Microgrid Laboratory System Protection

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I. Abstract

The Microgrid Laboratory System Protection Project is a small-scale, modular power system designed to give students hands-on experience with the solid-state protection, communication, and automation equipment found in today's electrical power systems. This experience will supplement the theory and analysis of power systems presented in lecture, as well as provide experimental support for new courses in the emerging field of microgrids.

To accomplish this, the Project is a "power system on a bench," consisting of electrical generation, transformers, simulated transmission line, passive electrical loads, an induction motor, and Schweitzer Engineering Labs (SEL) microprocessor-based protective relays and communications and control equipment. This equipment comprises a microgrid power system that fits on the lab benches found in Cal Poly's Energy Conversion Lab. While self-contained, this power system can be easily modified, expanded, and connected to other microgrids, allowing the system to be easily scaled to meet the needs of students and instructors.

The Project provides the foundational hardware unit of new laboratory experiments and coursework under development by Cal Poly's Electrical Engineering department, most notably the faculty involved in power systems and related fields, as part of an effort to update the curriculum to reflect the theory and operation of current and emerging practices and technologies in the electrical power industry.

II. Background

The Grid

The power grid is the electrical system that connects producers of electricity to consumers. The U.S. power grid is a nationwide system of interconnected networks that comprises 2000 electric utilities with a combined total of over 300,000 miles of transmission and distribution lines, and connects some 7200 power plants and other generating facilities to millions of customers.

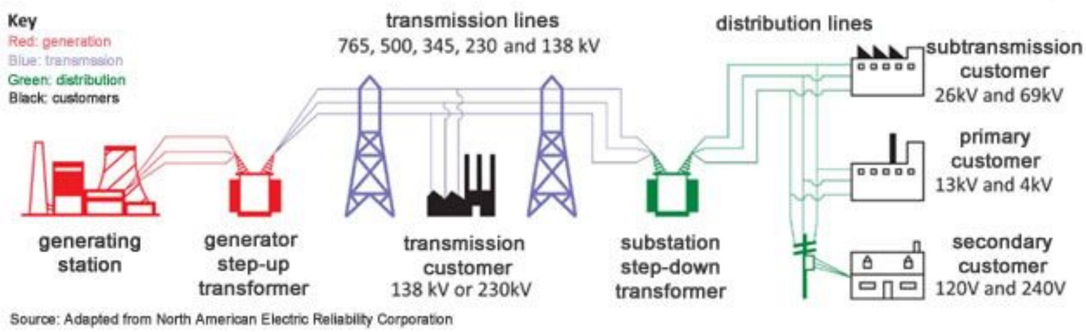

Figure 1. Power Grid Overview [1]

The traditional power grid, as it has generally existed in the decades following World War II, is shown in Figure 1. A generating station produces electricity from sources such as coal, natural gas, and water (as in hydroelectric generators in dams). The voltage is stepped up via transformers to reduce losses associated with transmission. High voltage transmission lines run for tens or hundreds of miles to distribution substations, where the voltage is stepped down, again using transformers, to the distribution level. Low and medium voltage distribution lines provide electricity to customers ranging in size from large factories to individuals houses, most of which are far from the generating stations.

Microgrids

At the most basic level, a microgrid is similar in many ways to the larger power grid. It contains the same elements: Electrical generation, transmission, distribution, and loads (customers). Microgrids, however, tend to be smaller, more localized, and are usually connected to the power grid. The most important aspect of a microgrid, however, is that they can continue to operate while disconnected, or “islanded,” from the grid. This offers many benefits, including

Figure 2. Microgrid [2]

providing a backup if grid service is interrupted and allowing local customers to take advantage of local generation, such as solar panels on houses, which might reduce costs.

Power System Protection

To ensure safe, reliable, and affordable operation, electrical power systems use protection equipment to detect and remove faults and malfunctioning equipment in a process called "selective isolation." Electrical faults can result in service interruptions and expose people to dangerous conditions, such as a fallen high-voltage power line lying in the road after a storm. Selective isolation removes these faults by opening a circuit breaker, ideally as close to the fault as possible and as quickly as possible to prevent further safety hazards and equipment damage. In addition, power should be maintained in the rest of the system while only the faulted equipment is removed from the system.

Selective isolation with circuit breakers is commonly controlled with protective relays. These relays sense currents and voltages, compare them to set thresholds, and open circuit breakers to remove detected faults. In the past, relays were purely electromechanical devices, and still have a place in the industry.. Today, however, solid-state microprocessor-based relays such as those made by SEL provide additional functionality such as remote monitoring, adaptable control, and network-wide communications and protection of power systems. Due to their effectiveness and versatility, these relays are widely used in industry, and knowledge of their operation and implementation is an important part of power engineering. Electrical engineering students, especially those pursuing a career in power systems in general and protection engineering in particular, would be well-served with hands-on experience with these relays in a laboratory setting.

