Visualizing Power-Quality Phenomena in a Hands-On Electric Power Systems Laboratory

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Dr. Grainger's research interests are in electric power conversion, medium to high voltage power electronics (HVDC and STATCOM), general power electronic converter design (topology, controller design, magnetics), resonant converters and high power density design, power semiconductor evaluation (SiC and GaN) and reliability assessment, military power systems, DC system design and protection, fault identification techniques, and power electronics for microgrid applications.

Dr. Grainger has either worked or interned for ABB Corporate Research in Raleigh, NC; ANSYS Inc. in Southpointe, PA; Mitsubishi Electric in Warrendale, PA; Siemens Industry in New Kensington, PA; and has regularly volunteered at Eaton's Power Systems Experience Center in Warrendale, PA designing electrical demonstrations. In his career thus far, he has contributed to 50+ articles in the general area of electric power engineering (emphasis on electric power conversion) and all of which have been published through the IEEE. Dr. Grainger is a member of the IEEE Power and Energy Society (PES), IEEE Power Electronics Society (PELS), and Industrial Electronics Society (IES) and is an annual reviewer of various power electronic conferences and transaction articles. Dr. Grainger is a Senior Member of the IEEE and served as the IEEE Pittsburgh PELS Chapter Chair over the last 3 years for which the section has won numerous awards under his leadership.

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Abstract

A topic in electric power engineering that students commonly struggle with is power quality. Traditional power quality issues in electric power system architectures such as harmonics, transients, and unbalanced load phenomena are now more noticeable with the introduction of nonlinear components, such as power electronic converters. These equipment interaction concepts are sparsely covered in classes, and are rarely seen in a laboratory setting. Students, especially those graduating with only an undergraduate degree, generally experience these issues when they enter the workforce, having to complete on the job training in order to become comfortable with power quality matters.

A new power quality course was created at the University of Pittsburgh, in the Spring 2018 semester. This course uses a novel approach to teaching students power quality concepts by using an electric power laboratory designed specifically for undergraduate education. Students work with real electric motors, transformers, variable frequency drives, and DC power electronics to understand the impacts of these loads on a 208Vac, 75kVA rated system. A custom, 5kW rated work bench featuring compact fluorescent loads, as well as traditional single-phase or three-phase linear resistive, capacitive, and inductive loads is also used to highlight the issues of having an unbalanced power system. The student experience is based upon measurement and data acquisition to develop visual frameworks coupled with traditional whiteboard discussions.

This paper contains a description of the course, its learning outcomes, lecture plans, assignments, laboratory experiments, and exam content. Student assessments, evaluations, and opinions are also included to show the benefits of how the class improved student understanding of power quality. A rubric was designed and employed which provides prognostics and analytics about the perceived value of the course. Lastly, a conclusion of the course from the instructor's point of view, including lessons learned and future improvements is provided.

Introduction and Background

Universities and engineering schools across the United States are developing a new sense of purpose in the field of electric power engineering which is bolstered by an invigorating job market. This industry is being driven by aging workforce demographics and a need for new innovations [1]. Recently, universities are being offered government funding for modernized educational programs and research activities with electric power being at the forefront of a revolutionary period of advancement. As an example of this resurgence, the University of Pittsburgh has developed an electric power program over the past several years (starting in 2007) in collaboration with industry, government, and other constituents to provide innovative education and collaborative research programs in the areas of electric power and energy engineering, [2]. Working with our partners, the electric power program in the department of electrical and computer engineering (ECE) is contributing to solutions that address the aging workforce issue in the electric power and energy sector through modernized educational programs and laboratories, as well as to advances in technology development, basic and applied research, and outreach.

The Electric Power Systems Lab (EPSL) at the University of Pittsburgh, sponsored in-kind by Eaton, is a multi-use facility that is currently used for educational activities. The lab is shown in Figure 1. The lab provides opportunities for faculty and students of all types to explore electric power phenomena in the areas of AC and DC microgrids, smart grid technologies, variable speed drives, power electronic devices and converters, power quality, renewable energy systems, controls and communications, automation and relaying, distribution engineering, and other emerging electric power technology areas. Supplied by a 75 kVA feeder at 480 volts, the EPSL incorporates a diverse mix of generation, including photovoltaic panels, localized gas generation, and the traditional grid tie. Through variable system strength, these generation sources feed a variety of loads, centered on innovative laboratory workbenches (pictured in blue) combining passive and motor loads in a system with advanced metering and control. Capabilities for testing equipment in cases of voltage surges and sags are also incorporated [3].

Figure 1: Lab Layout

From an official IEEE university course survey and review from 2005-2006 focused on power engineering curriculum, Table 1 lists the available power quality courses that were offered at 13 different universities with only 4 being available to undergraduates. Note that none of the courses offered a lab component [4]. From the same IEEE university course survey conducted

from 2015-2016, the total number of universities offering a power quality course increased to 18 with 8 classes being available to undergraduates but with only one of them offering a lab component [5]. These course offerings are listed in
Table *2*. Power quality phenomena is often observed and qualitatively understood by gathering field data as opposed to intense, mathematical derivation based approaches from fundamental laws. Without a laboratory component, undergraduates may struggle in learning the subject matter adequately. The latter was indeed observed early on in the course and will be emphasized later in the article.

In [6], the authors define educational simulation as an educational task that connects content to solving real world problems in ways that students understand. Educational simulations promote student learning by improving student motivation, encouraging depth of learning, helps to achieve student learning objectives, and, most importantly, bridges the gap between academia and the profession in which a student will work. With these motivational, educational facts, in the spring of 2018, electric power engineering faculty at the University of Pittsburgh designed an undergraduate electric power systems laboratory course called "Power Quality". Power quality is a subject used continuously in practice to understand the impact of electrical equipment and their distortion effects on electrical voltage and current signals when integrated into power systems. Students learn commonly used industry terminology, perform analysis on systems and components which frequently have power quality issues (motors, power converters, etc.), and become familiar with industry grade equipment and measurement devices in the laboratory. Engineering students receive a lot of analytical training at the University of Pittsburgh but, with this course, students acquire a substantial level of hands on experience that is not taught in other electric power classes at the undergraduate level.

Table 1: 2005-2006 Power Quality Courses

Course	**University**	**Course Path**	**Lab Component**
Electric Power Quality	Arizona State University	Graduate Required	No
Power Quality and Power Systems Protection	Clarkson University	Undergraduate and Graduate Elective	No
Power Quality	Colorado School of Mines	Graduate Elective	No
Electric Power Quality	Georgia Tech	Graduate Elective	No
Power Quality	Rensselaer Polytechnic Institute	Graduate Elective	No
Power Quality and Harmonics	The University of Texas at Austin	Undergraduate Elective	No
Power Quality	University of Alberta	Graduate Required	No
Power Quality of Power Systems and Machines	University of Colorado-Boulder	Graduate Elective	No
Understanding Power Quality	University of Idaho	Graduate Elective	No
Electric Power Quality	University of Missouri-Rolla	Undergraduate Elective	No
Power Quality	University of Texas Arlington	Graduate Elective	No
Electric Power Quality for the Digital Economy	Virginia Tech	Undergraduate Elective	No

Table 2: 2015-2016 Power Quality Courses

Course	University	Course Path	Lab Component
Electric Power Quality	Arizona State University	Graduate Required	No
Power Quality	Baylor University	Undergraduate Elective	No
Power Quality	Colorado School of Mines	Graduate Elective	No
Electric Power Quality	Colorado State University	Graduate Elective	No
Service and Power Quality in Distribution Systems	Drexel University	Undergraduate and Graduate Elective	Yes
Power Quality	Florida International University	Graduate	No
Electric Power Quality	Georgia Institute of technology	Undergraduate and Graduate Elective	No
Power Quality	Kansas State University	Graduate	No
Electric Power Quality	Missouri University of Science and Technology	Undergraduate Elective	No
Power Quality	Rensselaer Polytechnic Institute	Graduate Elective	No
Power Quality and Power Disturbance Analysis	University of Alberta	Graduate Elective	No
Electric Power Quality	University of Arkansas	Graduate Elective	No
Understanding Power Quality	University of Idaho	Graduate Elective	No
Electric Power Quality	University of Memphis	Undergraduate and Graduate Elective	No
Power Quality	University of Missouri-Kansas City	Undergraduate and Graduate Elective	No
Power Quality	University of South Florida	Undergraduate and Graduate Elective	No
Electrical Power Quality	University of Wyoming	Undergraduate and Graduate Elective	No
Electrical Power Quality	Wichita State University	Graduate Elective	No

The following sections of this article contain a description of the developed course, its learning outcomes, lecture plans, assignments, laboratory experiments, and exam content. Student assessments, evaluations, and opinions are also included to show the benefits of how the class improved student understanding of power quality. A rubric was designed and employed which provides prognostics and analytics about the perceived value of the course. Lastly, a conclusion of the course from the instructor's point of view, including lessons learned and future improvements is provided, including the introduction of Hardware-in-the-Loop into the curriculum.

