A State-of-the-Art Energy and Electric Drives Laboratory Designed and Implemented by Undergraduate and Graduate Students

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Abstract

Energy Conversion courses for the past 100 years have primarily focused on the fundamental concepts of machine theory and the conversion between mechanical and electrical energy. Based on these concepts an undergraduate energy conversion course would typically cover topics in DC motors and AC synchronous and asynchronous motors. The trend in the last 10 years has been to reduce the amount of time spent on the fundamentals of DC and AC machines and to incorporate DC and AC electric drives into the course content. To support this trend, South Dakota State University has incorporated major revisions to the Energy Conversion Course which now includes topics in electric drives. With these changes, a new energy conversion and electric drives (ECED) laboratory has been designed and implemented, providing students a laboratory for which they actually operate systems that make use of these technologies, while conducting the laboratory exercises. The uniqueness of this laboratory is two-fold: 1) The laboratory is completely automated, using (a) Human Machine Interface (HMI) and a power processing system (PPS) for safe distribution of resources (power sources and loads) student Power Workbenches (PWBs), and (b) Supervisory Control and Data Acquisition (SCADA) hardware/software to monitor and control Automatic Load Bank (ALBs), 2) the entire laboratory, including the HMI, PPS, PWBs, ALBs and SCADA system, were designed, constructed and tested by 13 undergraduate students and one graduate electrical engineering student over a period of four years. The new laboratory, commissioned in September of 2002, has worked flawlessly for three full semesters, and has been a showcase for prospective incoming electrical engineering students. This paper describes the general philosophy and design of the laboratory, the functionality and operational use of the laboratory, an overview of how students were integrated into the overall laboratory design and development phases, and finally, perspectives from students who are taking the modified version of the Energy Conversion course and its associated laboratory course.

I. Introduction

For 45 years SDSU electrical engineering students conducted electrical machine experiments in a spacious energy conversion (EC) laboratory, which housed a large number of medium-power DC and AC machines mounted on large raised-concrete pads (see Fig. 1). When the laboratory was constructed in 1956, it boasted 20 stations, each with it own concrete pad and combination of coupled motor/generator sets, all of different varieties.

With support from the NSF CCLI A&I program, SDSU has redesigned the course content to stay consistent with the trend of incorporating electric drives into the energy conversion course [1-5]. With the new building addition to the engineering hall (completed in May of 2002), the old energy lab was dismantled and the space was allocated to civil engineering. The new lab is housed on the third floor of this new addition in a smaller area then the original lab.

Figure 1: Original energy conversion lab at SDSU

The old lab served its purpose well but also exhibited a number of issues which are listed as follows:

1. Large concrete pads limited the flexibility and use of the lab, limiting its configuration, as well as its possible use by other classes.
2. Lab was used for both undergraduate studies and research, making use of the same space and equipment, posing a security issue, among other problems.
3. All power and loads were routed to each station through a distribution center requiring students to spend a significant amount of time completing these connections using patch cords at the distribution center's patch panel.
4. Four water rheostat load banks (LBs) were available in the lab and shared by the different

stations, limiting the lab to four groups. Also, the LBs required students to use a hand crank to lower plates into a barrel of water to reach a desired power loading. As the water heated up, the resistant would vary significantly, making it difficult for students to obtain consistent measurements.

5. Wood benches with a back panel of exposed knife-type switches were used to make final connection between source and load, presenting a safety issue for the students.
6. Benches had no convenient means for housing test equipment, and no space for a personal computer, let alone an oscilloscope.
7. Antiquated cradled dynamometers with a spring-lever dial-type scale were used to measure torque on a handful of motors, for which accuracy was always suspect.

Based on this set of concerns the following objectives for the new energy lab were proposed:

1. Lab should incorporate a variety of electrical engineering technologies that students may interact with while performing the actual lab exercise, thus giving them immediate insight into the field of electrical engineering.
2. Lab should exhibit numerous electrical engineering technological features to serve as a marketing tool for prospective students.
3. Lab should provide flexibility in configuration lending itself to the incorporation of future technologies in the area of machines and electronics.
4. Lab should be multipurpose, useful for teaching other labs, such as circuits, electronics, and controls.
5. Lab should be divided into two rooms, one for undergraduate studies and the other for research, while maximizing the sharing of resources, such as load banks and power sources.
6. Lab should minimize student's time in routing power and loads to benches by incorporating state-of-the-art control features in the routing of sources and loads between stations, both for graduate and undergraduate labs. These control features should be user-friendly to minimize student's time in allocating resources, and full-proof to eliminate unsafe routing of resources.
7. Lab should have automated load banks, for which a student can enter the desired power setting at a computer interface, such that the load banks regulate to the commanded setting.
8. A minimum of six load banks should be available, and shared between the graduate and undergraduate lab, with priority given to the undergraduate lab while in session.
9. Benches should have ample space to store test equipment, a PC, students' lab notebooks, and components for testing, such as power transformers, inductors, capacitors, etc., and be designed with safety as a top priority.
10. Each station should have a moveable motor/generator set, which can be easily reconfigured for different motor types.
11. Each motor/generator set should have modern accurate torque measurement devices installed and readable through an LED or LCD display.
12. All equipment should be on castors so that the lab can be easily emptied for custodial purposes, or in the event equipment is needed for other purposes in a different location.

