LPRDS – A Requirements-Driven team-Based Design of a 2kW Solar Energy System

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Abstract

This paper will describe a capstone senior design course that features a team-based requirements-driven project. The project scope is selected such that the technical requirements are sufficiently complex to require a team-based solution. The project implementation is designed to force the students to consider realistic formal engineering requirements and specifications while offering significant opportunities for student leadership. The most recent embodiment of this project is the Lafayette Photovoltaic Research and Development System (LPRDS) which addresses the design, fabrication, and testing of a 2kW solar energy system. This project will be described to illustrate various pedagogical objectives of the capstone course.

Introduction – Capstone Design at Lafayette College

Lafayette College is an independent co-educational college of 2400 undergraduate students and 206 full-time faculty, with approximately 20% of the students and faculty being in the Engineering Division. The Division offers four ABET accredited Bachelor of Science engineering degree programs including electrical and computer engineering (ECE), mechanical engineering, civil engineering, and chemical engineering as well as a Bachelor of Arts degree program in engineering studies. While the requirements for senior design differ somewhat across degree programs, all programs strive to provide the students with a solid capstone design experience.

As the curriculum is currently structured, ECE students are required to take a two-course design sequence during their senior year. During the first of these courses, senior design I, the students work on a structured design project that has been pre-packaged for them by the faculty teaching the course. Recently, this project has been writing Verilog code to implement a wireless LAN using pre-designed FPGA and RF hardware that is supplied to them. The students are taught in lectures about formal design process, but their design freedom in the project itself is limited. Project management tools such as milestone and Gantt charts are introduced; however, high-level task planning is still done by the faculty for the students. Typically, students work in the usual lab-pair teams. Each team of students has the same design requirements, but the teams are discouraged from inter-collaborating.

The first semester of senior design would be almost indistinguishable from a typical undergraduate lab assignment if it wasn't for one critical difference: the scope of the project requires a multi-week effort. For the two-student teams to have any chance of success, they need to plan ahead, spreading their work over a multiple weeks. In addition to the scheduling challenge, our first semester senior design also emphasizes testing and verification of design elements. Learning the importance of testing and planning are valuable lessons that many of the students take away from this first semester of senior design, but many equally important design and engineering project lessons are skipped. Most significant of these omissions is that students are not yet introduced to a true, team-oriented working situation. Even though they are grouped in two-student "teams", most issues of team dynamics cannot arise in such a small group. Another limitation of this first semester project is that students work in one narrow technology. Students are not challenged by any significant multidisciplinary requirements. Although students are expected to successfully complete their designs on time, and the scope of the work does require some rudimentary planning, they have little concern for larger issues such as system engineering, multi-level schedule development, system acceptance testing, staff management, and budgets. Nor do they seriously grapple with manufacturability, reliability, or maintainability aspects. The second course of the senior design sequence, senior design II, is radically different.

In senior-design II, all the students in our senior class are grouped into a single, large design team and are presented with a challenging design problem that requires a multidisciplinary, systems engineering approach. The students are presented with the equivalent of a real-world statement of work (SOW) defining a set of high-level system requirements that comprise both technical and non-technical constraints. They are given this document on the first day of class and are expected to demonstrate and deliver a working system that meets its requirements by the last day of class – a mere fourteen workweeks later.

In our model of a real world work arrangement, students are required to work as a team to perform system architecture tradeoffs, develop a schedule, and organize into sub-groups for design and project management. They are required to conduct a design review with an outside group of industry engineers. Finally, they are required to procure parts, build and test subsystems, integrate everything into a system, and demonstrate compliance with the SOW in a final acceptance test and demonstration.

Over the past ten years, the size of the design teams has ranged from eight to twenty-two students. It has been our experience that such a large group of inexperienced student-engineers will not naturally "self organize" sufficiently to achieve complete project success during the one semester schedule allotted for the project. Student teams require significant coaching and mentoring. Currently, the senior design II course is team-taught by two faculty members who each have significant industry experience. Each faculty member is scheduled to provide nine contact hours each week, constantly shepherding such a group in the direction of progress by providing both management and technical guidance to the design team.