Course Structure and Lecture Content

A. *Prerequisites and Course Description*

In order to offer this power quality course to as many students as possible, students would only need to have one introductory course in electric power as a prerequisite. Students would only need to take (1) Power Distribution System Engineering and Smart Grids, (2) Power Systems Analysis and Design 1, or (3) Electric Machinery. Each of these courses only requires the prerequisite of a basic linear circuits and systems course and may be taken independently of any other course in the electric power track. This makes it possible for this class to be taken in the first semester of the junior year at the very earliest.

The description of the course, which was offered to all ECE students in advance of the Spring 2018 semester, is:

"This course serves as an introduction to industrial power quality concepts. The structure of the course is a lecture based class with a lab component to supplement it. Students will learn commonly used industry terminology, perform analysis on systems and components which frequently have power quality issues, and become familiar with industry grade equipment and measurement devices."

From this description, students were made aware that the focus of the course was on power quality and the associated concepts, but that they would also become familiar with industrial grade equipment.

B. Course Goals and Objectives

The goal of the course was for the student to gain a more practical understanding of electric power systems, variable frequency drive operation of electric machines, basics of power electronics, and how these major components impact power quality on electrical systems. In addition, students would acquire extensive hands on skills that are not taught in other electric power classes or other general electrical engineering courses at the undergraduate level. The high level objectives for the course were that upon completion of the course, students should have been able to:

- Compute balanced three-phase and single-phase voltages, currents, and real, reactive and apparent power.
- Define some of the common causes of harmonic distortion in electric power system. Students should also be able to perform basic harmonic analysis.
- Analyze induction machines that make use of variable frequency drives. Students should also be able to provide reasons why variable frequency drive systems are beneficial.
- Perform measurements on three-phase and single-phase loads in a laboratory setting using power quality meters. Students should also be able to acquire, interpret and analyze data that was gathered in the laboratory.

C. Textbook

There was no official textbook chosen for the course. However, course notes were constructed based on information from multiple textbooks or industry application notes. These textbooks were listed as supplemental materials for the course on the syllabus and are listed below:

1. J. Duncan Glover, Mulukutla S. Sarma, Thomas Overbye, Power Systems Analysis and Design, 6th Edition, Cengage Learning, ISBN-10: 130563618X | ISBN-13: 9781305636187
2. S. Chapman, Electric Machinery Fundamentals, 5th Edition, McGraw-Hill Education, ISBN: 978-0073529547
3. W. H. Kersting, Distribution System Modeling and Analysis, 3rd Edition, ISBN-10: 1439856222 | ISBN-13: 978-1439856222
4. R. Erickson, D. Maksimovic, Fundamentals of Power Electronics, 2nd Edition, ISBN-10: 0792372700 | ISBN-13: 978-0792372707

D. Method of Instruction

The course was delivered as a lecture based course on power quality and its application to engineering systems with a supplemental lab component. The lectures consisted of power systems components which are known to cause harmonic issues and were supplemented with derivations and example problems. Because there was not enough contact time to cover everything, reading assignments were provided to supplement the lectures, and the students were required to do some independent learning.

In addition to the readings, students were given homework assignments which made use of the derivations and examples. These homework assignments were designed to be slightly more challenging than the in-class examples. This was to push the student and prepare the student for the challenge of the engineering profession.

Quizzes were modeled after the homework and reading assignments. Students were instructed that if they could do all of the homework problems without using the solution, and had completed the reading assignments, than they would do well on the quizzes. These quizzes were meant to assess the student's understanding of the homework and reading assignments.

Students took two exams. There was a midterm exam and a final exam. These exams were built off of the homework assignments, in-class examples, reading assignments and the in-class derivations. Again the students were instructed that if they could complete all homework problems, in-class example problems and derivations without a solution, and the student had completed all reading assignments, the student would do well on exams.

The class met twice a week for theory discussions. When a lab session was being conducted for a given day, the traditional lecture was focused on understanding the equipment and the procedures being used to complete the lab exercises.

E. Lecture Plan

This section details the lecture number and the associated topics that will be useful for other universities who plan on building a similar course. This list of topics will be modified in the forthcoming semesters with suggestions described in detail later in this article.

Lecture	Topics
1	• Balanced Three-Phase Systems • Phasors and Phase Sequence • Three-Phase Connection Types
2	• Real, reactive, and apparent power • Complex power, power triangle, and power factor • Three-phase power • Per-unit system
3	• Overview of exterior features of laboratory benches • Major instrumentation – Dranetz Power Visas • **Overview of Laboratory #1: Electric Power Measurements**
4	• Harmonics and sources of harmonics in power systems • Total harmonic distortion • Power factors: distortion, displacement, and total
5	• Source harmonics • Analysis of a 6-pulse rectifier • 6-and 18-pulse rectifier comparison • Effective transformer impedance • Associated harmonic problems
6	• Harmonic impacts of capacitors and detuned capacitor selection • Parallel resonance concerns and harmonic resonance frequency calculations • Harmonic impacts on generators and motors
7	• Capacitor switching transients • Inductor switching transients • **Overview of Laboratory #2: Power Quality: Capacitor Switching and Harmonics**
8	• Introduction to induction motors • Total harmonic distortion • Power and torque in induction machines
9	• Introduction to variable frequency drives • Inverter operation
10	• Derivation of idealized waveforms for voltage- and current-source-inverters • Calculation of the fundamental component for voltage-source-inverter line-to-line voltage • Induction machine torque
11	• Motor starting background • Soft starting induction motors • **Overview of Laboratory #3: Motor Starting and Motor Measurements**
12	• Induction machine torque at different frequencies • Starting motors with variable frequency drives • Example of harmonic distortion in voltage-source-inverter fed induction motor
13	• Damage to ac motor bearings

	• Motor losses due to variable frequency drive harmonics • Derating induction machines due to harmonics
14	• Review of variable frequency drives • **Overview of Laboratory #4: Induction Motor Control with Variable Frequency Drives**
15	• What are DC-DC converters? • DC-DC converter operation • Buck converter analysis
16	• DC voltage of a buck converter • Further analysis of buck converter • Buck converter equilibrium • **Overview of Laboratory #5: Power Electronic Boost Converter Characteristics**
17	• What is a transformer? • The ideal transformer • The real transformer
18	• Transformer ratings • Transformer inrush current

Method of Direct Assessment

The students were directly assessed using seven homework assignments, five quizzes, five lab reports and two exams. This section details these direct assessment methods.

Homework Assignments:
Students were given seven homework assignments which were crafted by the instructor. These homework assignments usually involved an open ended component so that students were required to make valid engineering assumptions. This provided a more realistic real world approach to problem solving while at the same time quelled the ability for students to plagiarize. A brief description of each assignment is found below with tasks for each assignment.

1. Power System Fundamentals
    a. Draw one line diagrams
    b. Calculate line currents
    c. Using ratings to model impedance of equipment
    d. Calculate real, reactive and apparent power
    e. Perform per unit calculations
2. Power Systems Harmonic Analysis
    a. Plot voltage waveform with harmonic component using MATLAB
    b. Plot harmonic spectrum of a waveform using MATLAB
    c. Calculate total harmonic distortion of a waveform
    d. Decompose the plot of a voltage waveform into its Fourier series components
    e. Calculate distortion power factor
3. Induction Motor Analysis
    a. Calculate induction motor slip, current and air-gap flux

    b. Write a MATLAB script that outputs output power, input power, power factor and efficiency due to a voltage, frequency and speed inputs
    c. Calculate leakage inductance in rotor and stator circuit at synchronous speed
    d. Write a MATLAB script to plot the line-to-line voltage for a voltage-source-inverter motor drive
    e. Write a MATLAB script to plot the Fourier coefficients for harmonics of a voltage-source-inverter
4. Induction Motor Analysis II
    a. Calculate total harmonic distortion for a motor-drive system
    b. Calculate harmonic power, efficiency, power factor, current and torque and compare versus the fundamental for a motor-drive system
5. Analysis of DC-DC Converter
    a. Find the output voltage for a converter topology as a function of duty cycle
    b. Plot DC-DC converter output waveform over the range of duty cycle
    c. Analyze converter using MOSFET realization
    d. Plot diode current for realization in Part C.
6. Transformer Analysis
    a. Plot flux versus magnetomotive force
    b. Plot B-H curve for transformer
    c. Plot core permeability as a function of excitation
    d. Plot harmonic spectrum and calculate total harmonic distortion
7. Reflection on Eaton’s Power Systems Experience Center Tour
    a. What makes Eaton’s Power Systems Experience Center unique?
    b. Name three pieces of equipment that were not known about prior to tour
    c. Explain how industry tour will benefit career

Note that assignment #7 is a very unique experience for the students. The facility that was toured is a much larger facility in which the power engineering lab to be described in this work at Pitt was modeled after. Thus, students were able to correlate this experience with equipment utilization during the semester long course at the University of Pittsburgh.

<u>Quizzes:</u>
Students were given 5 quizzes. These quizzes ask students to carry out the same calculations from the homework assignments with the problems slightly modified. Each of these quizzes had one analytical question and either one short answer, multiple choice, or true and false based on the assigned reading.

