutdown limits, enable or disable load sharing, and float or equalize settings. There are a variety of accessible remote alarm and control connections available which are connected to the SSD2 System Status/Control Panel [14]. These signals are branched over to the monitoring system software and will be mentioned in detail later.

B. Battery Storage Banks

There are two battery storage banks on this UPS system. Both banks contain four 12 VDC batteries compliant with the IEC 896-2 standard [15]. Designed for their durability in telecommunications and electric utility applications, these batteries are capable of storing 28 to 180 AH of charge [16]. Each deep cycle battery is constructed using sulfuric acid for premium charge capacity. Each battery bank is connected in series and provides a balanced -48 VDC back to the DC bus.

C. Inverter

In the event of a loss of electrical power, the inverter uses the DC supply bus to provide uninterruptible power back to the AC load [13]. This system utilizes a 500 VA Topaz S3 inverter [17]. The Topaz S3 provides high isolation between AC and DC allowing for a clean, efficient power of up to 480 W and can withstand a surge up to 6 kV. An onboard microprocessor is used for a range of controls, status indicators, LCD metering data, and communication with the other equipment. The voltages and currents of the battery banks are monitored as well as the frequency of the AC utility and output lines. A sine wave reference signal is generated to compare AC utility and output lines and confirm they are operating within a normal range. In the event of a problem with the AC utility voltage, DC supply bus voltage, or the inverter, four external alarm outputs are provided through relay contacts. These contacts are sectioned for two major failures and two minor warnings. When an alarm is activated, the device displays a description of the problem on an LCD screen and opens the corresponding relay contacts. A measurement of resistance across each of the terminals can determine the state of each alarm.

IV. LabView™ Development Platform

In the selection of the platform to develop a monitoring system, the National Instruments LabView presented an excellent solution to provide an interactive visual interface. LabView presents the opportunity to continuously sample a variety of signals with ease while simultaneously allowing for signal processing functions. With the connection of a variety of external modules, the user can read raw analog or digital signals and design the suitable outputs to control devices. This UPS system contains so many types of signals that need to be read and sent that the LabView software provided the critical link to developing a functional, user-friendly information system.

Programming in LabView is very different from a text-based language such as C or Basic. Every program is separated into two views: a front panel and a block diagram. The front panel is reserved for the user interface, and block diagram for programming. The LabView system uses graphical symbols to describe program functions [7]. Programs built on this interface are called Virtual Instruments (VI's), as they imitate actual instruments used in a laboratory setting. VI's can be independent programs built to handle one device or purpose, or can be called inside a higher program as a subroutine (also known as a sub-VI). An example of this technique is shown later in Fig. 5, where a square block named "I Data" represents a sub-VI being used as a function inside a larger program.

For the UPS device, 22 signals need to be handled at the same time with individual processing, a task that would be difficult to accomplish with standard laboratory equipment. LabView has the ability to analyze and interpret these signals as well as provide the algorithms for manipulation. The flexibility of real-time processing makes LabView a powerful development interface and a suitable choice for programming. The development of software that can combine all the functions needed to control and read data from the system can offer educational value to undergraduate engineering students.

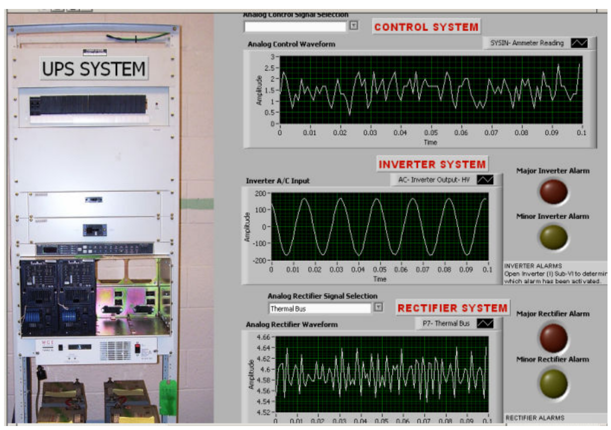

Fig. 3. Front Panel View of UPS Main Program Interface

A. *Front Panel*

The front panel is the user interface side of the program. This panel contains the graphs, indicators, and a number of controls [18]. Graphs can represent analog, digital, or mixed signals and can be scaled or colored to differentiate certain parts. The controls and indicators can vary from knobs and push buttons, to numeric controls and LED pilot lights. Controls can be adjusted using a mouse and keyboard and the changes are indicated on the computer screen.