Project Selection – Pedagogical and Practical Issues

The selection of a team-based capstone project must be considered carefully. It should include important design elements from all major stems of the curriculum and incorporate an appropriate mix of digital and analog hardware and software design. Ideally, the project should be appealing to students, address contemporary issues, and offer interesting, non-trivial opportunities for the analysis of ethical and economic issues and the various “illities” constraints including reliability, maintainability, sustainability, and manufacturability. Pedagogically, we have adopted a formal requirements-based philosophy that forces students to carefully consider whether or not their design choices are serving to meet performance requirements specified in a formal statement of work and related engineering standards. In our experience, the groundwork for such a project must start at least a year in advance of the first course offering in order to provide adequate time to write an effective statement of work and to obtain necessary project approvals including funding and/or infrastructure installation.

In the following sections, our most recent design project will be described to illustrate our capstone project pedagogy and implementation. This project is called the Lafayette Photovoltaic Research and Development System (LPRDS).

LPRDS - Motivation

The National Academy of Engineering (NAE) has identified “making solar energy economical” as one of fourteen Grand Challenges for engineering[1]. Photovoltaics (PV) is the best known solar energy technology and it has been around for a long time - the seminal paper that theoretically analyzed silicon PV cell energy conversion efficiency was written by William Schockley (who also won the Nobel Prize in 1956 as one of three inventors of the transistor). Most commercial PV products have efficiencies in the 10-15% range, significantly less than the 30% theoretical maximum predicted by Schockley. The PV industry has been trying to achieve a cost of $1/Watt-peak for over 30 years and much of current industry activity is focused on low-cost PV technologies and reducing manufacturing costs. Moreover, a large percentage of the installed PV infrastructure can be attributed to significant subsidies and tax incentives. Finally, the use of PV, like wind energy, poses significant energy storage and grid integration challenges due to variable power production. As a result, PV comprises only a fraction of a percent of the total US energy production. It is little wonder that economical solar energy is considered a “grand challenge” by the NAE.

How can the global challenge of renewable energy be addressed locally in an already crowded undergraduate engineering curriculum? The Electrical and Computer Engineering department at Lafayette College has created the Lafayette Photovoltaic Research and Development System (LPRDS), a photovoltaic laboratory for use in capstone senior design projects.

LPRS Baseline Infrastructure

The LPRDS project was conceived in the spring of 2008 and was first run as a course in the spring of 2009. The basic infrastructure provided for the first course offering included a significant PV array of a size roughly equivalent to what might be found in a residential system Also provided are transfer switches and other infrastructure that gives safe access to the utility power grid as well as to sets of power outlets around the building. The system was configured so that the PV array could be connected to a commercial grid-tie inverter when it was not being used to support student project work. In this way, the energy from the system could be used by the College. A block diagram of this baseline LPRDS system is shown in Figure 1.

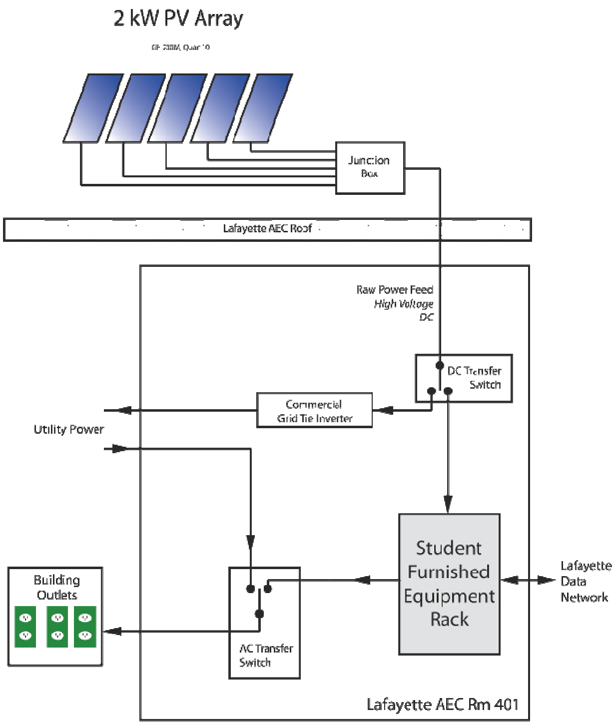

Figure 1. Lafayette Photovoltaic Research and Development System (LPRDS)

Each year, as the LPRDS supports senior design, its baseline architecture can grow and change as students add new integrated capability that can be utilized by future teams.