III. Product Description

The Microgrid Laboratory System Protection package is a small-scale hardware microgrid for university and college power systems and protection engineering courses, designed to simulate a electrical power grid in order to give students practical experience in power system operation and protect. It consists of a core unit of simulated transmission lines, power transformers, a load bus with resistive and motor loads, and microprocessor-based protective relays. The default setup of the package consists of a bi-directional system with two transmission lines, voltage transformation, a load bus, protective relays, and a communications processor, as shown in Figure 3.

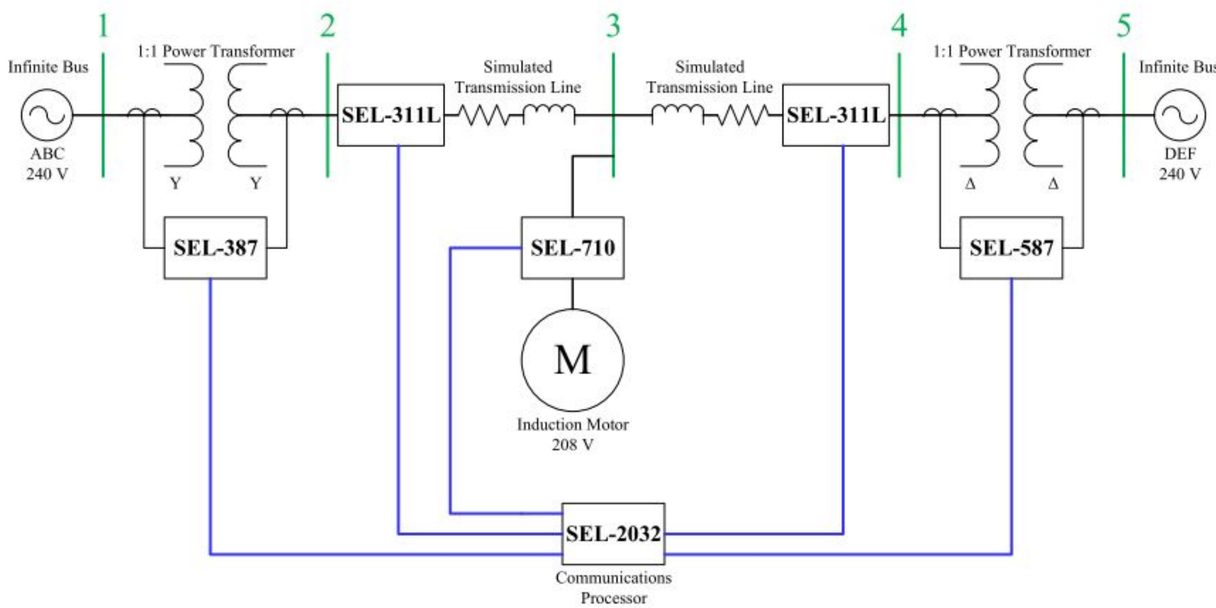

Figure 3. Microgrid Laboratory System Protection core package

The package is essentially a "lab in a box," fits on a lab bench or table, and includes the necessary test leads and connections to operate the system. The system is designed to be self-contained, that is, AC power input to the system can come from a connection to the local utility grid, in which case the package operates as a traditional power grid, or from other local sources, in which case the package operates as an islanded microgrid. This allows universities to use the same hardware for traditional power protection laboratory work and microgrid operation experiments.

System protection is provided by SEL relays and custom-made circuit breakers. System monitoring, visualization, and event recording is provided by an SEL communications processor. SEL equipment dominates the solid-state protection market, and the ability to program, coordinate, and operate SEL devices system-wide is a highly desirable skill for today's protection engineers.

The system is fully characterized in its default configuration, and premade laboratory exercises are provided for each relay, allowing customers to begin offering laboratory coursework to students immediately after installation. In addition, the package is designed to be easily modifiable and expandable, providing versatility and adaptability. Multiple core packages can be networked together to form larger systems.