With these objectives in mind, a proposal for the new energy conversion and power electronics laboratory was birthed in the fall of 1997, with original estimates of $275,000 for completion.

Section II describes the laboratory layout and some of the functional features and how they meet certain objectives. Section III describes specific equipment within the laboratory, e.g., the new state-of-the-art the automated load banks, power distribution control center, power work benches, and the cradled dynamometers. Lastly, results from two semesters of student survey results regarding their impression of the new laboratory is discussed in section IV. The paper is concluded in section V.

II. Laboratory Layout

Taking into account the need to make the new energy laboratory flexible, both in configurability and multipurpose use, the layout for this laboratory is shown in Fig. 2. The undergraduate laboratory (EL) has six stations, the research lab (RL) has three stations, and the instructional lab (IL) has one station. The EL has six fully functional power workstation benches (PWBs) that are mounted on locking-type castors, whereas the RL has only one fully functional PWB, with the other two stations provided with basic benches. The primary use of the IL is for teaching lecture courses, but has a station equipped such that a PWB can be moved from the EL allowing for in-class demonstrations.

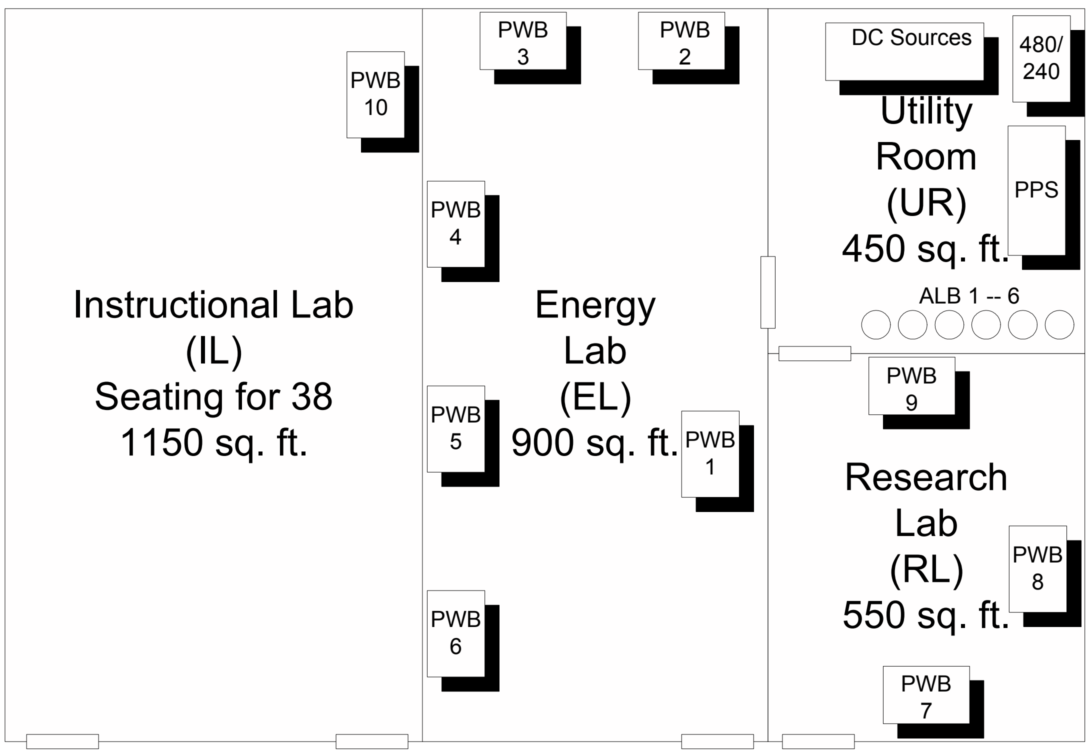


Figure 2: Laboratory Layout

The combined square feet for these laboratories totals approximately 3050 square feet.