LPRDS Statement of Work and Requirements

The Statement of Work that was given to the student design team emulates a real world requirements document. The document is about 25 pages long and lists hundreds of requirements associated with a set of deliverables. The deliverables list in the 2010 LPRDS was the following

Deliverable	**Description**	**Due Date**
D001	CDR Presentation Materials	Delivered to web site and reviewers 24 hrs prior to CDR
D002	Users Manual	Draft at CDR, final 7 May (5 PM)
D003	Final Report and Maintenance Manual	Draft at CDR, final 7 May (5 PM)
D004	Acceptance Test Plan	Draft at CDR, final prior to testing.
D005	Acceptance Test Report	30 April
D006	QA Audit Report	30 April
D007	Project Web Site	Must be updated regularly.
D008	LPRDS-BMS-2010 Integrated System	Final disposition per GPR012 no later than 7 May (5 PM)
D009	Conference Paper	TBD
D010	Project Poster	7 May (5 PM)

The SOW attempts to avoid specifying the system architecture, but some high level detail is necessary in order to specify constraints. Figure 2 shows the system-level block diagram included in the SOW. Six major subsystems are identified:

- Supervisory Control and Data Acquisition (SCADA)
- SCADA Data Interface (RS-485)
- Raw Power Interface (RPI)
- Energy Storage System (ESS)
- Energy Delivery System (EDS)

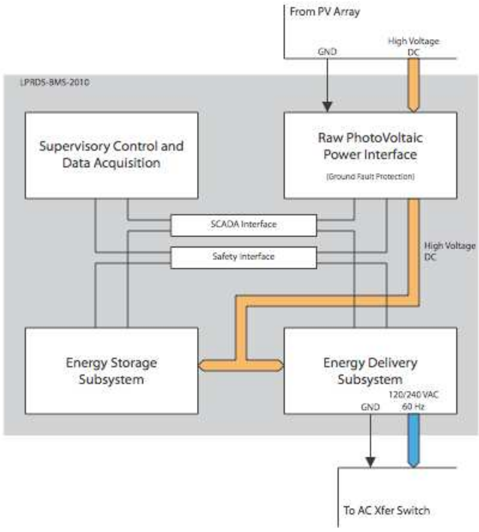

Figure 2. Top Level System Architecture in SOW

As is usual with real SOWs, requirements given to the students fall into several categories. For example, there are management requirements associated with deliverables, mandated project activities and milestones such as regular status reports, and the development and adherence to a project schedule and budget. .

There are high-level technical requirements for system functionality and performance. These requirements set out the main technical goals and constraints for the effort. In writing technical requirements for these projects, we do our best to avoid giving explicit hints as to what sort of design could satisfy the requirements, putting the students in a predicament they've not commonly experienced. We tell them what they must do, and what they can't do, but considerable freedom remains in their design space. For example, the following is the technical specification of the energy delivery system (EDS) portion of the LPRDS in Spring 2010. Although a pulse width modulation (PWM) based inverter is almost certainly part of the preferred solution, nowhere in the requirements is PWM or inverter mentioned.