<u>Lab Reports:</u>
Labs were assessed on the students being able to perform the steps laid out in the lab assignment document and achieve the expected results and measurements. Labs were also assessed on the student’s data analysis and ability to carry out power quality concepts taught in class. Lab reports were designed to be short and succinct, similar to how a report would be written in industry for work performed. The number of hours taken in performing the lab and writing the report were required portions of the report and were to introduce students to the concept of on the job “billed time.” The lab grading rubric was made for each lab to be out of 10 points with the total lab

grade being worth 25% of the overall course grade. The lab was broken down to 7 points for completing the lab with all required collected data and calculations. Then three additional points were available for answering three questions at the end of the lab that involved significantly more analysis. Questions usually involved explaining why certain phenomenon seen in the lab was occurring and how that relates to the power system as a whole. The lab experiments are given below but are explained in greater detail in the Power Quality Lab Development section:

1. Lab experiment #1: Electric Power Measurements
2. Lab experiment #2: Capacitor Switching and Harmonics
3. Lab experiment #3: Motor Starting and Motor Measurements
4. Lab experiment #4: Induction Motor Control with Variable Frequency Drives
5. Lab experiment #5: Power Electronic Boost Converter Analysis

<u>Exams</u>

Students were given two exams which were crafted by the instructor. These exams assessed the student's ability to analyze systems with known power quality issues, answer questions based off of laboratory data, and answer open-ended questions about power quality problems in power systems. A brief description of these exams is written below.

1. Midterm Exam
    a. Analysis of signal based off of Fourier coefficients
        i. Find total harmonic distortion
        ii. Find fundamental voltage sinusoid
        iii. Analyze RLC circuit for 7^{th} harmonic voltage component
    b. Perform a harmonic analysis on a power converter output waveform
        i. Find fundamental frequency
        ii. Find dc voltage
        iii. Find fundamental voltage sinusoid
        iv. Plot fundamental voltage sinusoid overlaid onto signal waveform
    c. Analysis of simple power system
        i. Convert system to per-unit of specified base values
        ii. Find per-phase equivalent per unit circuit
        iii. Solve for grid voltage
        iv. Find per-unit real and reactive power
    d. Analysis of lab bench waveform
        i. Determine the inductance of a load based off of sensor waveform
2. Final Exam
    a. Power quality issue reporting
        i. Answer a customer complaint explaining diming lights when air conditioning unit starts up
        ii. Provide solution to complaint in part i.
    b. Transformer analysis
        i. Calculate transformer currents based off of input voltage and load conditions
        ii. Calculate transformer losses and efficiency

iii. Show distorted waveform of transformer waveform to due magnetization current

c. Induction motor analysis
   i. Show difference in rotor resistance between locked rotor conditions and full load
   ii. Calculate machine losses and efficiency
   iii. Calculate rotor and stator currents at full load conditions
   iv. Explain inrush current
d. DC-DC converter analysis
   i. Analyze converter topology as a function of duty cycle
   ii. Determine DC voltage at output of converter
   iii. Calculate Fourier coefficients for converter voltage
   iv. Calculate converter losses and efficiency

Laboratory Used by Students, Equipment Exposure, and Safety Protocol

The power quality course takes place in a unique power engineering lab that was co-designed and developed with Eaton by engineers employed at Eaton's Power Systems Experience Center [3]. The lab was structured so that students could use it for not only guided labs but also research by being highly adaptable for several different experiments. The main power feed into the lab is rated for 480V/100A that is distributed through an Integrated Facility Systems (IFS) switchboard. A 75kVA 480V/208V Delta-Wye transformer inside the IFS provides isolation and is the main feed into the rest of the lab. In the IFS, the user is able to operate off of a Normal Source, SAG generator, or a weak source in order to see different power quality effects throughout the lab. Also, inside the IFS are six motor control center (MCC) controllers and six variable frequency drives (VFDs) that can be used to run either six, 5hp motor-generator sets located inside of a cabinet or three movable 15hp motors on carts. The VFDs are reconfigurable and the 15hp motors can simply be plugged into an outlet at the front of the MCC cabinet to run. Safety is a primary concern with each individual MCC and VFD being protected by a 30A breaker. Eaton Power Xpert Meters are used in the IFS for basic monitoring of the power being used inside the IFS. The facility one-line diagram is found in Figure 2.

In addition to the equipment inside the IFS, there is a 5kW Eaton Solar Inverter that is connected to a solar array on the roof of the building for research in distributed energy resources. There is also a 25kW rooftop diesel generator that is capable of running the lab in the event of a power outage or for testing from a non-grid source. An Uninterruptable Power Supply (UPS) is also available in the lab and is used to power the labs separate lighting circuit and perform additional testing [3]. These three sources are not used as part of the Power Quality Lab course. A 350MHz 4-channel oscilloscope, 1.2kW electronic loads, real time solar panel simulator and additional solar inverters are available in the lab but were not integrated in the first offering of the course.

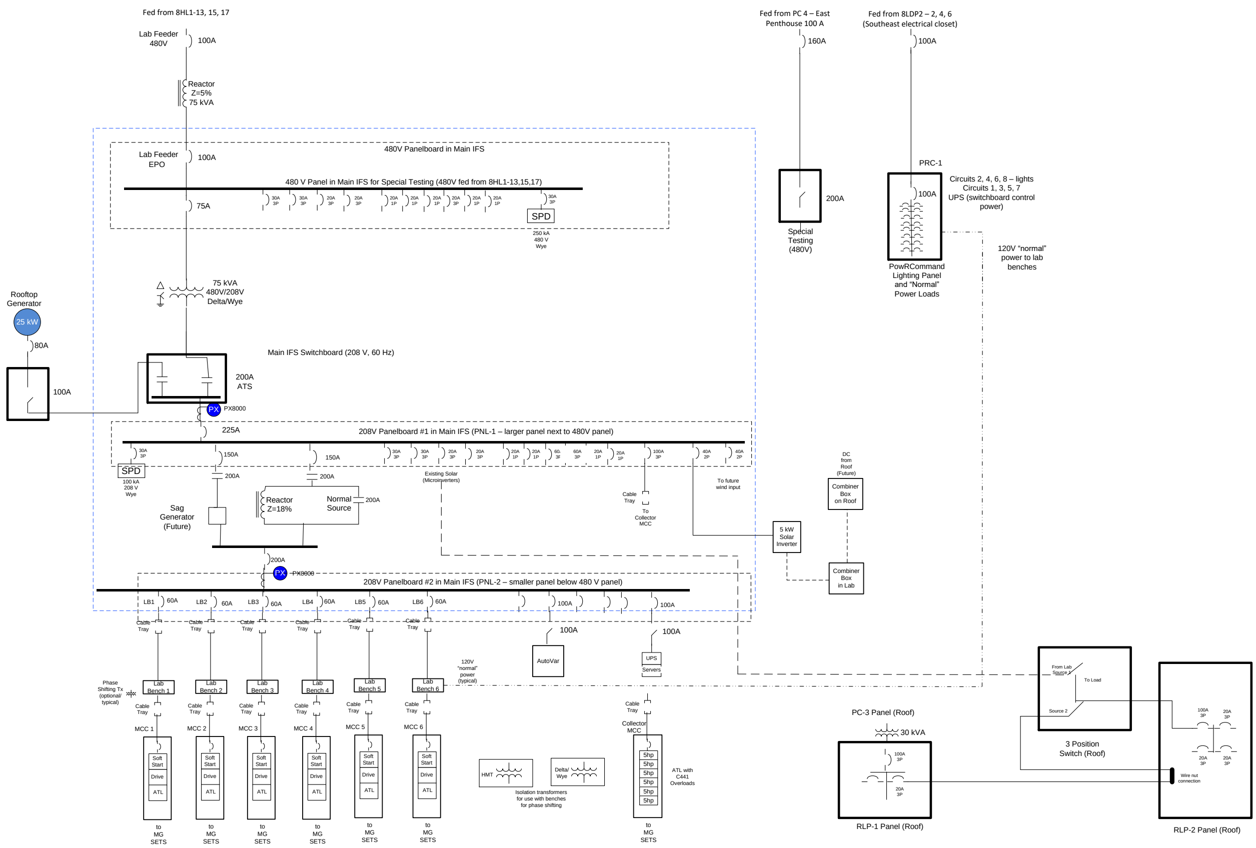

Figure 2: Lab One Line Diagram

The facility centers around six custom design workbenches, seen in Figure 1, that provide the framework for the lab experiments [3]. Each bench is fed by a 208V, 3-phase 60A feed from the IFS. Inside each bench there are several load banks that can be switched ON and OFF through hand switches or through an Eaton XV100 Human Machine Interface (HMI) Programmable Logic Controller (PLC) as shown in Figure 3. Three phase loads are balanced and allow for typical power circuit analysis to be used when performing lab experiments. The single-phase loads are able to be switched ON individually to create unbalanced three phase conditions. Additional 120V outlets are located at the front of the bench that allows for a multitude of loads to be connected and monitored. Both three phase and single-phase loads are able to be switched ON at the same time for creating a variety of balanced and unbalanced loading situations as well as capacitor and inductor switching events. The bench contains the following table of components:

Table 3: Lab Bench Loads

Component	Rating	Component Value	Connection Type
Resistor	2kW	21.6Ω	3-phase Y
Resistor	1kW	43.3 Ω	3-phase Y
Resistor x3	0.5kW	28.8 Ω	1-phase
Reactor	2kvar	57mH	3-phase Δ
Reactor	1kvar	115mH	3-phase Δ
Reactor x3	0.5kvar	76mH	1-phase
Capacitor	2kvar	3x38 µF	3-phase Δ
Capacitor	1kvar	3x19 µF	3-phase Δ
Capacitor x3	0.5kvar	92.0 µF	1-phase
Compact Florescent Lightbulb (CFL) x9	68W		A, B, C

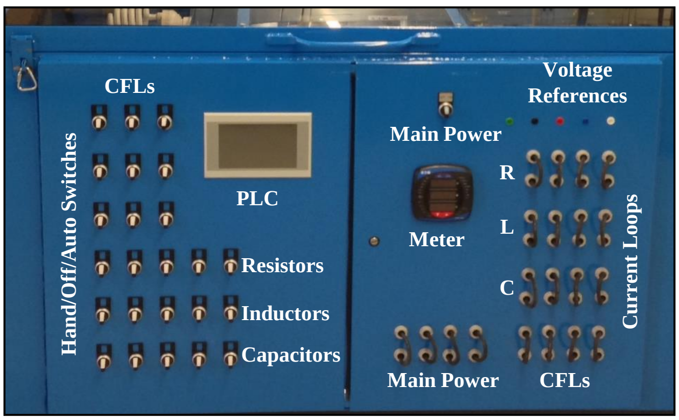

Figure 3: Bench User Interface

These benches serve as the interface for students to interact with real three phase power in the lab and contain several pieces of metering equipment for monitoring the power. Each bench contains an Eaton 2000 series Power Xpert meter that monitors the load banks in the bench using fixed current transformers around the main power feed to the bench and fused-protected voltage leads at the same point. Each lab bench also comes equipped with a Dranetz PowerXplorer PX5 Power Quality Meter that is rated for up to 600V and 6000A with four voltage and current inputs for simultaneously measuring all 3-phases and the neutral line in a power system. The meter integrates with the lab bench with built-in voltage measurement banana cable ports and current measurement loops for current clamp meters. The test points are used for monitoring and collecting data of the loads inside the bench, the MCCs, and VFDs inside the IFS, as well as any additional loads connected to the bench through the outlet. The test points can be used to easily monitor the voltages and currents on individual loads or the main power going through the bench. Various actions happening inside the IFS can be seen and recorded on all six benches in the lab simultaneously such as source switching, main power voltage sag and swell, and circuit breaker opening transients.

The safety of each student as well as the equipment is of primary concern in the lab. For operator protection, all students are required to take a lab safety class as well as pass a quiz. Only authorized personal have key access to the lab and can turn on the main power breaker. At least one authorized person must be present in the lab at all times whenever the lab is being operated. All benches are equipped with an emergency stop button which consists of a 120V single phase circuit that opens the main circuit breaker, causing the entire lab to shut down. The benches have two main lights, one red and one green. The green light indicates control power and is a separate isolated system from the lab for running the Dranetz meter as well as the PLC logic controllers. The red light indicates main power and turns ON when the main breaker in the IFS is closed and the lab is energized. This gives a visual indication of the power in the lab when it is being used. For equipment safety, each load and connection in the bench is connected through a 20A breaker in case a fault occurs in a load.

Power Quality Lab Development

Labs were developed for undergraduates to work in groups of two or three and groups were varied for each lab so that no group was ever the same from week to week. Labs built upon each other sequentially with a total of five labs being performed over the semester covering a variety of power quality concepts such as voltage sag, harmonic distortion, motor transients, and power electronics.

The first lab consisted of students getting comfortable with the equipment (lab bench, IFS, Dranetz meter), going over the safety procedures, and taking measurements in a real power system environment. Students were introduced to the concept of a one-line diagram and how to analyze it with respect to how loads will interact with a power system. Students were required to take voltage and current measurements in order to characterize the three phase and single phase loads inside the bench, which would be useful for later labs. Students also were introduced to the concept of harmonic distortion and its measurement in real time using the Dranetz meters. Students also saw how balanced and unbalanced three phase loading of resistors, inductors, and capacitors affects the current and voltage waveforms of each phase differently in the power system. The resistive, inductive, and capacitive loses of cables in the power system is also discussed with students.

The second lab had students capturing the voltage and current waveforms of capacitor and inductor switching and comparing the difference in harmonics when the lab is operating off a normal source vs. a weak source. Students had to explain which combination of source and switched load produced the worst harmonics and their reasoning behind this phenomenon. Fourier analysis of logged current and voltage waveforms from the Dranetz meters was performed by hand to confirm the total harmonic distortion calculations done in real time with the Dranetz meter. The students were also able to see how the CFLs produce a different harmonic than that of the capacitor and inductor switching.

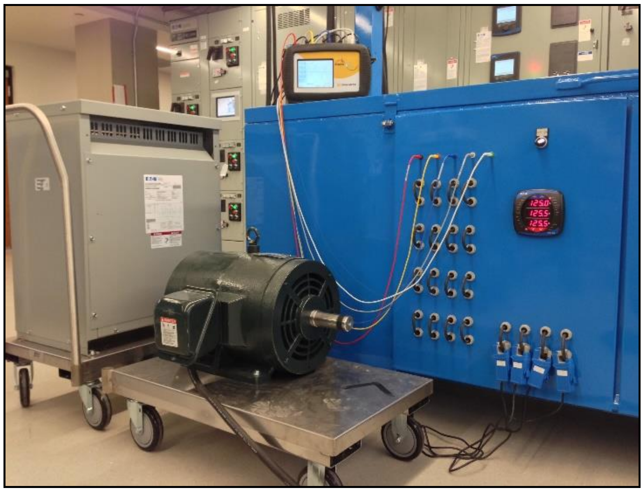

Figure 4: Using 15hp Motor with Lab Bench

The third lab had students running the 15hp motor using both a hard start contactor and a soft starter through both the normal and weak sources, see Figure 4. Students had to perform the inrush current analysis as well as harmonic content analysis from both motor starting techniques. Students saw that the motor had different levels of current drawn from each phase of the motor and were asked to explain the reason for the differences. Students also had to explain the benefits and tradeoffs of one type of starter over the other. Students then had to characterize the 15hp motor using the stated nameplate data as well as the data gathered from the motor startup. This analysis was primarily performed in MATLAB and Excel after the data was gathered from the lab.

The fourth lab had students running the 5hp MG sets and getting comfortable with operating a VFD from a keypad. This lab involved significant teamwork and coordination of one person recording data at the lab bench with the Dranetz meter and another person operating the VFD at the MCC. Students were asked to generate the torque-speed curve from the motors using the data collected from the Dranetz meters. Motor speeds and voltages were acquired from 40Hz up to 61.5Hz. Motor harmonic content and inrush current seen from the VFD was compared to that seen from the soft starter of the 15hp motor. Students were introduced to the concept of volts per hertz (V/Hz) control and how it is used to run a motor at a reduced speed without adding additional load to the motor to slow it down. Students had to compare the benefits and tradeoffs of running a VFD on a motor in comparison to just a hard starter (improved efficiency with the disadvantage of increased costs and harmonics).

The fifth lab had students utilizing a DC-DC Boost converter evaluation board from Texas Instruments to show how modern power electronic devices utilize transistor switching, inductors, and capacitors to change voltage levels in DC power systems just like a transformer in an AC power system. Various loss mechanisms were introduced as well as the concept of voltage and current ripple. Students were introduced to how to perform differential voltage measurements over a current sense resistor in order to measure the current through an inductor. Different switching operation modes of discontinuous conduction mode (DCM) and conditions conduction mode (CCM) are discussed and how these effect the efficiency of the converter. Converter switching frequency was also discussed and how it relates to input and output voltage ripple as well as efficiency. A DC power supply, fixed resistive loads, and an oscilloscope were used to measure the transistor switching waveforms, inductor current, and overall converter efficiency in both CCM and DCM operation. Input and output voltage and current waveforms were measured for two different switching frequency setups and two different input voltages in order to see how these parameters affect the efficiency of the converter.

A laboratory sample provided to the students is found in the Appendix of this article.

Instructor and Course Indirect Assessment

The indirect assessment of the course was done using a midterm survey which was given in the sixth week of the course, and an end-of-term survey which was given in the thirteenth week of the course.

It is well known in the academic community that while teaching surveys are valuable, they do not always tell the full story [7]. There have been numerous publications and presentations which have eluded to the opinion that these surveys are as much a popularity contest as they are a measure of teaching effectiveness. Based on this, the instructor asked a question that [he/she] thought was more representative of student learning in the midterm survey. Students were asked to rate the degree to which:

"My knowledge of the subject is increasing as a result of this course."

Eleven of the thirteen total students took the survey and the vast majority of the students felt that they strongly agreed with this statement. The results from this question are shown in Figure 5.