All resources, such as utility supplies (208/240 Vac 3-phase, and 120 Vac 1-phase), battery bank, automated load banks (six ALBs), and the PPS, are located in a separate utility room (UR). Additionally, a photovoltaic (PV) array is located on the top of the building with all its power cables routed to the UR. All resources within the UR are routed to the PPS, which houses electromechanical contactors. All resources are shared between the EL, the RL, and the IL, with control given to the PPS, which acts simply as a large switch matrix, able to connect respective power cables and data cables between the source and the corresponding station. The design of the PPS disallows unsafe routing of these resources.

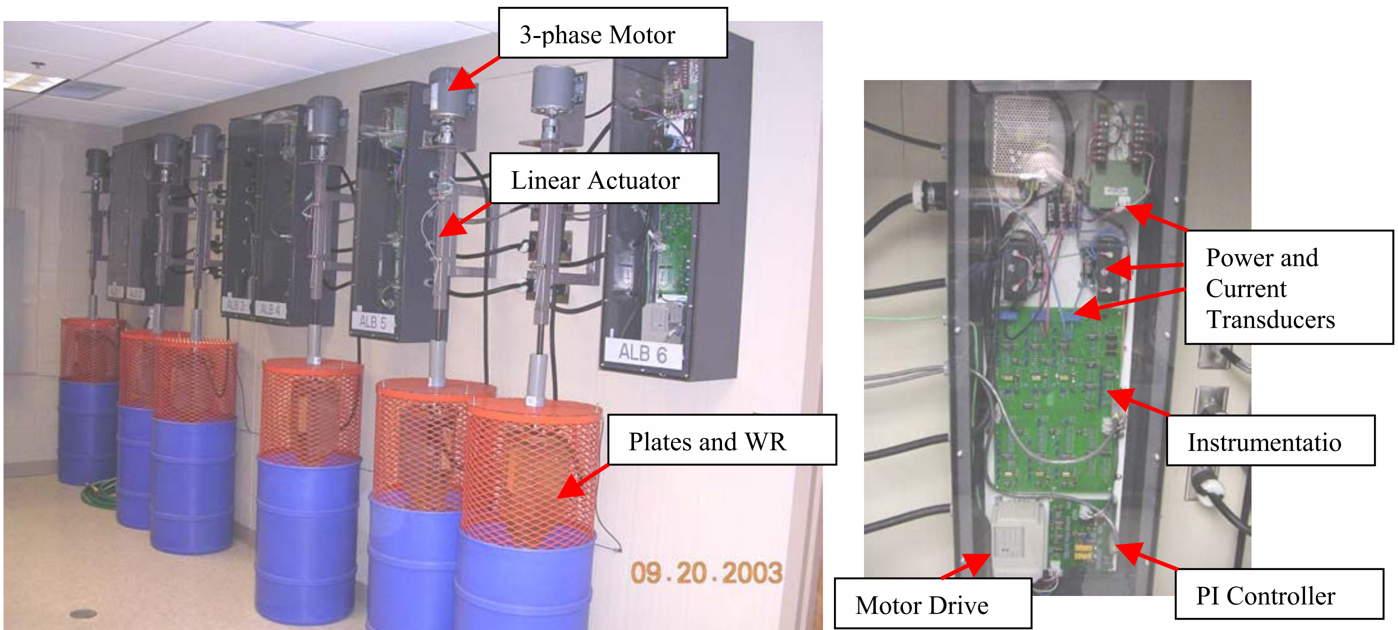
The output of each of the PPS contactors is permanently routed to specific industry-standard locking receptacles mounted at the walls next to each of the 10 stations. To make a final connection between a station and resource, the user either operates a manual push button on the PPS (for transferring a source to a station receptacle), or a touch screen display (for transferring a single ALB to a station receptacle). When an ALB is mated between the UR and a power station, a physical connection is made for each ALB power cable and for each line within the data cable.

This layout and automated approach using either push-button or an HMI at the PPS allows students taking the course to operate sophisticated equipment and resources that they will be exposed to in industry and provides an excellent tool for marketing and promoting the engineering program. An added benefit with regards to marketing and promotion is that all components of the system were designed, fabricated and tested by 13 undergraduate students and one graduate student over a period of 5 years.