> ***R003: Energy Delivery***
> *The LPRDS-BMS-2010 shall include an Energy Delivery Subsystem (EDS) that will accept raw, high voltage DC from the RPI and EDS, convert the energy as required, and deliver well regulated 120 VAC sinusoidal 60 Hz electric power to the LPRDS transfer switch connector.*
>
> *The LPRDS is an experimental system that will serve as a testbed for PV research. For this reason, the power management algorithms used by the EDS shall be coded in software, firmware, or programmable logic by the LPRDS team, and made available as part of the SDK so that they may be altered or expanded easily. The use, in whole or in part, of proprietary, vendor-supplied power/energy management algorithms is not permitted.*
>
> *EDS is not required to be self-contained with respect to the power/energy management algorithms and software. These algorithms may reside and/or run in other system components (e.g. SCADA).*

EDS will be connected to the safety interface that connects to both the RPI and the ESS. Breaking or disconnecting the safety interface shall cause all systems to enter a fault state and disconnect HV from their outside terminals.

The following requirements describe the basic algorithm that must be implemented in this effort.

- *The EDS shall remain in shutdown until all faults are cleared and the main startup switch is actuated.*
- *Should a fault be detected at any time, the EDS will use the safety interface to shutdown the ESS and RPI and enter a fault state.*
- *Once activated, so long as there is no fault, with first priority the EDS will convert DC energy from the PV array to meet AC power delivery needs.*
- *If power delivery can be fully met by converting energy from the PV array, any additional energy available from the PV array shall be used to charge the ESS until the ESS is charged to full capacity.*
- *If insufficient power cannot be derived from the PV array to meet AC power delivery needs, the EDS will supplement PV power with stored energy from the ESS.*
- *If insufficient power is available from both PV and ESS systems combined, such that it is impossible to maintain load regulation, the EDS shall drop the load and enter an undersupply fault state.*

There is no requirement for PhotoVoltaic Maximum Power Point (MPP) tracking.
The EDS shall not over-charge or over-discharge the ESS, nor shall the EDS charge or discharge the ESS at rates beyond its rated capacity.

The EDS shall be properly designed with consideration of the high voltages and currents per the electrical safety plan.

The EDS shall be able to deliver high quality, regulated, 120 Volt RMS, sinusoidal 60 Hz AC electricity, continuously, at a maximum sustained current of 10 Amps RMS, to a load of any power factor.

The 60 Hz sinusoidal frequency shall be accurate to within 0.05%. Locking to commercial mains frequency is desirable but not required so long as the frequency tolerance is maintained. Total harmonic distortion into a linear load shall be less than 3%.

Load regulation steady state error shall be better than 3%, and the transient response overshoot shall be less than 5%, for any step load change within the sustained capacity of the system. Step response settling time within 2% shall be less than 33 ms

The EDS shall be able to switch between sources of power (PV array or ESS) without interrupting the delivery of power to the load.

An RS-485 interface to the SCADA system shall be provided, with format as required for supervisory functions.

At a minimum, the SCADA shall be able to monitor voltage and current on all interfaces of the EDS subsystem, internal temperature in all critical locations of this subsystem, and operational or fault state. In the case of sinusoidal AC interfaces, measurement of the phase angle between voltage and current is also required.

There are also requirements for acceptance testing. For example, the following is the description of the Acceptance Test Plan the students must generate:

> ***D004: Acceptance Test Plan***
> *The Acceptance Test Plan (ATP) is a document that describes how the system as a whole will be tested so as to prove compliance with all requirements and specifications. The ATP should include forms that can be filled out by testers during execution. These filled out forms will be used to create the ATR.*
> *Compliance can be proved in any of the following three ways:*
> - *Analysis – detailed logical analysis can demonstrate compliance by reasoning from known facts (a priori or empirically) in the form of a proof.*
> - *Test – an explicit test, experiment, or demonstration can be used to make compliance with a certain requirement obvious*
> - *Inspection –compliance is already evident by directly examining the system*
>
> *The ATP should be arranged to minimize the work involved in testing. If possible, multiple requirements should be demonstrated by each test.*

Finally, all projects must comply with a standard boilerplate set of general requirements (much like in real world SOWs). These include specific constraints for safety, good practice, EMI/EMC, environmental tolerance, along with various “illities” constraints on such topics as: hazmats, reliability, maintainability, sustainability, manufacturability, and ethics. We attempt to cast these requirements in a form that constrains the student design in realistic, useful ways that students can address within the scope of their project. For example, here is the manufacturability requirement.