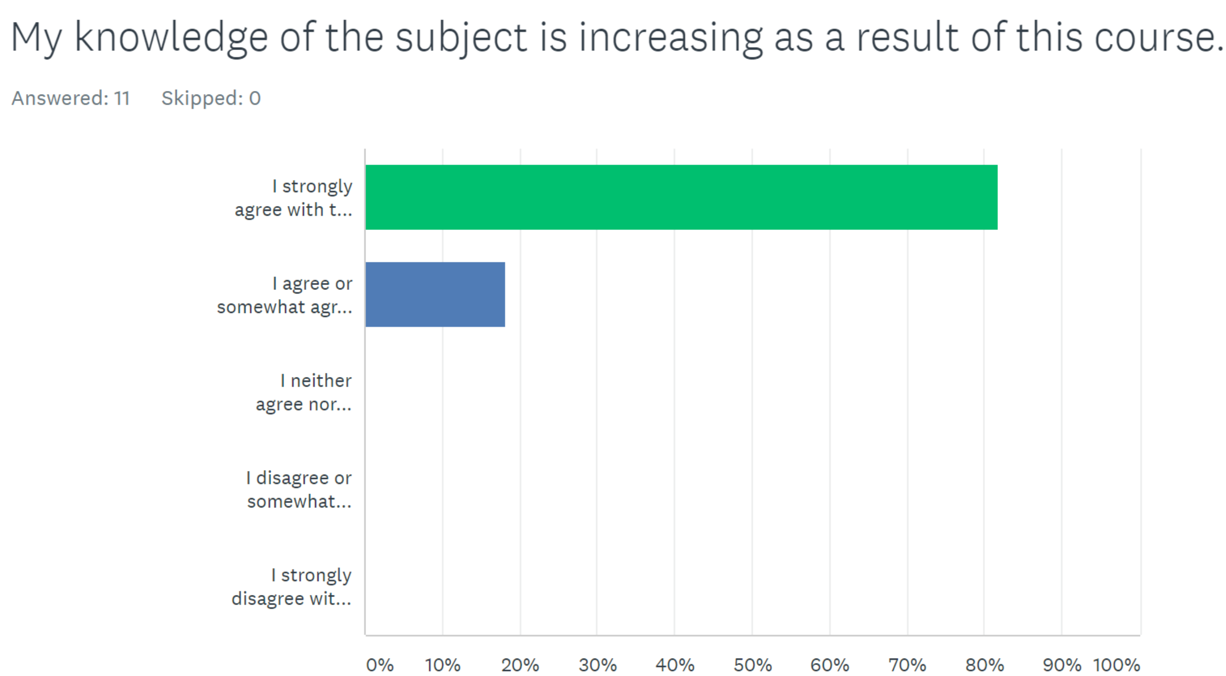

Figure 5: Results of Indirect Assessment Question on Increasing Knowledge

To strengthen the importance of such a question, the instructor also asks the "traditional" question to the students if they would recommend the instructor to their friends. The results of this question are shown in Figure 6.

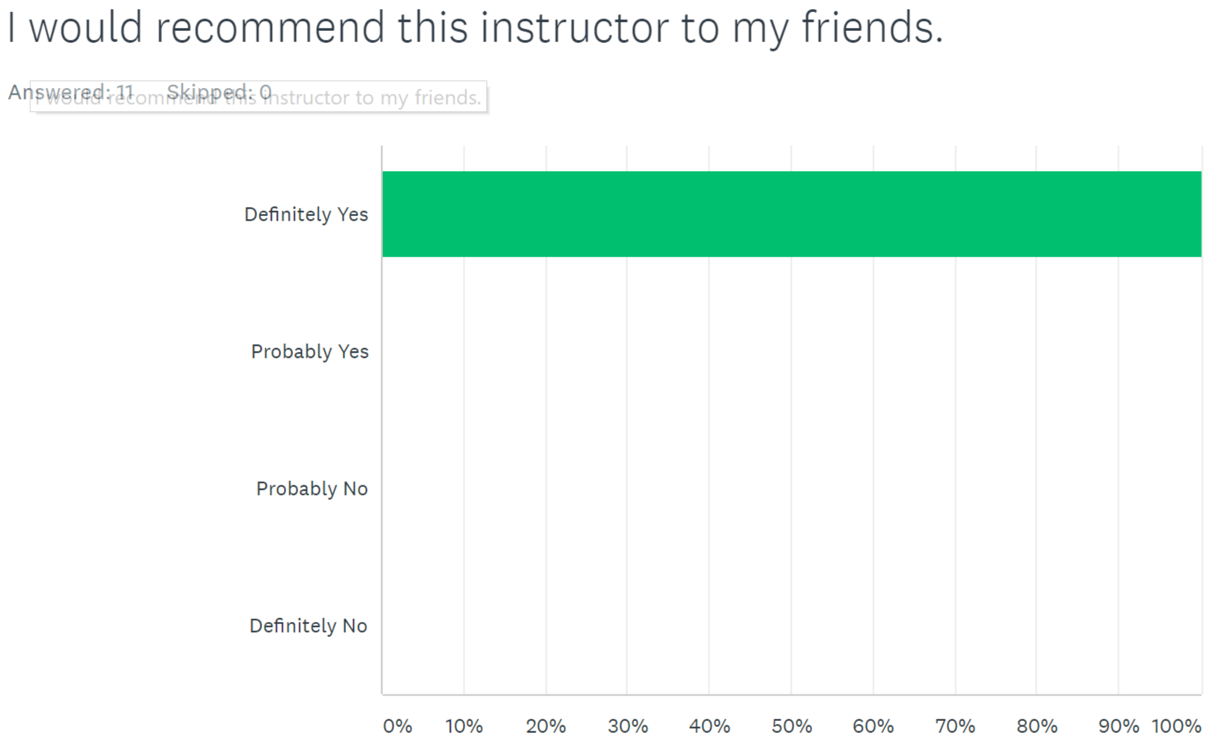

Figure 6: Indirect Assessment Question on whether Students would recommend this Instructor

The slight discrepancy should be noticed. In this first question, students were asked if their knowledge was increasing as the course progressed and most but not all strongly agreed. However, if asked if the instructor would be recommended, all strongly agreed. This shows that the perceived effectiveness of the instructor doesn't correlate one-to-one with what students think is a good instructor. Nonetheless, the vast majority of the students said that they were learning and that should be the primary goal of any course.

Students were also asked what they liked most about this course. A rubric was formed to indirectly assess student responses to the perceived value of the course based off of this. The rubric is given below.

Table 4: Rubric of Indirect Assessment on Perceived Value of the Course

Student indicates that the course will directly help them in a job out in industry (I)	Student indicates that the course has filled gaps in their knowledge (II)	Student indicates that the course has strengthened their knowledge of EE, immediately impacting their grades (III)	Student indicates that the course did not benefit them in their career as EEs (IV)	Did not answer (N/A)
≈ 27.3%	≈ 36.4%	≈ 18.2%	0%	≈ 18.2 %

The aim of this rubric was to determine the value of the course. The rubric is enumerated using Roman numerals I-IV. The highest value was placed on Roman numeral "I" and the lowest value was placed on Roman numeral "IV".

Students in category "I" saw the course as something that would directly impact their careers out in industry. This has the very highest value and directly correlates with the soon-to-be-replaced ABET outcome (i) – "a recognition of the need for, and an ability to engage in life-long learning." Students in category "II" saw the course as filling a gap in their current knowledge. There were several references students made to not fully understanding Fourier series components and what their physical meaning was. This course cleared that up for several students as can be seen from the rubric. Category "II" was the most common answer. Category "III" saw the course as simply strengthening their knowledge in the field of electrical engineering. This category was the minimum that one would hope for in delivering a new course. Category "IV" indicated that the students felt that they did not benefit from the course. Thankfully, there were no students who indicated this. Lastly, a few students did not answer this question.

Another method of indirect assessment is the end of year survey that students were asked to participate in. This survey was developed to focus on student perception of achieving ABET outcomes (a)-(k). The results of this survey can be seen in Figure 7.