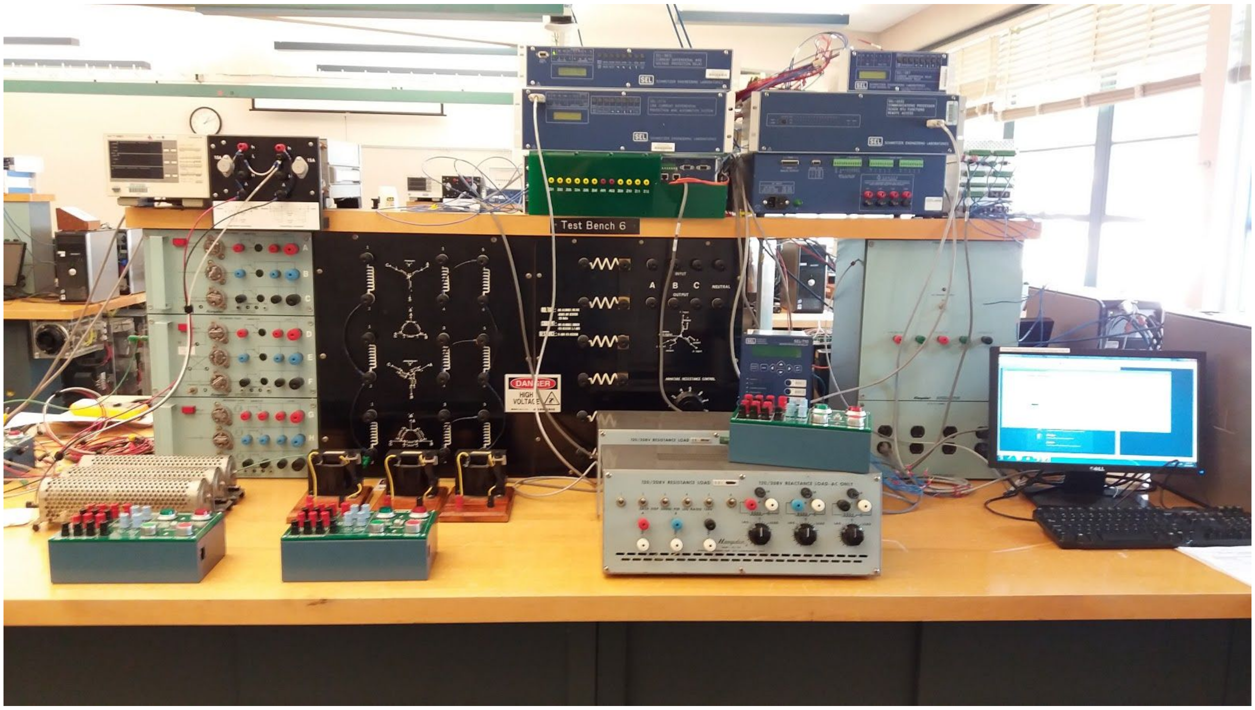

Figure 4. MLSP Equipment on Bench

IV. Market Research

Presently, Cal Poly's Power Systems Lab (EE 444) only provides basic instruction in protective relay operation and relay coordination using electromechanical relays over the course of a single laboratory experiment. This provides experimental validation of coordination schemes presented in lecture, which gives students a theoretical foundation for the field of protection engineering. However, Cal Poly's focus is on learning by doing, and the current curriculum falls short of that promise in several ways. First, the current lab experiment deals only with relay coordination, and does not use relay-operated circuit breakers to clear faults, which is the most critical part of protection engineering. Second, electromechanical relays are still used in industry due to their reliability and simplicity of operation, but have been supplanted by microprocessor-based solid-state relays, which have become ubiquitous in industry. First pioneered by Edmund Schweitzer in his garage, solid-state protection devices offer functionality far beyond the capabilities of electromechanical relays. Familiarity and practical experience with these devices is critical for new protection engineers, since they will be using them extensively in their careers.

The MLSP project fills this gap by providing hands-on experience with SEL relays to protect motors, transmission lines, and transformers in a laboratory setting. Using SEL equipment not only provides the same instruction in relay coordination as the current curriculum, but also trains students to program the relays to operate circuit breakers to clear faults, monitor system operation using a communication processor, and communicate with networked devices just as they would during their career as an engineer. The Project prepares students for the reality of modern protection engineering, which relies more heavily on smarter devices and networked automation every day.

V. Customer Archetype

Our customers will almost exclusively be universities. There are three different categories universities fall under for our considerations when targeting them as potential customers. The categories are universities that offer Power Engineering degrees/emphasis and microgrid/power systems protection laboratories, universities that offer Power Engineering degrees/emphasis without microgrid/power systems protection laboratories, and universities without a Power Engineering degree/emphasis or microgrid/power systems protection laboratories. Our first customer we are targeting is California Polytechnic University, San Luis Obispo which falls under the category of a university that offers Power Engineering degrees/emphasis, but not a microgrid/power systems protection laboratory.

We will focus on the individuals at universities that will become the internal advocates for such purchases as our microgrid with power systems protection elements included. The advocates are the Dean of the College of Engineering and Department Chair of the Electrical Engineering Department. As advocates, they will use two main factors when supporting the purchase of our product. Those factors are how much will it contribute to higher recruitment and how much additional grant money this may this lead to in the future. Our product is one that can become a center piece for both of these factors. Putting a laboratory with technology that will aide in the future of utility grids on display can peak interest from potential students and their parents leading to increased student recruitment. In addition, our product can be used to be a medium for organizations looking to fund research to aide the future development of our utility grid and companies looking to fund projects at top Power Engineering universities.

Our product will aim to help the customer with their pains as well as giving them gains. Pains associated with being a university's liaison, the Dean and/or Chair, to the public is the ability to quickly establish a department's credibility in a short amount of time. One popular and efficient way to do this, is by touring the guests through the department's campus while highlighting unique pieces that aide in the education process, such as advanced laboratories. Our product will be designed with this mind to ensure it attracts both potential recruits and industry leading professionals. The customers will also benefit from gains associated with our product. Our product will allow our customers to ensure they're in the forefront of microgrids/power systems protection to best petition for grant funds in this sector of Power Engineering. Our customers will now have the ability to study/research physical power systems with a wide range of capabilities which is not common across the United States. This will also attract employers and their pocketbook to assist in university events to higher their own recruitment on Power Engineering students with education in the latest technology.