III. Student Designed Systems

<u>Automated Load Bank Design</u> In 1998 the first of three senior design teams developed the first ALB prototype, which was rated for 3-phase 240 Vac and 10 kW. After two more senior designed teams participated, a final design was completed in 2002. A picture of these ALBs is shown in Fig. 3a, a detailed view of the electronics is shown in Fig. 3b, and the overall functional block diagram shown in Fig. 4. The first team was made up of three students who designed the system for closed-loop operation using analog proportional plus integral (PI) compensation. One student designed the drive circuitry for controlling the operation of an off-the-shelf 3-phase 208 Vac motor drive. The electronics and drive operated a ¼ hp 3-phase induction motor which was connected to a student-designed lead-screw actuator attached to the load plates. The linear actuator controlled the depth that the 3-phase delta-connected metal plates were submerged in the water. A supervisory control and data acquisition (SCADA) user interface, using LabView and a data acquisition board, was designed by another student. The user-friendly interface allowed the user to enter a desired power in kW, which was sent to the control interface to the motor drive.

The actual AC power was measured using an off-the-shelf 3-phase power transducer, and displayed at the LabView/PC interface . The difference between the demanded power and the actual power was input to the PI controller to adjust speed and direction of the linear actuator. Particular attention was given to the design of the PI controller for dealing with hysteresis and forward/reverse control of the linear actuator to minimize unnecessary wear and tear. After successful demonstration of the first prototype, a second group, in 1999-2000, consisting of three seniors, made improvements in the control circuitry, LabView interface, and developed an instrumentation circuit for accurately measuring each AC voltage and current. These measurements were processed by the LabView and the DAQ card for display on the PC.



(a) (b)

Figure 3: Six ALBs located in the UR

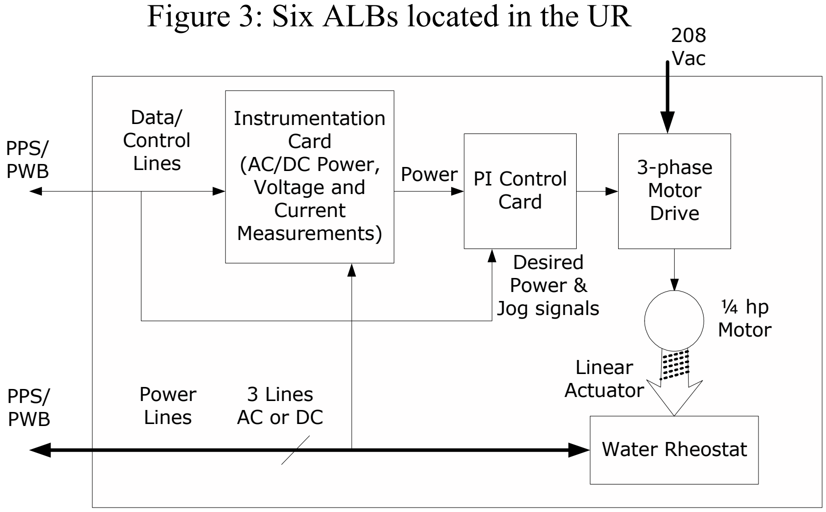


Figure 4: Functional block diagram of an ALB

Following successful completion of the second prototype, a final design group in 2001, consisting of two seniors, upgraded the ALB to allow for DC applied voltage (0-250 Vdc, 10 kW). Various modifications were made to the control circuitry and instrumentation. Special attention was given to the design of an analog DC power measurement circuit and a circuit that allowed for automatic transfer of control loops for when AC voltage was present verses when DC voltage was present.

Further modifications were added to the LabView interface to allow the user the ability to place the ALB in closed-loop control or open-loop control. Under open-loop control the user is able to jog the position up or down at an adjustable rate. In the summer of 2002, the author made required design modifications in the instrumentation and control circuitry to ready all circuits for printed circuit board (PCB) fabrication and integration into the final system. Figure 5 is the LabView interface that students use to adjust the power setting of the ALB.

