Design and Development of A Low-Voltage, Low-Current 3-Phase Power Enabled Lab Bench

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Abstract

The capstone project course is an intrinsic part of the undergraduate education. The capstone projects are widely regarded as an excellent mechanism for assessing the outcomes of engineering and engineering technology programs and can serve as a direct measure of the quality of graduates. Capstone projects provide an opportunity for students to demonstrate their critical thinking skills, communication skills, as well as time and project management skills. In this article, the design, construction, and results of a low-voltage, low-current 3-phase lab bench as part of a senior design capstone project are discussed. The following article describes the potential for a lab bench that is more user friendly, but still provides the user with practical, real world experience. The current laboratory equipment that is used to teach Electrical Machinery course is outdated and unsafe. The proposed in this article solution provides an increase in the functionality and safety for learning concepts of 3-phase power systems. The construction of the device is documented with high level of details and provides the list of all the necessary components needed to replicate the proposed in this article system. The final design of the system is tested with the newly written labs so that the potential of the unit can be visualized.

Keywords

Electrical machinery, Laboratory equipment, Education

Introduction

The capstone project course is an intrinsic part of the undergraduate education. The capstone projects are widely regarded as an excellent mechanism for assessing the outcomes of engineering and engineering technology programs and can serve as a direct measure of the quality of graduates. Capstone projects provide an opportunity for students to demonstrate their critical thinking skills, communication skills, as well as time and project management skills. The capstone course prepares students to better understand the professional roles in the engineering and technology community[1]. In many universities, senior-level capstone courses have been incorporated as an integral part of engineering and engineering technology education in an effort to correlate the practical side of engineering design and the engineering curriculum. Such courses provide an experiential learning activity in which the analytical knowledge gained from previous courses is joined with the practice of engineering in a final, hands-on project.[2-4] The development of capstone design courses and corresponding requirements have been influenced by various sources, including the Accreditation Board for Engineering and Technology (ABET), industrial advisory boards (IAB), faculty leading capstone projects, numerous industrial companies, and engineering research.

Earlier research[4-15] showed the importance of industrial involvement in the capstone environment, which became more than just the financial support described above. However, support in the form of equipment, materials, and technical consulting is common and in most cases necessary.[6, 8, 11] Most industrial sponsors have a liaison engineer who assists the students and who follows the progress of the project.[7, 10] Other forms of industrial support include providing awards for meritorious designs and assisting in the evaluation of teams and projects.[4]

More recent studies provide further in depth analysis on the importance of the various benefits of capstone projects for the students' preparation for real world jobs. These include but not limited to the importance of industry involvement,[16-18]familiarizing students with product development process and system engineering,[16,19-23] improvement in the professional skills of students,[16,21] providing multidisciplinary training,[16,22,24,25]cultivating creative problem solving skills,[16,26] and preparing students for globalization.[16,27,28]

Recently, a new trend in conducting capstone projects became noticeable. Some capstone projects are sponsored by faculty members involved in research that play an important role of supporting some larger scale externally funded faculty research projects[16]. For example, at Texas A&M University, the undergraduate students involved in these projects as a capstone team had to work with the graduate students, faculty members, and potential customers. Software, hardware, interface, system integration, and testing all involved other researchers instead of just the capstone team.[16] These types of projects may resemble projects conducted in industrial settings, where multiple divisions have to collaborate on a single, large scale project.

In some instances, the support may come from the institutional departments so the team of students can design and construct an equipment that can be further manufactured and used to conduct laboratory exercises. In this article, authors describe this particular situation, where the capstone project was used a vehicle for producing a portable solution to be used to teach 3-phase concepts in Electrical Machinery course in Electrical Engineering Technology (EET) program at Michigan Tech

Capstone Course Description

In the past several years EET program in the School of Technology at Michigan Tech was very successful in establishing collaboration with the industry. This, in turn, triggered nearly all the capstone projects conducted in the EET program to be industry sponsored. Only during the last few years, EET program has successfully completed 15 capstone projects with 13 of them being industry sponsored. The benefits of having senior design (SD) projects industry sponsored are very significant for both the students and faculties. However, in some instances, the departmental support has been provided to design and manufacture a valuable piece of equipment to be used in the labs providing hands-on activities for the students.