This course has improved my:

Question	Results				
	Mean	Min	Max	Response Count	Standard Deviation
Ability to use math concepts to solve engineering problems.	4.70	3.00	5.00	10	0.67
Ability to use chemistry concepts to solve engineering problems.	2.00	1.00	5.00	10	1.70
Ability to use physics concepts to help solve engineering problems.	4.00	2.00	5.00	10	1.15
Ability to use engineering concepts to help solve problems.	4.50	3.00	5.00	10	0.85
Ability to design an experiment to obtain measurements or gain additional knowledge about a process.	4.50	2.00	5.00	10	1.08
Ability to analyze and interpret engineering data.	4.60	3.00	5.00	10	0.84
Ability to design a device or process to meet a stated need.	3.90	2.00	5.00	10	1.10
Ability to function effectively in different team roles.	4.20	3.00	5.00	10	0.92
Ability to formulate and solve engineering problems.	4.44	3.00	5.00	9	0.73
Ability to use laboratory procedures and equipment.	4.80	3.00	5.00	10	0.63
Ability to use software packages to solve engineering problems.	4.20	3.00	5.00	10	0.92
Ability to use CAD software.	3.70	1.00	5.00	10	1.34
Knowledge of professional and ethical responsibility.	3.70	2.00	5.00	10	1.25
Ability to write reports effectively.	4.20	2.00	5.00	10	1.14
Ability to make effective oral presentations.	2.30	1.00	5.00	10	1.42
Knowledge about the potential risks (to the public) and impacts that an engineering solution or design may have.	4.30	2.00	5.00	10	1.06
Ability to apply knowledge about current issues (economic/environmental/political/societal/etc.) to engineering-related problems.	4.20	2.00	5.00	10	1.03
Appreciation of the need to engage in life-long learning.	4.50	3.00	5.00	10	0.71

Figure 7: Indirect Assessment of ABET Outcomes (a)-(k)

It should be noted that some of these outcomes are pulled apart to assess different parts of them. For example, ABET Outcome (a) - "an ability to apply knowledge of mathematics, science, and engineering" was broken into four separate questions, such as "Ability to use math concepts for solve engineering problems".

To summarize this indirect assessment, students felt strongly that the course did what it was intended to. In the previous undergraduate power systems course offerings at [university], there were no courses where students would work in a lab setting, collect and analyze data, work in teams, write reports, or directly relate course work to industry practice. The indirect assessment shows that students felt that these areas of weakness were not only addressed, but done well. This can be seen with the following five key indirect assessment items found in Table 5.

Table 5: Key Items Indirectly Assessed in End of Term Survey

Question	Mean	Min	Max	Response count	Standard Deviation
Ability to analyze and interpret engineering data.	4.60	3.00	5.00	10	0.84
Ability to function effectively in different team roles.	4.20	3.00	5.00	10	0.92
Ability to use laboratory procedures and equipment.	4.80	3.00	5.00	10	0.63
Ability to write reports effectively.	4.20	2.00	5.00	10	1.14
Appreciation of the need to engage in life-long learning.	4.50	3.00	5.00	10	0.71

Key Faculty-Student Laboratory Observations

In electrical engineering, visualization is a key component to understanding a discipline that can often be instructed in an abstract fashion. One course that has high failure rates is the signals and systems course because (1) it may be one of the most mathematically rigorous courses in the electrical engineering curriculum for the undergraduate skill level and (2) students can have challenges in connecting the reasons for the mathematical analysis to real world scenarios.

In the introductory lectures of the course, the instructor reviewed Fourier series from the signals and systems course as Fourier series is vital in explaining harmonic concepts throughout the term. For the homework assignments, students would go through the standard calculation procedures but not until they went into the laboratory and measured the harmonic spectrum with the Dranetz power quality meters did the students begin to truly grasp the physical meaning of a harmonic and its impact on electrical systems. From the start of the class until the final exam, the instructor saw a drastic difference in student comprehension. As a basis of comparison, the instructor would receive questions from students at the beginning of the term such as, "What is the fundamental?" to being able to quantitatively and qualitatively explain the total harmonic distortion values from switching power supplies in the lab setting. With this lab based course, students were able to see the usefulness of the mathematical tools to acquire information from non-ideal signals.

In power system analysis courses, students begin to visualize the phase shifts that occur between current and voltage depending on the loads that are in the circuit. In an ideal scenario where you have a voltage source supplying power to a capacitor, the current waveform will lead the voltage by 90 degrees. During lab, the students understood that there were single-phase and three-phase capacitors in the bench being supplied by utility power if the bench was ON. When the students switched in specific capacitors, the students were able to record waveforms that looked similar to those in Figure 8. In this exercise, we asked, “Why is this happening?” This forced students to observe the one-line diagram of the lab and attempt to explain the resonance between the transformer that steps down the utility power and distributes the power to the lab benches and the capacitance in the benches. This was a good exercise in system forensics when in most microelectronic courses the students use ideal power supplies to supply their circuits.

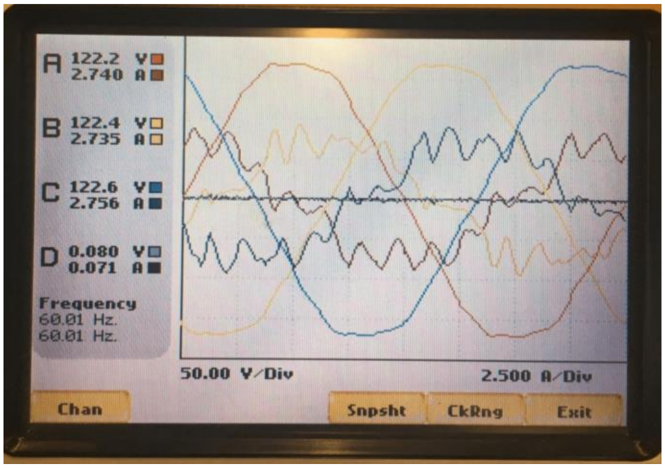

Figure 8: Resonance Developed when Capacitor Switched into Circuit

Sustainability and Impacts on the Teaching Mission of the School of Engineering

Specifically in the area of electric power engineering education, concentrations have been developed at both the undergraduate and graduate (MS and PhD) levels. The current curriculum consists of a strong set of courses (7 offerings at the undergraduate level and 17 at the graduate level) addressing the core principals in electric power, while being augmented with new offerings in emerging technology areas. To date, nearly one-third of all graduating, electrical engineers in the undergraduate program have completed the undergraduate electric power concentration, with 100% post-graduation placement either in industry or a funded graduate program position. The undergraduate students who declare electric power as their concentration of choice often perform an investigation in a power related area for their capstone senior design project, often sponsored through an industry partner of the program, like [industry partner]. To date, 200+ electric power engineering concentrations have been awarded since its inception in fall 2007 with classroom enrollments in the subject area averaging around 45 students per course offering.

The ECE department is committed to sustaining the electric power program at the University of Pittsburgh because of the global needs for power engineering solutions in industry and also because of Pittsburgh’s heritage in this technology space. Sustaining the engineering laboratory course will continue because of the nearly $500,000 investment from Eaton, who is updated regularly throughout the year with regards to its utilization amongst other partnership initiatives. The department plans to offer this laboratory course twice a year – once in the spring and once in the summer. The spring term is the earliest offering so that students have enough background from the core theoretical courses that are offered in their late sophomore and early junior years. The lab will also be offered during the summers to ensure that students enrolled in a COOP semester can enroll. The maximum number of students that can take the course in any given semester will be 18, which equates to 3 students per bench in the lab. This mandate is due to laboratory safety as 208Vac circuits are used.

Future Developments for the Course

The lab course mentioned has been offered once with plans on offering the course consistently in the spring and summer semesters. The next offering will be in the summer of 2019. As with all new courses and their first offering, the instructors always feel there are needs of improvement in course content and lab exercises. One major component that we want to introduce into the undergraduate curriculum for this laboratory is an understanding of Hardware-in-the-Loop (HIL) technology. HIL platforms are neither a pure simulation tool nor are they strictly for prototyping – it's an interface between the physical and simulation domains [8].

Before the growth in engineering simulation tools, engineers would develop highly conservative designs and immediately go to prototype to evaluate the response of the designed system. Solutions of this nature are not optimal and can result in higher weights, volumes, and costs of product. As available computational power increased with modern computing, simulation tools have become a vital resource for predicting how engineering designs will behave well before products are manufactured. Current simulation tools allow the engineer to run through countless experiments until a level of comfort is obtained ensuring adequate behavior of the physical product. However, the computer modeling that is conducted often is done with certain physical assumptions and modeling accuracy, in comparison to real world behavior, is often constrained by the experience and education levels of the engineer.

When designing equipment for high voltage (480Vac and above), the understanding of the dynamic behavior of electrical systems is absolutely critical when evaluating control systems for equipment regulation. If the system to be controlled is not understood adequately or assumptions applied in modeling the system dynamics are not appropriate, the controller will be designed poorly resulting in underperforming systems or system stability concerns resulting in catastrophic equipment failure. For this reason, the global manufacturers like ABB, Eaton, Siemens, and Mitsubishi Electric make use of HIL for a second layer of verification of their product performance prior to production.

With the minimal technical material on the HIL established and the value the tool brings to the manufacturers, a worthwhile engineering educational endeavor is to begin to train undergraduate students on a HIL platform. With the power quality laboratory established in the department, we plan to modify a few lectures and develop new labs in the following ways:

1. Create significant curricular improvements with new course materials. As argued, the HIL platform is a vital tool for manufacturer equipment verification. The HIL platform is being utilized for R&D activities by a handful of universities globally, but there are no official university course offerings on the subject that the proposers can find in top tier universities.

Controls are a requirement and must be understood from an implementation perspective more firmly at the undergraduate level. With guidelines provided by Typhoon-HIL, [9], the instructors will develop additional lecture material that bridges control system theory with implementation practices in the power quality laboratory. The HIL platform will be the core piece of equipment used by undergraduates. Several lectures will be designed that introduce students to the basics of DC/AC power electronic inverter design, which is one of the main purposes of HIL and how it is used in industry. An introductory lab will be designed for students to become comfortable with HIL as well as an advanced lab on three-phase inverter control with harmonic impact. One power electronic lab exists in the current set of developed labs as mentioned and will be replaced with this real-world set of tasks, which will motivate students throughout the duration of the course [10].