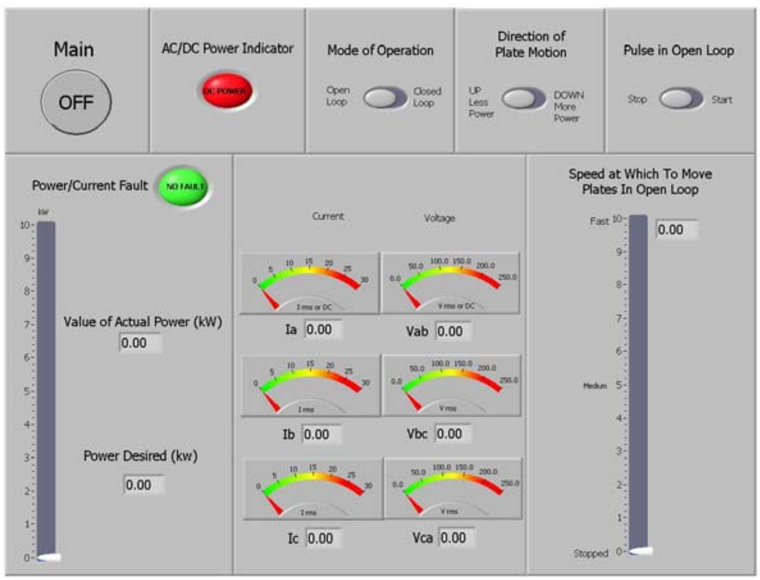


Figure 5: LabView user interface for the ALB

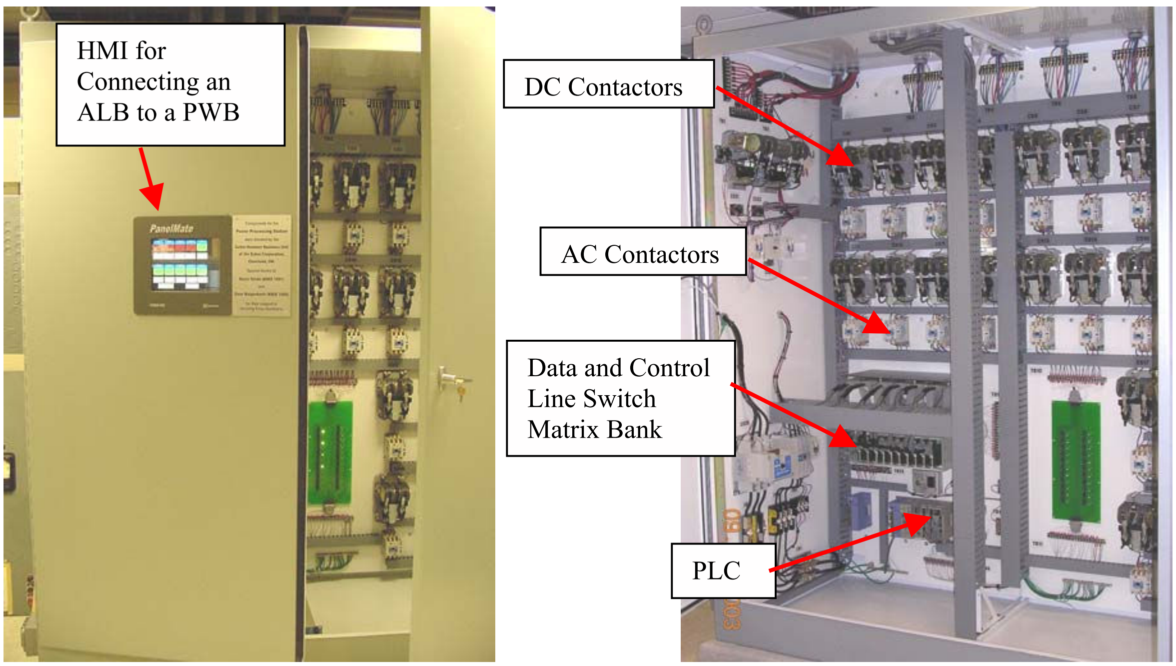
<u>Power Workstation Bench Design</u>: During the summer of 2000 a junior electrical engineering student designed and fabricated the first PWB prototype, with the final design, after one additional set of design iterations, shown in Fig. 6. The bench design was sized to house key equipment in a lockable storage compartment. Below this compartment, a shelf was provided to house standard equipment, such as oscilloscopes and digital multimeters. Just below this shelf, a patch panel was placed by which all connections to the test circuit could be made, including all power sources and the ALB. The bench top was sized so that three students could easily work on the bench with three separate notebooks, as well as some of the standard bench top components, such as capacitor banks and 2 kVA single-phase transformers. On the left of the bench, a panel with LED displays for all voltages and currents entering the rear-side of the bench

are measured and displayed. This panel also include both AC 3-phase breakers and DC breakers. The left side of the bench has safety lights mounted, one for AC power, and the other for DC power. When either of the panel breakers is switched on, power source is connected to the front panel and the corresponding safety light turns on. On the right side of the bench is a compartment sized to hold a 19 inch monitor. On the right side of the bench is attached a compartment to hold the PC and data acquisition interface instrument.

Figure 6: Final design of the PWB

The data interface instrument is an in-house design used to intercept all incoming and outgoing signals between the PC DAQ and the ALB. This bench went through a second iteration in the summer of 2001 to incorporate improvements into the final design. Five additional benches, based on the final design, were fabricated and tested during the summer of 2002 by students.