> ***GPR008: Manufacturability***
> *A production design is a project design that could reasonably be manufactured in large quantity (e.g. greater than 1000 units/yr). All production designs must be built from components and subassemblies that have a sustainable source of supply over the system lifetime. To demonstrate that this requirement is met, it must be shown that each item in the Bill of Materials (BOM) for the design is available from a minimum of two independent suppliers. In addition, industry trends shall be considered when selecting implementation options. Designs should choose options most aligned with future industry trends.*
> *The tolerances of components shall be considered in the design. Any component with a value that determines a critical voltage, time constant, frequency, or other parameter shall have a tolerance such that system requirements are met with 99% yield in manufacturing. An analysis shall be provided that identifies any tolerance critical components and proves that the tolerances are adequate to meet system requirements at that yield.*

LPRDS - Safety

The PV array and utility interfaces involve voltages and currents that are considerably above the domain of low-power electronics typically considered safe for students to work with in undergraduate labs. Thus, safety issues are paramount in the LPRDS development process. Our orientation toward safety begins with a comprehensive safety plan that is signed by each student. The plan is a synthesis of the safety plan used by the IEEE Formula Hybrid competition[2], constrained by the overall Lafayette College electrical safety plan, with adaptations to the specific needs of LPRDS including adherence to Article 690 of the National Electric Code on photvoltaics.

The safety plan has two main purposes. First, it establishes rules and procedures that serve to reduce the likelihood of injury to the developers during development and testing. Second, it mandates certain design requirements that further ameliorate risks to users and maintainers in the future. An example of a procedural aspect of our safety plan is the rule that students are prohibited from working directly on energized circuits with potential differences over 30 volts. An example of a design requirement we mandate is that circuits that may have potential differences greater than 30 volts must have an indicator light that illuminates when such voltages are present.

The Raw Power Interface (RPI) subsystem incorporates numerous safety features in its design and serves as our main interface to the high-voltage DC from the array. It incorporates a combination of commercially available components such as a ground fault interrupter (GFI) and a student-designed printed circuit board that provides various system monitoring functions. The RPI the following features:

- Strict isolation between high voltage and low voltage circuits.
- Double insulated high voltage section with transparent cover
- HV-present indicator lights
- DC ground fault detector
- Voltage, current, and temperature sensors
- RS-485 interface for SCADA monitoring
- Safety disconnect relays and logic
- Snubber circuits
- Anderson Power connector for HVDC

A photograph of the student-designed RPI is shown in Figure 3.