2. Develop innovative approaches to traditional teaching methods and cross-discipline collaboration among faculty from different departments. Control systems are taught in both electrical engineering and mechanical engineering in very similar fashions – white board discussions and application specific computer simulations with MATLAB. Integrating HIL into the ECE curriculum will generate a cross-fertilization of ideas amongst faculty, which has been done with other equipment from other vendors.

Conclusions

In the power program at the University of Pittsburgh, faculty members were able to design a lab course entitled, “Power Quality”. The first goal of this course was to add an extensive hands-on component into the current curriculum. The second goal was to design an innovative course where students worked in teams using industrial grade equipment and expressed their knowledge through written lab reports and other traditional educational methods of assessments (quizzes, exams, etc.). All lectures, homework assignments, exam content, and five unique labs with one shown in the appendix have been provided. The course exposed students to deeper understanding of electric power quality but also enhanced their understanding of other core ECE curriculum components, such as signal processing, through visualization. The faculty members have thoroughly described the course and the laboratory sessions for other universities to consider and have also provided evidence for its first successful course offering through the listed direct and indirect assessments described in this work. Future enhancements that are planned to be introduced into the next offering as well as plans for sustaining the course have been addressed.

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Appendix – Laboratory Procedure Sample

Induction Motor Control with Variable Frequency Drive

Objectives: To understand how induction motor performance can be controlled with power electronics.

Pre-Lab: Read the attached appendix on motor control options in the lab. Read Eaton's Quick Start Guide for the Variable Frequency Drive (find under CourseWeb); pages 1-3 and 8 are the most important. From past labs: make sure you have PQDiffractor installed on a group member's computer. Make sure you remember how to operate the Dranetz PowerVisa and identify voltage sags. Make sure you remember how to make statistical harmonic distortion estimates as in EPSL Lab #3.

Overview: You will first set up the PowerVisa to capture power quality events and also to make timed "journal" recordings every 30 seconds. The journal recordings will augment your lab notes, by providing an electrical record of conditions in the lab while you collect data. In this lab, you will perform a number of motor operations at your lab bench or the IFS, and also record events generated by motor starting. At the end of the lab, you will download PowerVisa data for emailing at one of the instructor computers.

Procedure: You will be using the Dranetz PowerVisa instrument to monitor voltages and currents on a lab bench in Benedum 814. These lab benches have access to resistive, inductive, capacitive and compact fluorescent light (CFL) loads, amounting to about 5 kW. The lab benches are also able to run 5-hp motor-generator sets, and to start a 15-hp motor across the line or at reduced voltage.

1. Hardware labs are group projects; you will work together and submit one group report. All data collection must occur during the Friday afternoon class period.

2. Keep track of the time your group spends on this lab. This mimics the requirement of timekeeping found in most companies. Round to the nearest integer hour.

3. The PowerVisa can transfer data to a computer for analysis using the PQDiffractor software (download from CourseWeb). In this lab, you will also receive a text file of timed data recordings call a "journal". You should also take notes during the lab.

4. **PowerVisa connection and setup procedure**:
   a. Make sure that you and all team members are wearing safety glasses.
   b. No open-toe shoes are allowed in the EPSL.
   c. Turn on the bench control/fan power switch at the front (green light should come on).
   d. Make sure the PowerVisa is plugged into the outlet labeled "Separate Source 120V Control Power". Turn on the PowerVisa.
   e. Connect four voltage leads to the PowerVisa red, yellow, blue and right-most white inputs. Then connect the other ends to A, B, C and G inputs on the lab bench. Once connected and verified, these leads should not be moved during the lab.

f. Attach three clamp-on current transformers (CTs) to the “Main Load” set of current loops (i.e. the first three on the left for phases A, B, and C, leaving the neutral current unmonitored). The clamp-on CT current polarity arrows should point downward for benches 3 – 6, or upward for benches 1 and 2. It is okay to move these CTs to other bench measuring loops during the lab, but make sure the jaws are fully closed each time.
g. Turn on the bench main breaker (red light should come on).
h. Use “Wizard Setup” of the PowerVisa, and accept the defaults except for:
   i. Make sure the CT types are TR 2550 A, 100A RMS.
   ii. Make sure the voltage scale is 1
   iii. Choose 3-phase wye connection. If the PowerVisa issues a warning about the current, you can either ignore it, or turn on some bench load, which provides current for the PowerVisa to sense.
   iv. Choose Standard Power Quality, Dmd, Eng.
   v. On the “Advanced Options” page:
      1. Set the Characterizer Options to be None (Raw Data). This will prevent the PowerVisa from deleting or aggregating events that don’t seem severe enough to record.
      2. Under Journal Interval:
         a. Power Values every 30 seconds, waveforms on
         b. Harmonics every 30 seconds
         c. Demand and Energy “off”
         d. Flicker – no changes
      3. Under RMS Variation Limit: (default voltage thresholds, plus I > 15 Amps RMS)
         a. Switch to Amps
         b. Group ABC
         c. Set the high limit to 15 A
         d. Push Next and Finish
      4. Under Transient Limit: (trigger on 255 Volts peak or 20 Amps peak on any phase)
         a. Switch to Amps, then select Group ABC, select Enable, and enter 20 Amps peak
         b. Push Next (Cycle-to-Cycle Waveshape), select Group ABC and then de-select Enable
         c. Push Next (RMS Distortion), select Group ABC and then de-select Enable
         d. Push Next until you are able to push Finish
   vi. Under Memory Card:
      1. Change the Site Name to “Bench #”, where # is your actual bench number. This way, your data files will have your bench number in the file name.
      2. Format the card.
i. Press Finish and then Start Now. After several seconds, you should see that the PowerVisa is armed. It will trigger on events caused by switching operations at your bench or at the IFS.
j. Try to keep the instrument in recording mode throughout this lab. If you have to stop and restart, you can choose “monitor the same circuit” to save time, if your first

instrument setup was correct. Also note the file name, e.g. "Bench 5_00.DDB" shown on the display.

5. **15-hp motor testing**. There are two 15-hp motors in the lab, so two groups will begin this procedure while the others begin 5-hp motor testing in part 6. You will start the motor across the line and record no-load running data in Table 1.
   a. Make sure all of your bench loads are turned off.
   b. When it's your group's turn, connect a three-phase 15-hp motor lead to the S811+ motor drive socket corresponding to your lab bench. These sockets are located near the bottom of the control cabinet.
   c. Start the 15-hp motor across the line, while watching the PowerVisa display in either Scope or Meter mode. One person will stand at the MCC and set the bypass switch positions to ATL (for across the line) and then turn the manual switch to "Hand". The instrument should capture an Event. Use the graphical and text displays to record the peak RMS inrush current on each phase, the minimum RMS voltage on each phase, and the duration of the disturbance. Using either the PowerVisa or the bench's Eaton PXM 2000, record the steady-state line-to-line voltages, line currents, and real power. Using Scope mode, observe whether the motor currents appear to be sinusoidal.
      i. Based on its nameplate data, some of the 15-hp motor equivalent circuit parameters have been estimated as:
      ii. $R_1 = 0.065\ \Omega$
      iii. $R_2 = 0.054\ \Omega$
      iv. $X_1 = 0.255\ \Omega$
      v. $X_2 = 0.382\ \Omega$
      vi. Calculate the X_m and $P_{rotational}$ motor parameters and record them in Table 1.

6. **5-hp motor testing**. In this part, you will use the VFD to start a 5-hp motor, and control its input frequency. The second 5-hp motor in your M-G set will act as an induction generator, circulating power through the bench and back to the IFS. Both 5-hp machines are identical.
   a. Make sure your bench loads are turned off.
   b. Make sure your bench's 5-hp generator is off; these switches are at the IFS left front.
   c. Find and turn on your bench's SVX 9000 VFD; this will be located above the S811+ used for the 15-hp motor.
   d. The SVX 9000 is controlled with Run/Stop membrane buttons, and a menu navigated with left/right and up/down arrow keys. The functions we need are at the top-level (M8) Operate menu. If you get "lost" or need more detail, refer to the quick-start guide provided on CourseWeb, or consult an instructor. It's been configured for a soft start, and an output frequency limit of 61.5 Hz.
   e. Navigate into the Operate menu with left-right arrows, and make sure the Frequency Reference is 60.0 Hz. To change this value, use up-down arrows, which immediately take you to Keypad Reference. The response can be sluggish, so make sure the value settles at 60.0 before proceeding.
   f. Press the Start membrane button. The 5-hp motor will ramp up to a no-load operating condition at 60 Hz. Use the left-right arrows to view the VFD's estimated motor speed, power, torque, etc. You can't edit any of these values (other than Frequency);

they are predicted from the VFD's own measurements and estimated motor parameters. Record values from the VFD display and your bench meter in Table 2; then calculate the slip.