Power Processing System Design. During the summer of 2001 a junior student and a graduate student designed a prototype power (power processing, PPS) distribution control center allowing connection between one of two PWBs to one of two ALBs. This involved the design of a data signal switch matrix bank and the design of a power line switch matrix. With proper input control signals, the user was able to connect appropriate control and data lines between one PWB PC/DAQ and the corresponding lines of the ALB. Once these connections were made, the PPS, through a programmable logic controller (PLC), completed the connection between the PWB and ALB by connecting the three corresponding power lines. The design of the data and power switch matrices and user interface was implemented with Cutler-Hammer components, such as the HMI, PLC, 600 Vac 3-phase contactors, and 600 Vdc contactors. The HMI gave the user the option to select a one of two PWBs. After a selection of a PWB was made, a second screen gave the user the option to connect to one of two ALBs. If one of the two ALBs was already in use by the other PWB, then the user was given only a single option, the unused ALB. After the PPS completed all necessary connections, the user at the PWB was given control of the ALB through the LabView PC/interface. In the summer of 2002 the PPS PWB-ALB matrix and control circuitry was scaled up to allow for user selection of one of 10 PWBs for connection to one of six ALBs. To incorporate redundancy, while maximizing use of shared resources, yet keeping complexity to a minimum, each PWB was given the ability to connect to one of two ALBs. This approach called for 20 distinct circuits between PWBs and ALBs, resulting in a fairly straight forward in-house designed data and control line switch matrix and power line contactor matrix. Other components housed inside the PPS included all electromechanical contactors for all utility supplies, the battery bank, and the PV array. A picture of the PPS and the significant components is shown in Fig. 7 (Fig. 7a shows the front panel with the touch screen HMI, where Fig. 7b shows the PLC, AC and DC contactors, and switch matrix bank).



(a) (b)

Figure 7: Completed PPS

A simplified functional diagram of the PPS, including the ALBs and PWBs, is shown in Fig. 8.