A capstone course in the EET program requires the application of knowledge gained in lower and upper division courses. Students participating in a capstone project demonstrate the ability to perform independent and creative work by successfully completing a major design project. Projects are normally team oriented, where the team consists of two to four members, with one member chosen as team leader. Team oriented capstone projects provide a better simulation of industrial environment, to better train today’s engineers. [2] Weekly progress reports are required, and the work culminates with a final report and oral presentations, including a poster of the project. Six credits of Senior Project are required for graduation, normally satisfied in two three-credit semesters.

Upon successful completion of the capstone project course, students should fulfill the following course objectives:

- Prepare background research on applied electrical engineering technology.
- Research and organize data for synthesis.
- Prepare written reports.
- Prepare and present oral reports.
- Work in teams.
- Coordinate and work to meet scheduled deadlines and facilities, manage resources, etc.
- Consider non-engineering considerations in your work (e.g., Economic issues, marketing issues, esthetics).

At the beginning of the first semester team is required to prepare a typed project proposal in a formal memo format, including a proposed timeline. During the course of the project student's team meet with their faculty advisor weekly to discuss the progress report. The weekly formal memo is required the day prior to each weekly meeting and addresses the following three areas: current progress, problems encountered and their resolution, and plan for the following week. The oral and written reports due near the end of each semester are to concern themselves with the progress made in each semester. The one at the end of the first semester will be a progress report, with a full final report due at the end of the second semester. To further improve the quality of capstone projects conducted in the EET program and make students experience as participating in undergraduate research, in the middle of the second semester the team led by the faculty prepares the paper to be further submitted in one of the engineering journals or conference proceedings. In the author's opinion, this experience should become an integral part of any capstone project since it derives an additional benefits previously not included in the capstone environment. First, this requirement makes the students to fill them proud to be engaged in undergraduate research, which in-turn derives more responsibility and teamwork. Second, it provides the students with the opportunity to learn different styles of technical writing following required formats associated with various journals and conference proceedings. The last but not the least, it significantly improves graduates portfolio that while looking for the job can "bring to the table" more than their competitors - applicants.

System Overview

Electrical Machinery course is a core course in most university curricula with laboratory experiments being an integral part. It is often the case that hands-on practices are delivered using an outdated industrial equipment. Michigan Tech is revamping Electrical Machinery course by offering various educational models: traditional, blended, and on-line. To close the loop on the course improvement and to provide the best educational practices to students, it was imperative to reconsider presently used laboratory equipment, shown in Figure 1. The current lab equipment is outdated, quite large to setup, and, as a result, hard to work with. In addition, the current system is fairly dangerous considering operating voltage and current conditions - students have to deal with 250V voltage and 30A of current levels.

Figure 1: Current System

In order to reduce the danger to students, a portable bench is purposed and is outlined in Figure 2. The unit is designed to work with 208/120V 3-phase power system readily available at Michigan Tech. As soon as the main conduit enters the unit it will be ran to a 3-phase 1A breaker this will limit the max current into the unit an addition to acting as a main switch for the entire system. After the main breaker, the line splits to power the four multi-meters as well as connect to a 3-phase variable transformer and variac. The variac provides a variable voltage from 0-120V line to neutral connections. The output from the variac is then connected through a Lumel ND20 3-phase power network meter. Further, each line is passed through a single phase breaker in addition to a fast blow fuse. Due to the first part of the system operating at a higher voltage, and somewhat complicated to wire, everything before the single phase breakers will prewired and inaccessible to the user. This should reduce safety conversions working with the higher voltage. From there, students will have access to three single phase transformers, three power meters, and three load branches. In many different configurations which will be used to teach various concepts of the Electrical Machinery course and provide hands-on activities to the students during the labs. Table below shows a comparison of both systems when dealing with the electrical portion of the labs.

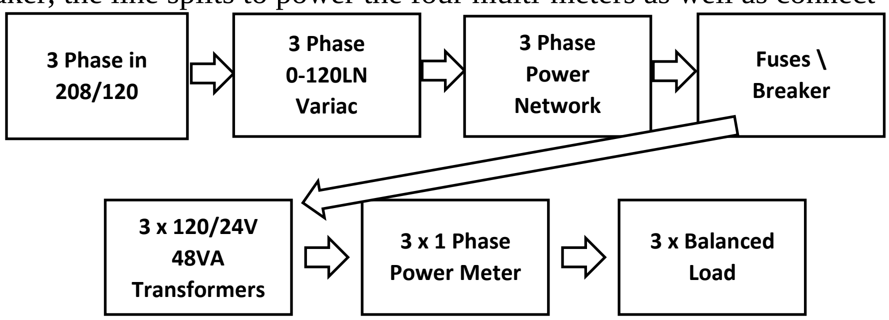

Figure 2: Project Sectional Overview

From the table, it is noticeable that the new system has lower voltage and current. Currently, in order to build a 3-phase transformer configuration the three 1kVA transformers have been used, however the new system implements transformers rated at only be 48VA so max power is