In the UPS monitoring program, five front panels have been constructed. The first is reserved for the main program interface, representing the entire UPS system as whole and basic information of each module is functioning. Shown in Fig. 3, this screen displays one graph per module and the major and minor alarms associated with that module (if applicable). Four front panels are designed for each of the individual modules as well. The Inverter front panel is shown in Fig. 4, showing the AC output waveform, alarms associated with the device, and AC Output Analysis. Major alarms are depicted as red circular indicators and minor alarms using yellow circular indicators. Each alarm is accompanied by a description of what triggered the fault. The AC Output Analysis column calculates the current RMS value of the signal, average frequency, and performs basic harmonic analysis.

B. Block Diagram

The block diagram represents the programming side of the software. This view shows the data flow, processing of signals, and implemented algorithms. The data flow lines are wired to virtual instruments in the block diagram to manipulate the signal and integrate the user interface controls. Graphs, controls, and indicators are connected to other operators and program structures. Each program structure has a different symbol and each data type is differentiated by a color or pattern.

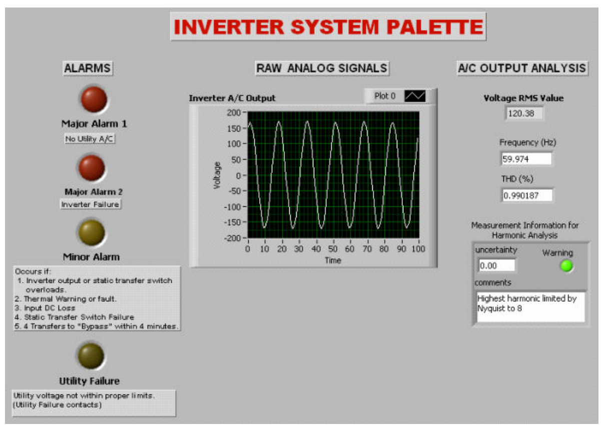

Fig. 4. Front Panel View of Inverter System

The inverter block diagram is pictured below in Fig. 5. Input signals routed from the UPS are depicted as blue lines. The inverter AC input signal is connected to a multiplier of 32.5 to scale the signal after it has been run through a transformer. A full description of the scaling and signal manipulation is discussed later. The other four signal-carriers represent the alarm outputs from the inverter. An algorithm is designed to calculate a RMS resistance value from each alarm and compare it to a decision threshold. If the resistance value of an alarm goes to 0 Ω, the alarm is active. Conversely, when the resistance level approaches infinity, the alarm is deactivated. To avoid false triggering that can be caused by noise in the system; a value of 10 Ω is used as a threshold. The alarms are separated into two major and two minor faults. In order to save space on the main program interface, only one major and one minor alarm is displayed. To overcome this constraint, a logic circuit is used to sum the major and minor alarms for their respective output indicators.

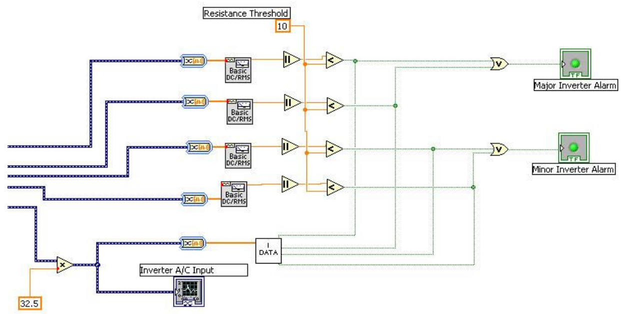

Fig. 5. Block Diagram View of Inverter System

V. Development of the UPS Monitoring System

To connect the UPS system's "raw" signals, a National Instruments Data Acquisition box (NI-DAQ) was used to process and sample the signals for communication to the computer hardware [18]. The NI-DAQ modules used includes: NI 9205 for voltage & resistance measurement [19], NI 9211 for thermocouple connections [20], and NI 9481 for relay switching [21].