There is an existing market in the industry of educating engineers on products used with microgrids and power systems protection. There are currently two major US companies providing services in the field of mircrogrid products and power system protection, Schweitzer Engineering Laboratories and General Electric. Both of these companies provide educational service throughout the United States as well as the rest of the world. The market is also populated with the large European companies ABB Ltd, Siemens and Schneider Electric, who provide educational services worldwide.

Table 1: Competitors in Market Place

SEL SCHWEITZER ENGINEERING LABORATORIE	Schweitzer Engineering Laboratories was founded in Pullman, Washington in 1982 by Edmund O. Schweitzer III upon the invention of the first all-digital protective relay. Presently, the company designs and manufactures embedded system products for protecting, monitoring, control and metering of electric power systems. SEL products specialize in circuit breakers, switches, meters, enclosures and switchboards.
	General Electric was founded in New York in 1892 by Thomas Edison, Charles Coffin, Elihu Thompson and Edwin Houston. As of 2015, the company had interests in the following industries: appliances, water/power, oil/gas, energy management, aviation,medical device, life sciences, pharmaceutical,software development and engineering. Historically there have been two Nobel Prize winners who were employees of GE at the time of award. In 2012 was ranked as fourth largest company in the world among the Forbes Global 2000.
ABB Power and productivity for a better world™	Created in 1988 through a merger of ASEA of Sweden and Brown Boveri & Cie of Switzerland, ASEA Brown Boveri is a multinational corporation headquartered in Zurich, Switzerland. Operating mainly in robotics and the power and automation technology areas, it ranked 158th in the Forbes 2013 ranking. One of the largest engineering companies as well as one of the largest conglomerates in the world. ABB has operations in over 100 countries with approximately 150,000 employees. Power products include low

	voltage, distribution and transformers as well as engineering services.
	Siemens is a German multinational conglomerate company formed on October 12, 1847 in Berlin (In the Kingdom of Prussia) by Werner Von Siemens. Siemens is currently headquartered in Berlin and Munich and is the largest engineering company in Europe. The principal divisions of the company are industry, energy, healthcare and infrastructure and cities. Siemens energy products include high voltage transmission products, power transformers, high voltage switching products and systems, transmission systems and power automation products.
	Schneider Electric was founded in 1836 by Eugene Schneider and incorporated in 1981. Headquartered in Rueil-Malmaison, France, Schneider Electric is a European multinational corporation that specializes in electrical distribution and automation management, and produces installation components for energy management. Products include circuit breakers, switches, meters, enclosures and switchboards.

The solutions provided by these different companies are similar in approach and technology, but differ by the individual design. Since each company has proprietary technology, they can only provide engineering and sales support for their own equipment. This means that if you were to purchase protection equipment from Siemens, then that company is the sole provider of training and support for your equipment. In addition each company provides training, limited to the coverage of their own proprietary technology as well as principles of distribution, protection, and basic electrical safety. Our product can bridge this large gap and create an educational environment modeling actual microgrids and power system protection schemes by incorporating products from all the leading manufactures.

According to the most recent IEEE Power and Energy Society release of information, there are 130 universities that consider themselves to have a degree/emphasis in Power Engineering within the United States of America and Canada [4]. This is the initial market our project will target due to the importance they hold Power Engineering already. Our project aims to be a solution to an educational hands on component for both microgrids and power system protection. Narrowing the market, there are 35 universities that teach courses on grid technology (6 with laboratories and 29 without laboratories) and 43 universities that teach courses on power system protection (14 with laboratories and 29 without laboratories) [4]. Assumptions about this market size are that universities with curriculum on grid technology and power system protection would be the easiest market to enter into with our product followed by the 87 universities that have a degree/emphasis on Power Engineering without courses pertaining to our project and lastly the other 193 universities with Electrical Engineering programs that are ABET (Accreditation Board for Engineering and Technology, Inc.) accredited. Our project can immediately address 43 out of 323 universities or 13% of the total market. We can expand this percentage as more universities are encouraged to add curriculum to their programs.

VI. Market Description

Detailed Product Description

The Microgrid Laboratory Protection System forms a self-contained microgrid that fits on a lab bench as commonly found in colleges and universities. The system consists of the components that would be found in a traditional power grid or local microgrid, but on a smaller scale for educational purposes. The system includes: generation, voltage transformers, simulated transmission lines, passive resistive load, motor load, and protection for all the above. Detail on each component is provided in the following paragraphs.

- Generation: Power input to the system is provided at 240VAC. At Cal Poly and similar schools, this occurs in a dedicated energy conversion or power systems lab, where a direct connection to the local utility grid is available. Depending on the resources available to the customer, this voltage could be provided via standalone generator, inversion of DC sources, or in other ways to power the system in islanded operation.

- Voltage transformation: Voltage transformation is a critical part of power transmission, and is provided in many institutions by power transformers available in the energy conversion laboratory. Standalone transformers may also be used. For this project, a 1:1 transformer is used in order to focus on transformer protection. Different transformer ratios may be implemented at the customer's request, and can even be changed from experiment to experiment, depending on customer hardware.