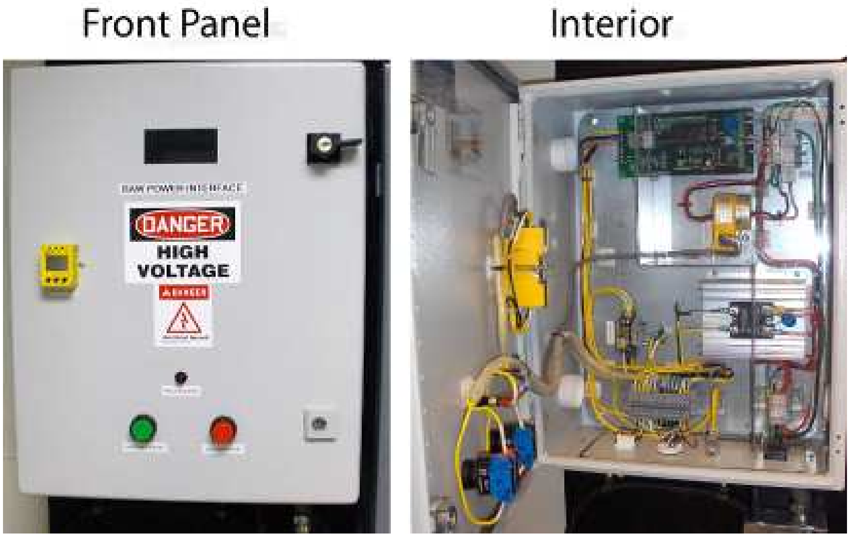

Figure 3. Student Designed Raw Power Interface

LPRDS Technical Approach

The LPRDS permits many interesting architecture considerations, both at the system level, and the subsystem level. However, with little prior experience in the “brainstorming” aspect of the design process, student teams are initially reluctant to develop and analyze their own architectures. Faculty gently pushes them to think creatively, trying not to do the thinking for the students. When students do eventually become engaged, do independent design, and propose a particular solution, we challenge them with educating the team with the merits and limitations of their solution. Finally, as various solutions are proposed, the realities of the constraining fourteen-week schedule and a $3,000 materials budget become ominous.

The following are examples of solutions considered and adopted by students during the architecture phase of the project:

Energy Storage. Multiple energy storage options were researched and compared by students in order to find the best solution for LPRDS. Students considered safety, complexity, and life cycle costs to find a storage system that meets all required specifications from the statement of work. Significantly, the SOW did not specify a storage capacity, so students had to develop this requirement themselves, along with several others.

Among the technologies they considered were:

- Sealed Lead Acid Cells
- NiMH Cells
- Li- Ion Cells

- $LiFePO_4$ Cells
- Super Capacitors
- Flywheel Storage

Ultimately students decided that the main storage would be a $LiFePO_4$ based battery array at a nominal 204.8V. This is a string of 64 individual 3.2V 10Ah cells in series to form a high voltage battery. The $LiFePO_4$ cell chemistry has numerous electrical and safety advantages over alternatives, particularly the fire-prone Lithium Ion chemistry. The total battery capacity was chosen based on considerations of isolation and predicted load, allowing the system to operate continuously under the typical cloud cover in Easton, PA. It’s interesting to note that the useable battery capacity in LPRDS is over twice the useable capacity of the battery in a Toyota Prius.

Battery Packaging. Given our strict safety requirements that prohibit exposure to voltages above 30V, the packaging of 64 cells into a 204.8V stack posed an interesting challenge. The innovative solution the team developed was the fruit of the design review process. Students, faculty, local machinists, and outside reviewers all took part in a collaboration that resulted in a system where the stack can be assembled without ever exposing the assembler to high voltage.
Groups of four cells were assembled into sixteen, 12V packs. These packs were arranged such that their plus and minus terminals aligned in a “U” shape such that a clear polycarbonate insulating panel with spring loaded solid copper shorting segments could be lowered onto the packs from above, closing the circuit only after this non-conducting cover was in place. Figure 4 and Figure 5 sketch this arrangement.