A majority of the signal outputs are voltages and are patched into the NI 9205 module [19]. The NI 9205 accepts a variety of signal types. Two thermistors are used to measure the temperature of the rectifiers and battery banks in the system, and are connected directly to the NI 9211 module [20]. The relay connections represent the four remote controls on the UPS system. These output controls can shutdown each individual rectifier, enable shelf load sharing, and initiate a high voltage shutdown reset following a system overload. The NI 9481 contains four relay switching channels and can handle up to 60 VDC [21].

Energy usage statistics and storage battery State-of-Charge were two major areas of interest because they are not typically included in the coverage of power converter theory. The power used by the UPS system is determined through ammeter and battery bank voltage measurements. Shown in Fig. 6, power is integrated over time to determine the energy used and displayed in Watt-hours (Wh) [22]. The State-of-Charge (SOC) display shows a percentage of the remaining energy in the battery bank as compared to its capacity when it is fully charged [23].

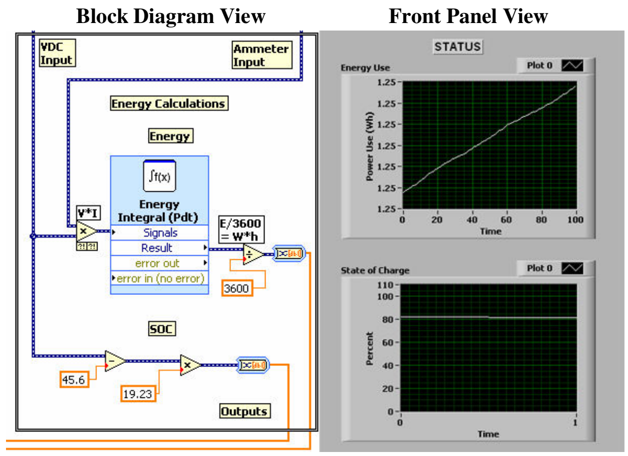

Fig. 6. Energy Storage Monitoring Front Panel & Block Diagram

VI. Integration into Power Electronics and Energy Systems Courses

The merits of practice-oriented curriculum and the benefits of integration of hardware-based laboratory experience in undergraduate power electronics courses are widely acknowledged by educators [8]. Guidelines suggested for embedding the experience within the curriculum includes: (1) analyzing and establishing expected results, (2) simulation to verify the analysis, (3) validation through hardware experience [8], [25]-[27].

Typical laboratory exercises in power electronics (software or hardware) [28] are focused on fundamental concepts and are therefore designed to study a single converter topology at a time. Experiments are designed to examine switching characteristics of devices, effects of duty ratio, dynamic response of switching model, feedback control design, frequency response characteristics, voltage/ current performance, power quality, and load performance, storage characteristics of inductors and capacitors, and efficiency.

The retrofitted interactive UPS system presented in this paper offers a different range of hardware-based laboratory experience that complements the traditional software or hardware experiments highlighted in the previous paragraph. The tool enables learners to examine a fully integrated UPS unit at the subsystem level. Unlike the experience gained from studying single converter topology at a time in traditional software/ hardware experiments, the UPS system does not offer the option for changing key converter characteristics. For instance, switching frequency, feedback controller parameters and converter circuit component sizes are fixed. The UPS system however focuses learning on signal transmission between cascaded converters (ac-dc, dc-ac), monitoring of line, load and storage functions, system protection and alarming, energy storage analysis, load studies and power quality assessment at both system and subsystem levels.

The strategy for embedding the interactive UPS system in the curriculum is dependent on the characteristics of the course where it is to be used as learning supplement. Four courses offered in the BSEE program at the location of this UPS system could potentially benefit from using the tool, namely: Power electronics, Energy systems and conversion, Power system analysis I and

Power systems analysis II. In the Power electronics course the early part of the semester is devoted to using software and traditional hardware laboratory to study single basic topologies as the theories are introduced. The UPS system is appropriate for use in the latter part of the semester to evaluate interconnected converters at system level, study protection and system monitoring functions, and finally focusing on energy storage, battery characteristics, and advanced studies on state-of-charge and state-of-health model development.