- Transmission Lines: The long transmission lines found in utility power grids are simulated by 10Ω power resistors and 100mH inductors, which provide line impedance equivalent to a 50-100 mile line. By varying the values of the resistors and inductors, lines of different length can be simulated. Lossless lines can be simulated by removing the power resistors from the circuit, leaving only the inductors.

- Passive Load: Three 25Ω power resistors create a 3-phase resistive load.

- Motor Load: A ⅓ hp 3-phase AC induction motor is connected at the load bus. Delivering power to customers to serve motor loads, from the large machines used in various industries to the washing machine in a home, is one of the key roles of the power grid, and motor protection is therefore critical.

- Protection: Each of the components described above is protected by a SEL device designed for that purpose: the SEL-311L for the transmission lines, the SEL-387 and -587 for the transformer, and the SEL-710 for the motor. Each relay controls circuit breakers that clear faults in the system. Each relay is connected to the SEL-2032 Communications Processor, which monitors the system and provides event recording for each relay.

Table 2: Hardware

Item	Description	Quantity	Price Each ($)
10Ω Power Resistor	Input current limiter / simulated transmission line resistance	6	28
25Ω Power Resistor	Passive resistive load	3	35
100mH Inductor	Simulated transmission line inductance	6	19
⅓hp induction motor	Motor load	1	90
SEL-710 Motor Protection Relay	Motor protection	1	2500
SEL-311L Line Current Differential Protection Relay	Transmission line impedance protection	1	5000
SEL-387	Transformer protection	1	5250
SEL-587	Transformer protection	1	2080
SEL-2032 Communications Processor	System monitoring and event recording	1	2840
Custom Circuit Breaker	Fault clearing and breaker operation	7	314
TOTAL			20345

Limitations of Present Solutions

Table 3: Limitations of Present Solutions

Subject	Present Solutions
Course length	Courses tend to be compacted into the minimal amount of time which leaves newer engineers unable to grasp most of the material.
Course price	Courses cost between $750-2000 per class in addition to travel. This is an expense some employers will not cover.

Learning environment equipment	Courses are set up around individual components. Learning in an environment that has multiple components interacting on the same system is rare.
Research ability	None. Engineering staff currently don't have a means to do research on grid technology or power system protection unless it is provided by the employer separately.

Key Strengths

Our project is able to leverage the academic community and its resources since the competitors are private organizations providing education on only their products over a short amount of time. Our product will be versatile in components used and be utilized in multiple ways as our customer sees fit.

Underserved Markets

The competitors provide most of the hands on education on products nationally due to universities having inadequate or no power laboratories. Our product will aim to give our customer, the universities, a larger role in hands on training for both grid technology and power systems protection.

Market Window of Opportunity

The opportunity with our product is limited in the potential total sales that are possible as there are only 323 Electrical Engineering ABET accredited universities in our target market. Our opportunity is increased with the ability of our product to sustain through upgrades and different add on packages later in its life cycle to generate customer interest to purchase from us again.

Market Entry

Our product will enter the market one campus at a time addressing the needs of the customer until our product is general enough to package and sale as an unit. Our first customer, California Polytechnic University in San Luis Obispo, has detailed needs we are incorporating into the microgrid. Once the first product is delivered in Spring '17, we will target and begin appealing to our second customer during the summer of 2017 with an estimated delivery time frame of Spring '18.

Key Partners

Schweitzer Engineering Laboratories (SEL) is not only a competitor with the classes they offer on power system protection, but would be an invaluable partner to us. SEL creates the industry standard microprocessor- based protection relays used in our current system, in addition to a majority of relays used nationally. Partnering with us would allow their products to be used by new grads which would enhance their relevance in all companies and allow our product to be more cost effective which in turn would make it more profitable.

Potential Customers

Our lead customer is California Polytechnic University, San Luis Obispo. We are in constant communication with the university through the Mirogrid project lead Dr. Shaban. Once initial testing and analysis is complete we can begin to look for additional customers and use our experience here at Cal Poly as a reference.

Our Solution vs. Present Solutions

Table 4: Comparison of Current Offering to the MLSP Project

Need	**Present Solutions**	**Our Solution**
Power system analysis	Manual monitoring of power system, limited data collection and visualization	Real-time monitoring of power system, event records kept for analysis, visualization of events and system operation
Relay coordination and operation practice	Only offer electromechanical relays, which teach fundamentals but are being supplanted in industry	Offers the same theoretical validation, but with equipment new engineers will encounter in the field
Relay-operated circuit breakers	Do not include relay-operated breakers	Includes relay operated breakers, just like in industry