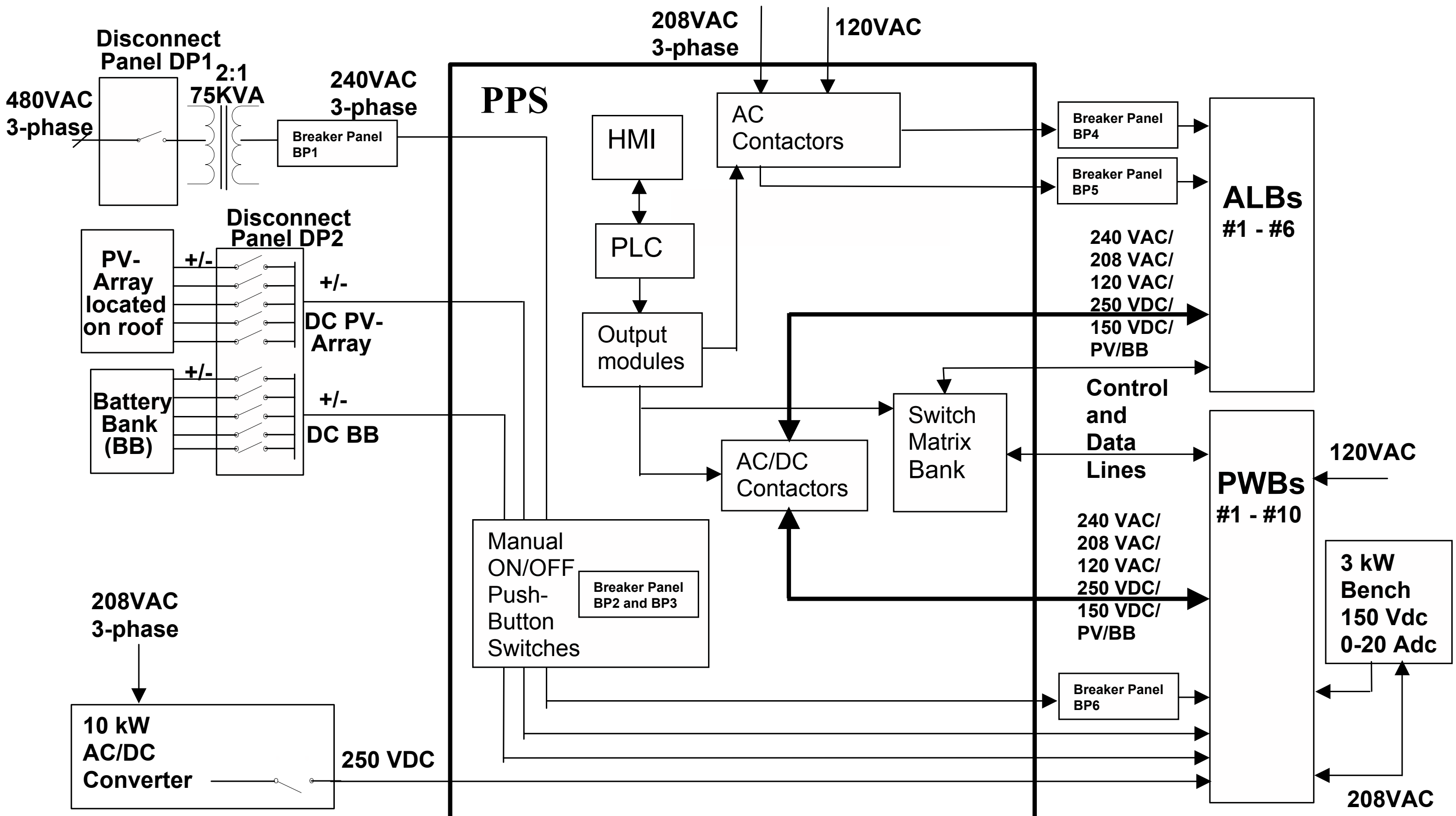


Figure 8: Functional block diagram of PPS, including the ALBs and PWBs

Cradled Dynamometer Design. The cradled dynamometer was design by two mechanical engineering students for their senior design project. The design consists of two parallel I-beam rails, with cross members, mounted on locking castors. Between the rails is mounted a 5 kW DC field wound generator, with shafts extended out each end, to enable connection of motors at either side. The generator is cradled with bearings at each side. A lever arm is mounted on the lower side of the generator and extended to a compression/expansion transducer, which is connected to one of the I-beam rails. The output of the transducer is sent to an signal transducer and display unit (original equipment manufacturer, OEM). With proper calibration, students are able to read directly the torque exhibited by the motor under test. The loading of the motor under test is accomplished by connecting the DC voltage output of the generator's armature windings to an ALB. A picture of the student-designed cradled dynamometer is shown in Fig. 9.

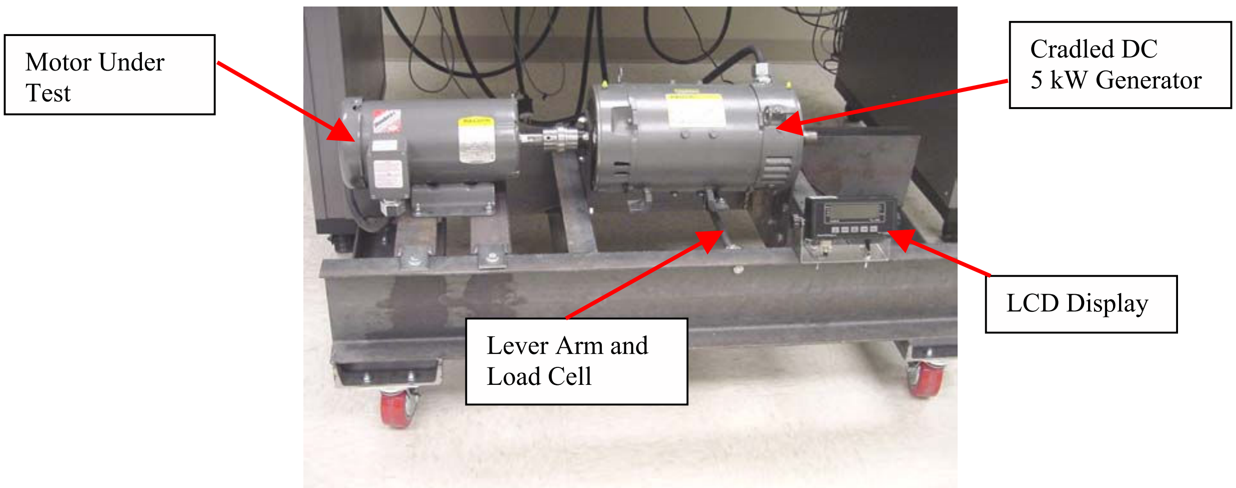


Figure 9: Cradled dynamometer

Final Design, System Integration, and Testing. The summer 2002 student design team, consisting of two seniors and one sophomore, was tasked with completion of the design and fabrication of the PPS and ALB. Aside from completing the design, the sophomore student was tasked with constructing a 3-D drawing of the PPS to insure proper and optimal fitting of all components, as well as fabrication and testing of the PPS. Another student was tasked with learning a sophisticated PCB layout tool and working with a local manufacturer in the production of seven in-house designed PCBs. The third student was tasked with tracking $75,000 in purchases and fabricating five new PWBs. All the students participated in the soldering of all PCBs, fabrication of six ALBs, fabrication of the PPS, and test and integration of the entire automated laboratory system.