In the other three courses identified in the previous paragraph only a very short instruction time is normally devoted to coverage of power electronic principles since the topics are only peripheral to those course objectives. Therefore, the traditional power electronics software or hardware laboratories are not incorporated into the courses, rather the interactive UPS system serves as a means for giving quick overview and introduction to converters and storage characteristics. This serves as the avenue to provide some laboratory exposure when there would otherwise be none. Without extensive setup time or dedicated semester-long laboratory sessions, students receive the benefit of some interaction with an industrial UPS system by studying its characteristics through the LabView interface.

The interactive UPS system is not intended to replace the traditional software or hardware-based experiments, rather is should be seen as a supplement that enables students to efficiently study the characteristics of a fully integrated system.

VII. Future Work

The energy storage feature of the interactive UPS system would be extended to provide an avenue for advanced work in battery research. To accomplish this, tools for modeling energy storage characteristics, as well as accurately measuring energy use and battery loading will be developed and integrated within the LabView interface. Furthermore, accessibility to the UPS system will be increased by providing remote access through computer networks and the Internet. Users would be able to operate and control the system, as well as study its characteristics same way, whether inside or outside the physical laboratory.

To date, a limited number of students have received an overview of the capabilities and features of the industrial UPS system while in development. Students are generally excited about the added benefits it has brought to their learning experience. The impact on learning and a survey of student experience will be collected and evaluated after several classes have had opportunity to interact with the UPS system.

VIII. Conclusion

In this paper, an industrial UPS system is transformed into an educational tool to supplement classroom and laboratory coursework in power electronics. Using LabView development platform, a software solution was constructed to monitor the power system and view changes being made in real-time. The learning system retained all the functions and features that were included in the original design. The tool serves as a supplement to traditional software/hardware laboratory experiments that focus on individual converter topologies. The UPS system extends the learning opportunity to cover integrated subsystems and provides features to study system performance, protection and control, as well as energy storage device characteristics.

REFERENCES

[1] J. Platts, J. S. Aubyn, "History and Market Growth" in *Uninterruptible Power Supplies*, Stevenage, UK: IET, 1992, ch. 2, p.9.

[2] A. Smit, D. Heer, R. Traylor, T.S. Fiez, "A Custom Microcontroller System Used as a Platform for Learning in ECE," presented at the *ASEE 2004 Annu. Conf. and Expo.*, Salt Lake City, UT, Jun. 2004.

[3] L. Schuch, W. Priesnitz Filho, C. Rech, H.L. Hey, J.R. Pinheiro, "Integrated Software to Assist the Design and Study of UPS's," presented at the *IEEE Power Electron. Educ. Workshop 2005*, Recife, Brazil, Jun.2005.

[4] V.M. Becerra, C.N.J. Cage, W.S. Harwin, P.M. Sharkley. (2004, Oct.). Hardware Retrofit and Computed Torque Control of a Puma 560 Robot. *IEEE Control. Syst. Mag*. [Online]. *24(5)*. pp. 78-82. Available: http://ieeexplore.ieee.org/ielx5/37/29513/01337867.pdf

[5] P.S. Shiakolas, D. Piyabongkan. (2003. Feb.). Development of a Real-Time Digital Control System with a Hardware-in-the-Loop Magnetic Levitation Device for Reinforcement of Controls Education. *IEEE Trans. Edu.* [Online]. *46(1)*. pp. 79-87. Available: http://ieeexplore.ieee.org/ielx5/13/26560/01183670.pdf

[6] Mathworks. (2009, Feb. 14). *Simulink – Simulation and Model-Based Design* [Online]. Available: http://www.mathworks.com/products/simulink/

[7] B. Mihura, *LabVIEW for Data Acquisition*. Upper Saddle River, NJ: Prentice H all, 2001, pp 3-15

[8] J.M. Williams, J.L. Cale, N.D. Benavides, J.D. Wooldridge, A.C. Koenig, J.L. Tichenor, S.D. Pekarek . (2004, Nov.). Versatile Hardware and Software Tools for Educating Students in Power Electronics. *IEEE Trans. Edu. 47(4)*, pp.436-445.