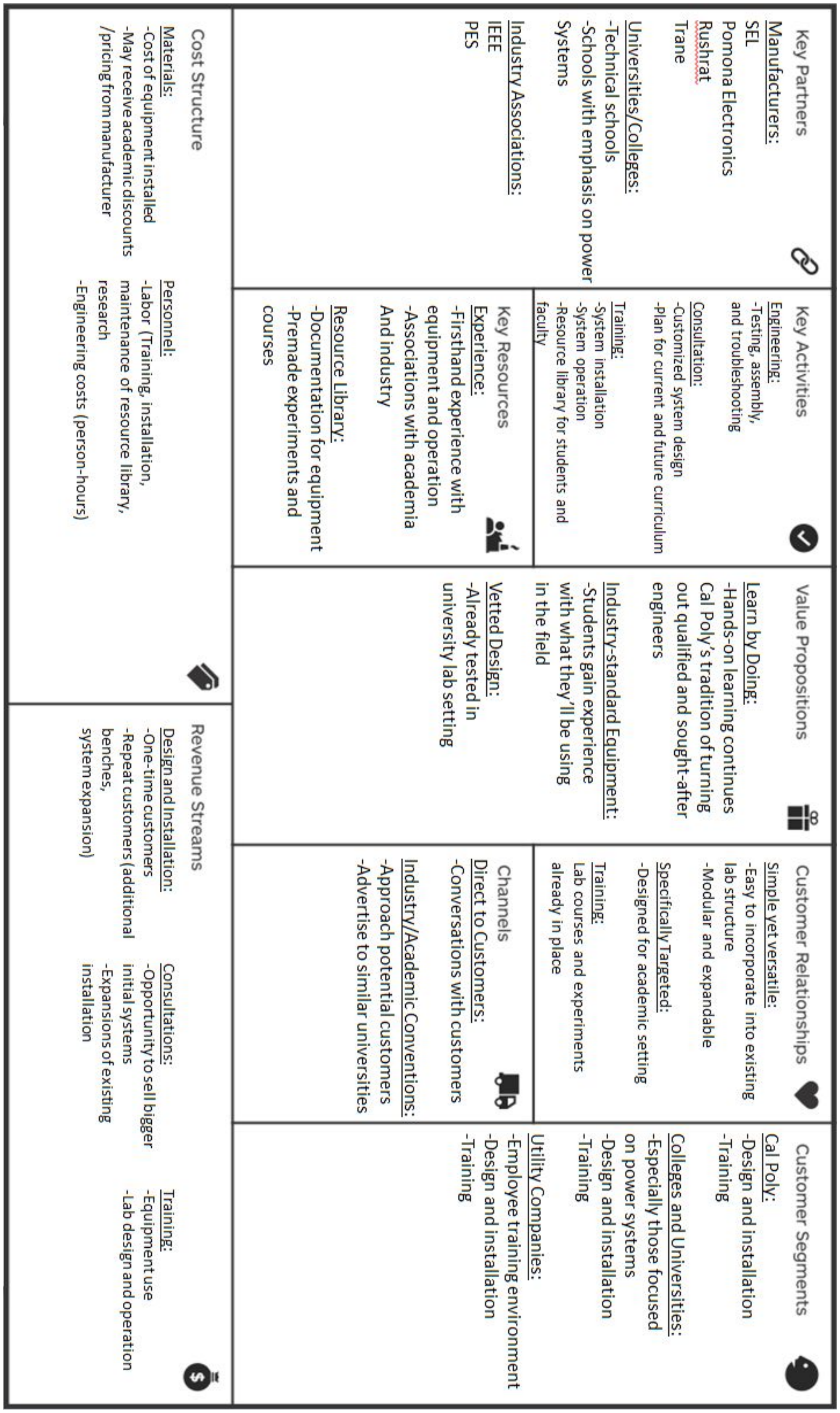

Figure 5. Business Canvas

Project Name: Microgrid Laboratory System Protection

Unmet Customer Need: Cal Poly's power systems lab provides only basic experimental instruction with electromechanical relays. The existing curriculum does not reflect the prevalence in industry of solid-state microprocessor-based relays and other protection devices.

Unique Value Proposition: The microgrid Laboratory System Protection project gives the University a "protection lab in a box" that gives students highly-sought practical experience with modern protection systems, directly preparing them for their careers.

Target Customer: University Electrical Engineering Colleges, particularly Cal Poly.

Positioning: State of the art protection lab in a box for future state of the art power engineers

Pricing and Availability:
- $22000
- Senior Project Expo
- Spring 2017

Product Objectives:
- Adoption for all power and microgrid labs at Cal Poly
- Adoption by other universities

Customer Benefits:
- Industry standard equipment
- Basis for future labs
- Make the curriculum match the state of modern protection engineering

Sustainable Differentiation:
- Enhance Cal Poly's "Learn by Doing" reputation
- Highly-qualified new engineers ready to work
- Reflects emerging trends in industry

Disruptive Go-to-Market:
- Tech talks / info sessions
- Project demo
- Occupy a bench in lab permanently
- Industry conference presentation

Figure 6. Marketing Data Sheet

VII. Market Requirements

Table 5: Market Requirements

Affordable Cost for Universities	• Affordable for academic institutions with limited budgets • Standard package - standard cost makes needed funding easy to estimate
Plug and Play	• Fully characterized system with lab experiments already developed
Equipment	• Industry-standard protection equipment prepares students for today's power systems • Includes relay-operated circuit breakers • Compatible with test leads, benches, other equipment found in university lab setups
Region of Service	• Initial customers of interest reside in United States and Canada • Institutions with power systems laboratory courses, give them an upgrade • Institutions without power systems laboratory courses, give them one
New System Set-up	• Full system creation will be done for those institutions wanting to develop a protection engineering lab course
Existing System Expansion	• Ability to network individual units together for microgrid studies • Additional components may be added to functional units as desired

VIII. Engineering Requirements and Specifications

Detailed in the table below are the engineering requirements and their relation to the marketing requirements.