After five years of design prototyping stages and three months of final design and system integration, the labs became fully functional and were commissioned on September 15, 2002. During the fall semester of 2002 and 2003, the lab has been used by two sections of Circuits I

Lab, two sections of Circuits II Lab, and two sections of Energy Conversion Lab. During the spring of 2003, the lab was used by Circuits I and II students only. Over the last year and a half the lab has experienced only 45 minutes of downtime (October of 2002), which occurred during a lab class and was due to a small OEM power supply failure located in the PPS. Once the problem was found and corrected, the lab has not experienced any major disruptions due to equipment failure since.

IV. Energy Conversion Students' Perspective Using New Laboratory

An informal written survey was given to the 42 student over a two-semester period, asking their opinion about the quality of the laboratory and test equipment. On a scale of 1 to 10, with 10 being extremely favorable, the average response to this question was a 9.19. Students were also asked what their interest was in the area of electromechanical machines and energy conversion prior to taking the course, with the result being an average response of 6.8. When asked what their level of interest was after having taken the course and the associated laboratory the average response increased to 7.6. In the old laboratory, one could have assumed or predicted a significant decrease from 6.8, rather than an increase.

Generally speaking, the student reaction to the new laboratory has been highly favorable both in terms of increased interest in the course and lab exercises but also in the discipline of energy conversion and power electronics. Some of those students that have now just finished the Energy Conversion course along with many of those from the fall semester of 2002, had the opportunity to "experience" the old laboratory. Many commented and appreciated the direction the new energy lab took, especially with the new ALBs. One key feature regarding the utility room and sharing of resources is for students to operate the system using a touch screen display and also to observe the use of motors and motor drives within the ALB. These features provide a visual and practical use for those senior students taking the energy conversion and electric drives course.

The sophomore students seem far less timid about circuits involving high voltage as a result of the improved safety measures incorporated throughout the lab and with the design of the PWB. Having the opportunity for these student to be exposed to a laboratory in which numerous technologies are in full view and require their interaction has brought a new and exciting dimension to the overall learning experience.

With increased emphasis on student attraction and retention, this laboratory is serving to assist the department in this important objective. Tours for prospective students and their parents through the integrated and automated energy laboratory has most certainly had an impact on enrolment. The electrical engineering department has recently experienced a 10 % increase in electrical engineering majors and is due, in part, to the sophistication of this laboratory and the fact that it was designed and constructed by the department's electrical engineering students.

VI. Conclusion

The new energy lab was completely designed, fabricated, and designed by thirteen undergraduate students and one graduate student over a period of five years, making the laboratory one of the most unique energy conversion labs in the country. The entire endeavor will be something that each of these students will remember long after their graduation [6]. The use of touch screen control and automation in the ALB have simplified the process students follow for conduction of experiments in both the circuits classes and the energy conversion class. The flexibility of the design provides further opportunity to expand its use for courses in power electronics and control systems. The unique design of the ALB serves an additional purpose, in that it incorporates both an electric machine and electric drive, the content for the redesigned energy conversion course, thus providing an additional teaching opportunity to the students. The informal surveys in the senior energy conversion course suggest that the laboratory design approach has heightened student interest in the areas of energy, power systems, machines, and control. Lastly, of significant importance to any organization is recruitment, and this laboratory has been successfully used for this purpose.

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Bibliography

1. NSF-Faculty Workshop on Teaching of Electric Drives, University of Minnesota, Department of Electrical Engineering, Minneapolis, June 19-21, 1997.
2. N. Mohan, Electric Drives: A Systems Level Approach University of Minnesota Press, 2001.
3. S. M. Hietpas and M. E. Ropp, "Improving Undergraduate Power Engineering Education: A System-Level Approach to Teaching Electromechanical Energy Conversion," NSF-CCLI A&I Grant, # DUE-9952517, June 1999.
4. S. M. Hietpas, "An efficient pedagogical approach for integrating power electronics, drives and the PMDC motor into the traditional energy conversion course," *2002 ASEE Annual Conference*, Montreal, Quebec, Canada, June 2002.
5. S. M. Hietpas and M. E. Ropp, "Incorporating Electric Drives into the Electrical Machines Course: A Systems Level Approach," *Proceedings of the ASEE Conference*, June 2001.

6. Justin Morrill, Stephen Bostrom, Joshua Olson, and Steven Hietpas, "Students' Perspective on a Student-Designed Energy Conversion and Electric Drives Laboratory," *ASEE North Midwest Section Meeting*, Ames, IA, Oct. 9-11, 2003.

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