g. On the front left area of the IFS, labeled "Return", find the GEN bucket corresponding to your bench. Turn the main switch on, if necessary, and then set the operating mode to "Hand". Press the Black Start button; the Red running light should come on. This starts the output 5-hp generator of the M/G set. Because the input 5-hp motor is only driven at 60.0 Hz, this generator is not yet supplying power back to the IFS. Record values from the VFD and your bench meter in the next row of Table 2; then calculate the slip.
h. Using Scope mode, observe whether the VFD currents appear to be sinusoidal.
i. Using the VFD Operate menu as described in step 6e, change the Frequency Reference to 60.25 Hz. The drive responds immediately as you change this value. When the Output Frequency stabilizes at 60.25 Hz, record your data in the corresponding row of Table 2.
j. Continue step 6h, increasing the Output Frequency in steps of 0.25 Hz until you reach 61.5 Hz. At this point, you should notice that the M/G set is circulating a significant fraction of its rating through bench and back to the IFS. This operation simulates an industrial M/G set, and also certain types of hydro or wind generation.
k. At 61.5 Hz, try using the capacitor switches on your bench to compensate the VFD power factor as read from your bench meter. It won't work. To see why, use the scope mode of your PowerVisa to examine the voltage and current waveforms at your bench. The Eaton PXM 2000 displays "apparent power factor", which includes harmonics. The PowerVisa can display both "true power factor" (TPF), and displacement power factor (DPF), which includes only the 60-Hz component. Which types of power factor do the capacitor switches affect?
l. When finished with this part, press the Red Stop button on your bench's GEN bucket. Then press the Stop membrane button on your bench's VFD.

7. At the end of the lab, follow this bench and PowerVisa **shutdown procedure**:
   a. Turn off all the R, L, C and CFL switches.
   b. Stop the PowerVisa monitoring function.
   c. After the PowerVisa says "done", turn it off.
   d. Turn off the bench main breaker (red light goes out).
   e. Turn off the bench control/fan power (green light goes out).
   f. Remove the Compact Flash (CF) card from the bottom of the PowerVisa. **Make sure you stopped the PowerVisa monitoring first**, in step 7b, before you remove the CF card.
   g. Bring the CF card to one of the instructors. We will email one of your group members a binary file of all your data in PQD format, and a text file of your journal harmonic distortion data in CSV format.
   h. Insert the CF card back into your PowerVisa.

8. Make any other notes or sketches you might need to complete your report.

9. **Analysis**:

a. Table 1: Draw an equivalent circuit for the 15-hp motor, and label its parameters. Solve this circuit for the starting current, I_1, and compare to your results in Table 1.
b. Table 3: The text file of distortion data will contain your journal minimum, average and maximum values of the voltage and current distortion on each phase. Based on your data, estimate the value of voltage distortion and the value of current distortion that would be exceeded no more than 1 hour out of 24[1]. These estimates should be lower than your peak recorded values. See the Appendix: Statistical Harmonic Distortion Estimates for an example calculation using Microsoft Excel.

Report: The main body of the report is limited to 3 pages in a Word or PDF file. Reference this assignment and PowerVisa documentation as needed, but don't repeat the details. Technical reports in the real world should be simple and direct. Include these main items:

1. Write an objective, summary of results, and explanation of your results. Use headings to highlight the answers to these questions:
   a. H1: When you run the 5-hp motor at different loads through a VFD, is the power vs. slip characteristic approximately linear? Why or why not?
   b. H2: Which type of power factor measurement do you think is the best, and why? Which power factor measurement do the bench capacitors influence?
   c. H3: What statistical voltage and current distortion levels did you record during the lab? Which events or operating conditions led to the highest harmonic distortion levels? How do these compare to what you recorded in EPSL Lab #3?

2. Put supporting tables and graphs into an appendix. Each graph should have a caption.

3. Signature, date and hours "charged".

Rubric: Grading will occur on a 10-point scale:
- 0 points for no submittal or a late submittal
- 7 points for a basic report structured as above.
- +1 point each for plausible answers to Q1, Q2 and Q3.

Due: By Noon on November 20, via email, CourseWeb or hard copy.

Table 1 – 15-hp Motor Test Data

Starting ATL:		**Running @ No Load:**	
Lowest RMS V_{AN} [V]		RMS V_{AB} [V]	
Lowest RMS V_{BN} [V]		RMS V_{BC} [V]	
Lowest RMS V_{CN} [V]		RMS V_{CA} [V]	
Highest RMS I_A [A]		RMS I_A [A]	
Highest RMS I_B [A]		RMS I_B [A]	
Highest RMS I_C [A]		RMS I_C [A]	
Event Duration [s]		Total Real Power [W]	
Calculate X_M [Ω]		**Calculate $P_{rotational}$ [W]**	

[1] This is the method prescribed in IEEE Std. 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"

Table 2 – 5-hp VFD Motor Test Data

Gen	Freq [Hz]	VFD: N [rpm]	VFD: % Power	Meter: P [W]	Meter: Q [VAR]	Calc: % Slip
Off	60.00					
On	60.00					
On	60.25					
On	60.50					
On	60.75					
On	61.00					
On	61.25					
On	61.50					

Table 3 – Total Harmonic Distortion

Quantity	Maximum	Value Exceeded 1/24 of the Time
Voltage THD [V]		
Current THD [A]		

Appendix: Motor Drives in the EPSL

Figure shows the one-line diagram for one of the lab benches connected to the motor control center (MCC) in the main **IFS** cabinet. The bench breaker panel has a 30 A three-phase breaker, labeled MCC Return, through which you can start and operate a 5-hp M/G set and a 15-hp induction motor. With metering connected at the normal location, shown in **red**, you can measure the sum of the motor load and other local bench loads. The **IFS** is fed by the building 480-V source, through a 5% reactor installed near the lab ceiling. Inside the **IFS**, a transformer steps down to 208 V; the total impedance of reactor plus transformer is about 10% on a 75 kVA base. Some experiments can also be done with additional 18% impedance in the **IFS** circuit, simulating a weaker source.

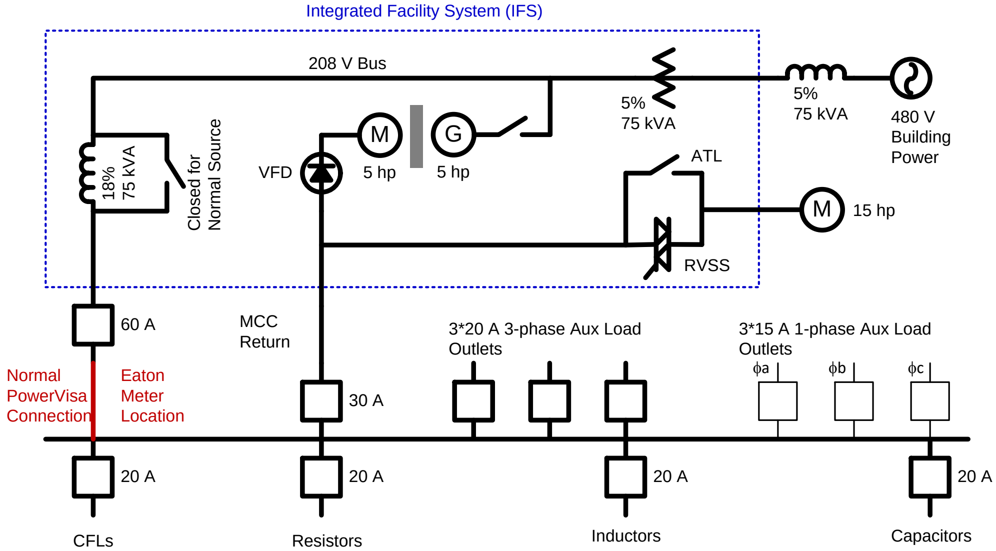

Figure 1 – One of the six lab benches, connected to motors and normal/weak source options through the main IFS cabinet

Part of this lab involves a variable frequency drive (VFD), illustrated in Figure . On the left, a three-phase rectifier connects to the bench MCC feed; it will draw harmonic current. On the right, an insulated gate bipolar junction transistor (IGBT) bridge provides adjustable voltage and frequency to the motor.

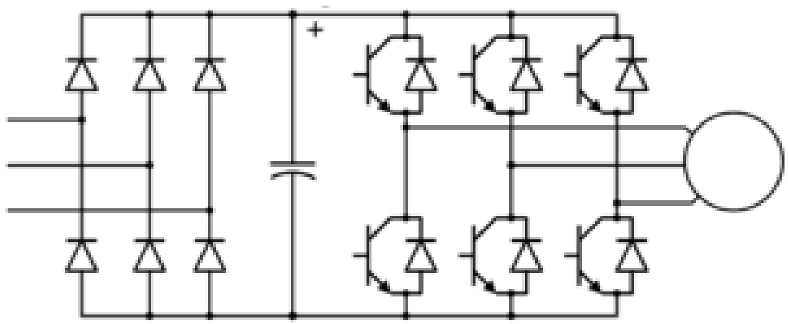

Figure 2 - A typical variable frequency drive (VFD) configuration