Table 6. Engineering Requirements

	Engineering Requirement	Marketing Requirement	Reasoning
1	Design simulated transmission lines of 100m	Cost	Transmission lines are bulky and expensive. To create a compact packaging, simulated transmission lines must be used.
2	Design must be contained in compact package bench (approx. 4ftx10ft) suitable for three student teams to work on	Cost	A compact bench will allow universities to allocate space for a new laboratory much easier thus making it more cost efficient.
3	Design a 3Φ bidirectional power system that contains transformers, transmission lines, and a motor. Include protection relays with pre-programmed relay setting profiles.	Plug and Play	The package must contain these components with installed protection capabilities. Pre-programmed relay settings will ensure “Plug and Play” feature.
4	Design the power protection scheme to utilize SEL relays.	Industry Standard Relay Protection (Equipment)	SEL is the industry standard for power relay protection therefore this is the only option of equipment to incorporate in the design to ensure students education in power system protection is relevant.
5	Design power system to utilize relay operated circuit breakers that accept trip signals from protection equipment and/or users.	Relay Operated Circuit Breakers (Equipment)	The circuit breakers included in the power system need to have the flexibility to trip via relay and controlled by either the protection equipment and/or the user.
6	Design power system to	Compatibility	This creates a familiarity with

	utilize banana plug leads to change configurations	(Equipment)	other university laboratory equipment and allows the university to utilize pre-existing equipment
7	Design power system to mimic typical power systems of the U.S.A. and Canada	Region of Service	This further ensures the laboratory’s relevance to industry to deliver the best education
8	Design power system to be fully operational on delivery	New System Set-up	This increases the marketability to universities with no previous power system protection laboratory
9	Design power system to allow system expansion tie ins at power buses	Existing System Expansion	This allows the product to be diverse and customizable to each university's’ needs and desires for the their power system laboratory

Functional Decomposition:

Level 0: The project contains four inputs and two outputs as seen in Figure 7. The inputs are two 240V, 60Hz, 3ɸ power inputs, 125VDC power input, and relay settings (via serial connector). The outputs are the relay status and fault event reports (via serial connector). These are described in more detail in Table 7.

Figure 7: Microgrid Laboratory System Protection Level 0 Block Diagram

Table 7: Microgrid Laboratory System Protection Level 0 Decomposition Functionality

Name	**Input/Output**	**Type**	**Description**
240V, 60Hz, 3ϕ	Input	Three wires	This input will come from an infinite bus such as a utility source.
240V, 60Hz, 3ϕ	Input	Three wires	This input will come from an infinite bus such as a utility source.
125VDC	Input	Two wires	This input can come from a generator or any other source that can provide a constant 125VDC input.
Relay Settings	Input	Serial wire	Settings are sent to the system through the use of a computer via a serial wire.
Relay Status	Output	Serial wire	The relay status is received through the use of a computer via a serial wire.
Fault Event Reports	Output	Serial wire	The fault event reports are received through the use of a computer via a serial wire.

Level 1: Contained in this level of the project are the SEL relays (2032, 311L, 387, 587, 710), transformers, transmission lines, induction motors and circuit breakers as seen in Figure 8.