Item	*Current*	*New*	*Difference*
Voltage In	208V/120V	208/120V	Same
Voltage @ Load	120V	24V	5 x Smaller
Max Current In	5A	.4A	12.5 x Smaller
Max Load Current	10A	2A	5 x Smaller
Power Max	1000VA	48VA	20.8 x Smaller
Size	160 ft^3	5.22ft^3	30.6 x Smaller
Portable	No	Yes	
Equipment year	1980’s	2016	36 years newer

Table 1: Comparison of Existing and Proposed Systems.

20.8 times smaller than the current system. Furthermore, the new units are drastically smaller, meaning that they are portable and can be moved if needed. Finally, students are more likely to be exposed to the modern equipment that is available in the purposed system. Before manufacturing all 8 units needed to run the lab section consisting of 16 students, the proposed was prototyped and is shown in Figure 3. The left quarter of the panel has the ND20 power meter, the main breakers, single phase breakers, and the variable transformer. The four binding post to the right of the breaker are the Line and Neutral connections to the system that the students will use as the main supply.
To the right are the three single phase transformers. Following that there are the three N30P power meters. Ending with the three load branches on the far right. After the prototype was completed, it was concluded that the proposed system above was feasible.

Figure 3: Prototype

Main Components in the Prototype

Variac : The first major component was the 3-Phase Staco Variable Transformer 201-3 [29]. Variable transformer. The Variac has a max current of 2A per phase, and a voltage input of 120V. The main purpose of the variac in this system is to provide a variable voltage to the down the line components.

Lumel ND20: Low voltage, low current three phase systems are not typically found in industry. Therefore finding meters to fit the purposed system was a challenge. However, a suitable three phase network meter was produced by Lumel [30] and is shown in figure 4. The meter has a supply voltage of 85-253V, a voltage measurement range 11.5-276V_{LN} with a .2% error, and a current range from 2mA to 1.2A with an error of .2%. In addition to Voltage Current, these meters also show apparent, reactive and real power, as well as the power factor, the impedance angle, and frequency.

Figure 4: Lumel ND20

Figure 5: Lumel N30P

Lumel N30P: The N30P single phase power meter [31] shown in Figure 5 have the same measuring capabilities as the ND20 meters, except their slightly different measuring range. It has a current measuring range of 5mA to 1.2A at .2% error. Furthermore, the N30P has a voltage measuring range is 5V to 120V at .2% error.

Triad F-107Z: The Traid F-107Z three transformers [32] used in the developed prototype are shown in figure 6. As it can be seen from the wiring diagram, shown in Figure 7, the transformers have two primary and two secondary coils. This transformer has the potential to be wired up with series primary coils to accept a voltage input of 240V or parallel coils to accept 120V. Its secondary coils can be fired up in series for a 24V output or parallel for a 12V output. These connections are all variable based on the needs of the students, however, a majority of the time the transformers will be wired for 120/24 volt operation. With the 120/24V configuration there will be 400mA of current on through the primary side and 2A of current on the secondary side.

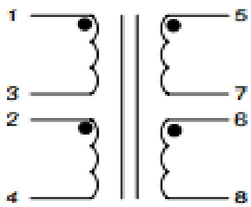

Figure 7: Wiring

Figure 6: F-107Z Transformer

The Load: The load is design to work with the 24V received on the secondary side of the transformers. The board itself consisted of three groups of components: a 50 Ω resistors, 4.7uF capacitors and 320mH inductors and the specifications of all the components are shown in Table 2. Each branch of the load will have 8x300Ω, 10W resistors handling a max voltage of 54.7V. In addition to the resistive load, each phase has 5x4.7uF capacitors and 1x.32H inductor.