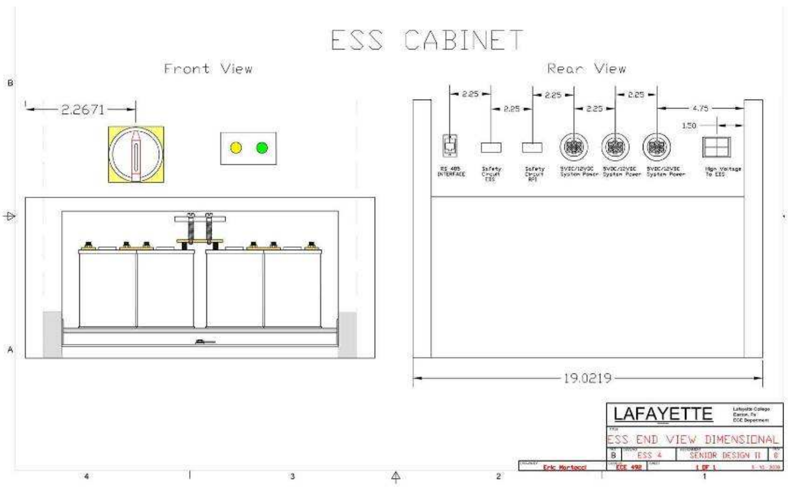

Figure 2. Battery Cabinet

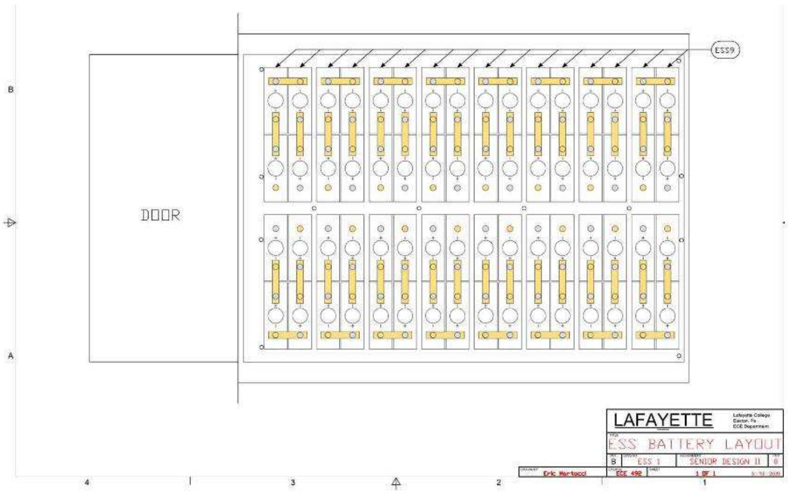

Figure 3. Layout of Cells in the Battery

Energy Management Algorithms. The SOW explicitly prohibited use of “canned” energy management algorithms: power storage and transfer must be programmable in the LPRDS system. This specification did two things. First, it required students to research the issues and tradeoffs involved in island energy storage system. Second, it forced the students to design most of their own power electronics hardware, as readily available commercial inverters and charge controllers are not programmable at the algorithm level.

High Power Inverter. Significant consideration was given to the best inverter and power conversion technology. Since previous experience with power devices was limited, students were guided by faculty toward low risk designs, but otherwise were responsible for significant detailed design work. The currently favored power conversion system in LPRDS uses a full bridge of IGBTs followed by an EMI filter and an isolation transformer. Suitable gate-drive ICs toggled through opto-isolation by a microcontroller is the source of the PWM waveform. The EMI filter was designed by students after researching FCC, Mil, and VDE regulations. It was an eye-opening experience for them to see the physical size of components needed to filter high frequencies while handling real-world AC power.

Supervisory Control and Data Acquisition (SCADA). Requirements in our SOW demanded a comprehensive data acquisition system with control capabilities a dynamic web page and an “interesting” display for visitors to see. These requirements led to an architecture study and research in databases, network communication, A/D conversion, and sensor technology. SCADA involved hardware as well as software. A typical student designed data acquisition board is shown in Figure 6. Constraints in hardware included generating isolated supply voltages for HV sensors, and issues surrounding opto-isolated data transfer. These posed a significant challenge to students who were not accustomed to these issues. Software wise, the SOW required a documented API, SDK, and application suite, but did not otherwise constrain the software architecture. Students considered myriad software possibilities, including MySQL data storage, PHP scripting.

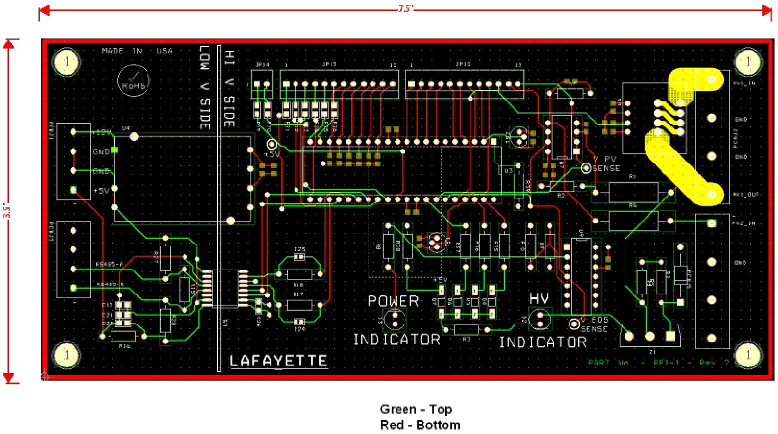

Figure 4. Student Designed SCADA Board (within the RPI)