[9] C.V. Knight, G.H. McDonald, "Modernization of a Mechanical Engineering Laboratory Using Data Acquisition with LabVIEW," presented at the *Proc. 1998 Annu. ASEE Conf.*, Seattle, WA, Jun. 1998.

[10] D.M. Beams, "Developing Computer-based Laboratory Instruments in a New Undergraduate Electrical Engineering Program," presented at the *2002 ASEE Annu. Conf. and Expo.: Vive L'ingenieur*, Montreal, QC, Jun. 2002.

[11] N.Mohan, et all, "Restructuring of first courses in power electronics and electric drives that integrates digital control**,**" *IEEE Trans. Power Electronics,* Vol 18, pp. 429 - 437, Jan. 2003.

[12] Power Conversion Products, LLC, *TwinPack Plus – CE*. Crystal Lake, IL: Power Conversion Products Inc., 1997.

[13] A.Emadi, A. Nasiri, S.B. Bekiarov, Uninterruptible Power Supplies in *Uninterruptible Power Supplies and Active Filters*, Stevenage, UK: CRC Press, 2005, Chicago, IL, ch. 1, pp.2-5.

[14] Power Conversion Products, LLC, *SSD2 System Status/Control Panel Instruction Manual*. Crystal Lake, IL: Power Conversion Products Inc., 2000.

[15] EXIDE Technologies AB. (2009, Feb. 23). The Lead-Acid Battery Theory and Design. *Industrial Energy Sweden* [Online]. Available: http://www.tudor.se/eng/standby/pdf/1-generalinfo.pdf

[16] MSR Marathon Batteries, *Installation and Operating Instructions for Marathon and Sprinter Batteries*. Lombard, IL: Marathon, 1997.

[17] Square D, *Powermark S3 Series 0.5 kVA and 1 kVA Owner's Manual*. Costa Mesa, CA: EPE Technologies, Inc., 1995.

[18] B. Mihura, *LabVIEW for Data* Acquisition. Upper Saddle River, NJ: Prentice H all, 2001, pp 3-15

[19] *Operating Instructions & Specifications NI 9205: 32-Channel, ±200 mV to ±10 V, 16-Bit Analog Input Module*. National Instruments Corp., Austin, TX, 2008.

[20] *Operating Instructions NI 9211: 4-Channel Thermocouple Input Module*. National Instruments Corp., Austin, TX, 2006.

[21] *Operating Instructions NI 9481:4 Channel SPST Relay Module*. National Instruments Corp., Austin, TX, 2006.

[22] R. L. Boylestad, *Essentials of Circuit Analysis*. Upper Saddle River, NJ: Pearson Prentice Hall, 2004, pp. 96-97.

[23] F. Zhang, G. Liu, L. Fang, "A Battery State of Charge Estimation Method with Extended Kalman Filter," presented at the *2008 IEEE/ASME Int. Conf. Ad. Intel. Mechatron.*, Xi'an, China, Aug. 2008.

[24] Solarseller.com. (2009, Apr. 7). 95 Battery Condition and State of Charge Charts. [Online]. Available: http://www.solarseller.com/battery_state_of_charge_charts.htm
[25] H. Widlok, "The Applications of Concurrent Simulation in the Power Electronics Laboratory," in *Proc. IEEE Int. Symp. Industrial Electronics*, vol. 2, Jun. 1996, pp. 573-577.
[26] S. S. Ang, "A Practice-Oriented Course in Switching Converters," *IEEE Trans. Educ.*, vol. 39, pp. 14-18, Feb. 1996.
[27] D. A. Torrey, "A Project –Oriented Power Electronics Laboratory," *IEEE Trans. Power Electronics*, vol. 9, pp. 250-255, May 1994.
[28] N. Mohan, "First Course on Power Electronics," MNPERE, 2009.