The Load						
	Phase Quantity	Nominal Value	Z (Ω)	Total (Ω)	Current Max (A)	Voltage Max (V)
Resistor	8	300Ω	300	12.5	0.182	54.7
Capacitor	5	4.70E-06uF	564	37.6	0.085	48
Inductor	1	0.32H	230	76.7	0.6	1500

Table 2: Components in Load

Each of the component can be added as an additional load through the use of a toggle switch. The design of each board is shown in Figure 8. After observing the board, one can see that all the components are attached to a common buss. By flipping one of the toggle switches, a connection from the power rail to the non-common side of the component is made. For every switch

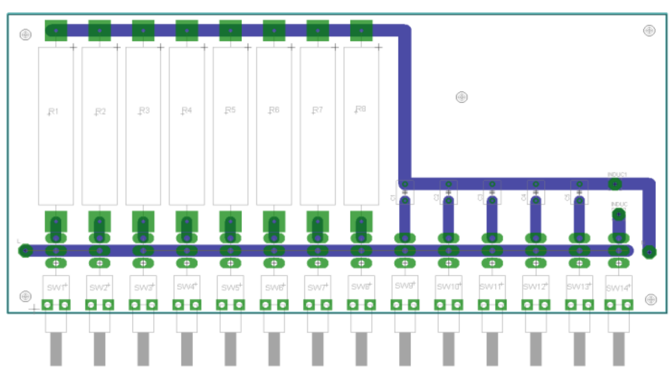
Figure 8: Single Phase Load Board Layout

flipped another component is added in parallel. The three-load boards can be connected in series, parallel, delta or wye configuration depending on what the application entails. If all the resistors were turned on, so current flowed through all twenty four resistors, 1.92A of current will flows through the load, if 24V were across it. Figure 9 shows the overall load assembly.

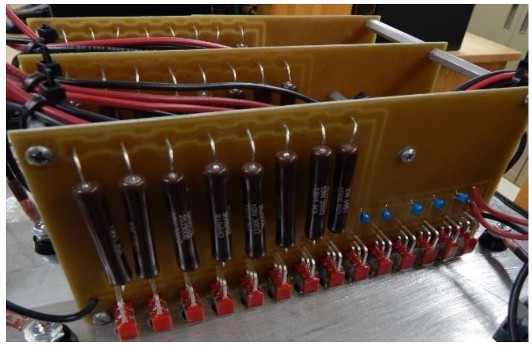
Figure 9: Assembled 3-Phase Load

The Developed Laboratory Exersizes:

With the new lab stations a variety of labs can be performed. Currently the first four labs have be developed and successfully tested on the prototype. The brief description of these labs are presented below:

- *Lab 1:* The Lab will consist of measuring voltages and currents and theoretically calculating the impedance of each of the components. Following that the students will realize that components are non-ideal and will discover the non-ideal model for an inductor. The lab will end with the student preforming power factor correction.
- *Lab 2*: In this lab, students will discover transformers and will wire up different configurations, such as step up and step down. Furthermore, they will observe how different coil configurations can change the turn’s ratio. Finally each student will be able to determine how the load is seeing by the primary side of the transformer how it compares to the turn’s ratio.
- *Lab 3:* The goal of this lab three is for students to realize non-ideal characteristics of the transformer. An open circuit test will be performed to find what the magnetizing loses of the transformer. Following the open circuit test, a short circuit test will be performed to account for the copper loses in the transformers. Finally, students will compute the transformer regulation and compare it with the data sheet of the transformer.
- *Lab 4:* The concept of the three phase power is the goal of this lab. Students will construct circuits with transforms in Delta and WYE configurations as well as the load in delta and wye configurations. Other topics of this lab include three phase power factor correction, unbalanced and balanced loads.

The Cost & Parts List:

Table 3, shows a list of all the components used in prototype and their cost. This high level of details is intentionally included for easy budgeting and replicability of the unit. A majority of the parts were purchased from Digitkey with the exception of the power meters, nuts and bolts, and the case.

Quantity	Component	Part Number	Distribuiter	Per Part Cost	Total
1	Varac	201-3-ND	Digitkey	$622.16	$622.16