LPRDS – Accomplishments and Status

In 2009 the first LPRDS team began with no previous work to build on. The project scope was in 2009 challenging and included system architecture design, analog and digital design, and software design. The students were expected to solve problems on their own with technical guidance (not assistance) from the instructors and to keep the project requirements in mind during design. The students did a great job figuring out problems on their own. In fact, they were at times a bit reluctant to take advice from the instructors (which cost them some time), but they developed a great deal of confidence in their ability to make decisions and work through difficulties.

The 2009 team was relatively large (22 students) and included a combination of full-time day students and part-time evening students forming a natural rift in the team. The team dynamic as a whole in 2009 was difficult to manage and they had some initial difficulty establishing a positive team dynamic. However, they pulled together during the second half of the semester and produced a working inverter prototype, ESS, and RPI that met many requirements and exceeded the instructor expectations. They also demonstrated a prototype IGBT based inverter that delivered 120VAC power to wall outlets at up to 10 Amps. At the final review and demonstration, power from the student-designed system was used to run a George Foreman grill to cook hamburgers for about forty people.

In its first year of operation, LPRDS has generated over two-million watt-hours, either injecting this power into the college electric grid, or directly driving outlets. This local electricity generation from LPRDS effectively reduces the utility power needs, and carbon footprint, of Lafayette College.

In 2010 the second LPRDS team has taken up the torch and is currently involved in developing and integrating SCADA and EDS, as well as perfecting the inverter design. Given the advanced starting point, we expect that this team will achieve full system-level integration.

Conclusions

The Electrical and Computer Engineering Department at Lafayette College instituted a team-based senior design course as part of a two-course capstone senior design sequence. The move from independent design to a team-based design was done ten years ago, in large part, due to ABET requirements. The introduction of a requirements-driven methodology is consistent with industry practice and serves to focus decision making during the system architecture and detailed design phases of the project. The complexity of the project was purposely scoped to be "broad" rather than "deep" to ensure a capstone experience that incorporates software and analog and digital hardware.

Teaching a course of this nature is challenging and is very different from teaching a traditional course and/or laboratory. The instructors must select an application that is relevant in order to engage student interest while keeping the system requirements challenging and achievable. The instructors should be comfortable with uncertainty and must allow the students to make their own design decisions and intervene only when it is clear that the students are severely floundering or are making a decision that would cause certain project failure. Instructor understanding and management of individual student personalities and technical strengths and weaknesses as well as group dynamics are important to project success. The instructors also must constantly keep contingencies in mind to ensure that the students can achieve project success in the event of an unforeseen problem (*e.g.* a critical component is out of stock). The model of two professors team teaching the course is essential for success. It allows the instructors to better understand the team dynamics and to play "good cop-bad cop" when necessary. It is also critical that that both instructors have practical engineering design and project experience and it is a plus if they have complementary technical expertise.

The use of external evaluators for architecture and design review is also important as the students take harsh criticism better from external evaluators than they do from their instructors. External reviewers for the LPRDS project worked at a major power-industry manufacturer, a small power-system consulting group, an electronics company, and the software department at a large New York bank. The reviewers included some Lafayette alumni.

The solar energy theme of LPRDS offers a significant opportunity for multi-year project since optimizing the maximal capture, efficient transformation, recoverable storage, and on-demand delivery of the electrical energy available from photovoltaic systems are all active areas of photovoltaics research. The energy storage aspect of LPRDS opens the possibility of other related projects such as electric vehicles.

The work reported here demonstrates that undergraduate students can successfully complete challenging team-based design work given the proper course structure, staffing, and environment. The LPRDS system represents a framework within which a sequence of teams can work in series over several years to develop a very significant end result. In a single semester, useful work can be done on subsystems, but it's difficult to achieve much of large-scale significance. Our student teams appear to need the better part of a semester to solidify into a productive unit. With two semesters allocated to the team experience, considerably more could be achieved with each group.

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