3	120/24 Trans.	F-107Z	Digitkey	$20.66	$61.98
15	4.7uF cap	RCER71H475K3M1H03A	Digitkey	$0.76	$11.39
4	320mH ind.	C-40x	Digitkey	$12.09	$48.36
42	switch	100SP1T1B1M7QE	Digitkey	$2.7132	$113.95
24	300ohm R	20J300E	Digitkey	$1.6604	$39.85
1	3p 1A Break (10pac)	TA35-CKDBHJ10C0	Digitkey	$29.66	$29.66
3	1p 1A Breaker	TA35-CFTBLJ10C0	Digitkey	$11.73	$35.19
1	Case	3I-2918-10B-E	NewEgg	$209.99	$209.99
46	black terminal	36-4094-ND	Digitkey	$4.008	$184.37
1	3P power meter	ND20 120100E0	Lumel	$158.30	$158.30
3	1P Power Meter	N30P 100000E0	Lumel	$79.50	$238.50
100	Female conector	WM18429-ND	Digitkey	$0.6956	$69.56
100	Ring conector	WM18400-ND	Digitkey	$0.5083	$50.83
10	Fuse holder	283-2717-ND	Digitkey	$3.930	$39.30
1	copper board	V2021-ND	Digitkey	$15.45	$15.45
10	stand_off 2.5"	36-1825-ND	Digitkey	$1.216	$12.16
15	6-32 screw	H372-ND	Digitkey	$0.36	$5.40
1	Din-Rail	Z841-ND	Digitkey	7.37	$7.37
2	Terminal Clamp	281-1503-ND	Digitkey	$2.93	$5.86
15	Terminal block	277-2026-ND	Digitkey	$0.9478	$14.22
10	16-4 cable	283-2717-ND	Digitkey	$1.9124	$19.12
2	1" x 1/8" x 48" Alum angle	N247-411	True Value	10.99	$21.98
32	1/4" Flat washer	H#830502	True Value	$0.0629	$2.01
32	1/4" Hex nut	H#829300	True Value	$0.0999	$3.20
32	1/4" Lock washer	H#830666	True Value	$0.0679	$2.17
32	1/4"-20 x3/4 Bolts	H#831506	True Value	$0.2299	$7.36
15	8-32 hex nut	829228	True Value	$0.0679	$1.02
15	8-32 Mahine screw	828478	True Value	$0.1149	$1.72
15	#8 flat Washer	830660	True Value	$0.0439	$0.66
Total					$2,033.09

Table 3: Parts List for the Prototype

Capstone Project Assessment

To effectively assess the capstone project course outcomes the direct and indirect assessment tools have been implemented. In general, **direct** assessment involves looking at actual samples of student work produced in the course. These may include initial project proposal and a time line, team weekly memos, written report & project brief, team poster, and oral presentation. **Indirect** assessment is gathering information through means other than looking at actual samples of student work. These include student's self-evaluation, faculty and IAB members' evaluations, and exit interviews. Each serves a particular purpose. Indirect measures can provide an evaluator with the information quickly, but may not provide real evidence of student learning. Students may think that they performed well or say that they did, but that does not mean that their perceptions are correct. As an indirect assessment tool the authors developed and implemented senior project peer feedback form and oral presentation scoring rubric with the last one being distributed to the faculty and IAB members during the final presentation conducted by the team at the end of the second semester.

The final grade is derived using both direct and indirect assessment tools and based on the satisfactory completion of the capstone project and the presentation of the final results in an appropriate engineering report. The final grade is based on individual and team performance throughout the semester. The points are awarded as follows:

• Initial Project Proposal and Time Line	10%	Team
• Weekly Memos	20%	Team
• Written Report & Project Brief	30%	Team
• Poster	10%	Team
• Oral Report	20%	Individual
• Peer and Self Evaluation	10%	Individual

To conduct peer and self-evaluation, students of the team were asked to complete and submit to the faculty advisor a senior project peer feedback form. To collect the faculty and IAB members' feedback, oral presentation scoring rubric was distributed during the final presentation conducted by the team at the end of the second semester. Students participated in the capstone senior design project described in this paper provided highly positive feedback to the team peers. Moreover, the students gained a very satisfactory score on the oral presentation evaluated by the faculty and IAB members.

Conclusion

Academic programs in the School of Technology at Michigan Tech are designed to prepare technical and/or management-oriented professionals for employment in industry, education, government, and business. This department sponsored Senior Design (SD) student project was successfully completed and the developed solution designed to teach 3-phase power systems concepts at low voltages and currents has proven to be possible and quite practical. The goals of creating a new, portable and safe solution for the labs of Electrical Machinery course were achieved. In addition the tests of the labs were successful even at lower voltages and currents. With the use of the 48VA transformers the power needed to run the test decreased drastically from 1kVA. This reduce the danger to the student and removing the risk of destroying laboratory equipment. Upon manufacturing of additional seven replica of the proposed in this article solution and successful test of all of the units, these benches will be incorporated into the curriculum here at Michigan Tech in the fall semester of 2017 school year.

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