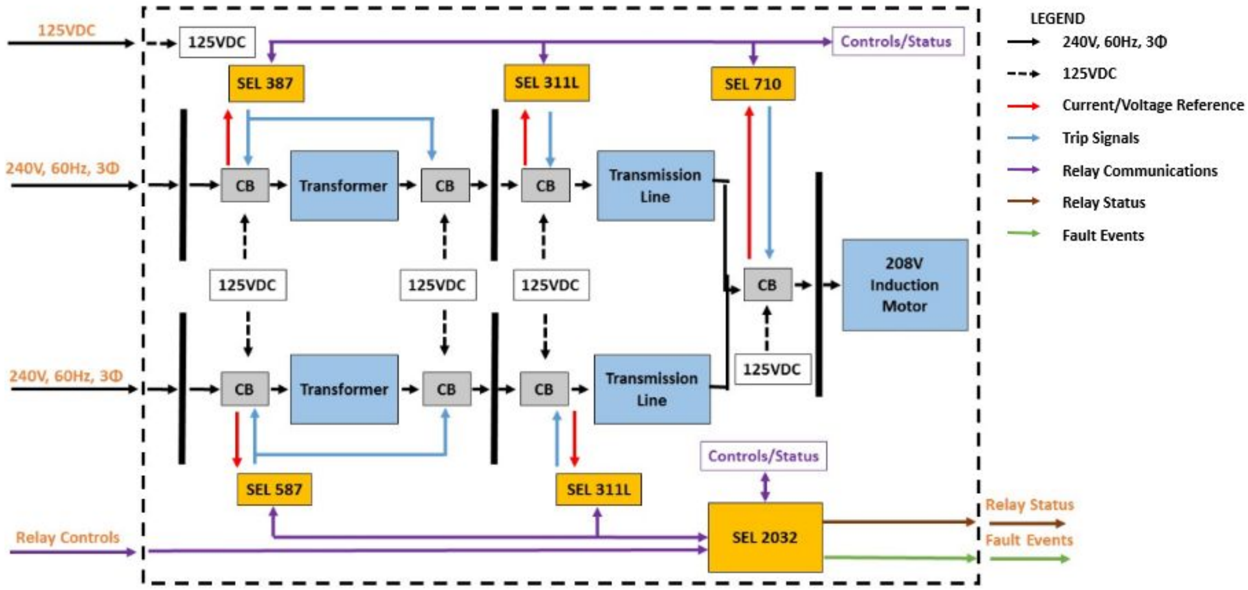

Figure 8: Microgrid Laboratory System Protection Level 1 Block Diagram

Testing/Verification Plan:

The items required to be verified are outlined in Table 8 below. The project is laid out to be verified in smaller steps to ensure ease of troubleshooting.

Table 8: Verification Plan

Engineering Requirement/Specifications	Plan of Verification
SEL 311L Radial and Differential protection settings for radial system.	Connect SEL 311L to power system without any other relays active and set faults to ensure settings are correct. Then operate
SEL 387 Radial and Differential protection settings for radial system.	Connect SEL 387 to power system without any other relays active and set faults to ensure settings are correct.
SEL 587 Radial and Differential protection settings for radial system.	Connect SEL 587 to power system without any other relays active and set faults to ensure settings are correct.
SEL 710 settings for radial system.	Connect SEL 710 to power system without any other relays active and set faults to ensure settings are correct.

Power System Protection Scheme verification for radial system.	Connect SEL 311L, 387, 587, and 710 to power system and set faults to ensure settings are correct and relays operate in protection scheme after integration.
Interface SEL 2032 Communications Processor.	Connect the SEL 2032 to the SEL 311L, 387, 587, and 710 protection relays. Verify that the SEL 2032 can send settings to the protection relays and retrieve relay status/fault event reports.
SEL 311L Radial and Differential protection settings for bidirectional system.	Reconnect SEL 311L to power system without any other relays active and set faults to ensure settings are correct.
SEL 387 Radial and Differential protection settings for bidirectional system.	Reconnect SEL 387 to power system without any other relays active and set faults to ensure settings are correct.
SEL 587 Radial and Differential protection settings for bidirectional system.	Reconnect SEL 587 to power system without any other relays active and set faults to ensure settings are correct.
SEL 710 settings for bidirectional system.	Reconnect SEL 710 to power system without any other relays active and set faults to ensure settings are correct.
Power System Protection Scheme verification for bidirectional system.	Connect SEL 311L, 387, 587, and 710 to power system and set faults to ensure settings are correct and relays operate in protection scheme after integration.

Responsibilities of Team Members:

Overall, all team members are responsible for successful completion of this project, but subject matter experts (SME) have been declared for separate relays to ensure work is evenly split. Ian Hellman-Wylie is the subject matter expert for the SEL 710, Joey Navarro is the subject matter expert for the SEL 311L, and Kenan Pretzer is the subject matter expert for the SEL 387/587. Below are detailed items each member is responsible for knowing as the SME.

> **Ian Hellman-Wylie**: Responsible as the SME for the SEL 710. This requires an understanding of motor protection schemes and how they correlate to SEL 710 relay settings. Must be able to interface with SEL software to the SEL 710 for settings transfer. Must interface the SEL 710 to the SEL 2032.

Joey Navarro: Responsible as the SME for the SEL 311L. This requires an understanding of transmission line protection schemes and how they correlate to SEL 311L relay settings. Must be able to interface with SEL software to the SEL 311L for settings transfer. Must interface the SEL 311L to the SEL 2032.

Kenan Pretzer: Responsible as the SME for the SEL 387/587. This requires an understanding of transformer protection schemes and how they correlate to SEL 387/587 relay settings. Must be able to interface with SEL software to the SEL 387/587 for settings transfer. Must interface the SEL 387/587 to the SEL 2032.

IX. Schedule and Milestones

Deadlines:

Below in Table 9, are seven deliverables laid out for this project organized by target deadlines.

Table 9: Deliverable Deadlines

Deadlines	**Deliverable**
9/26/2016	Proposal to Power Faculty
10/24/2016	Present Radial Protection Scheme
11/21/2016	Present Phase 1: Radial Protection Scheme with SEL 2032
1/23/2016	Present Bidirectional Protection Scheme
2/06/2016	Present Phase 2: Bidirectional Scheme with SEL 2032
2/13/2016	Senior Project Design Review
6/2/2016	Senior Project Expo

Gantt Charts:

Below in Figure 9/10, is the gantt chart for the work required in this project. This is a tentative schedule and has flexibility within its time frame due to the early start and coordination with our advisor. This flexibility will allow us the time to fully troubleshoot any issues encountered during the project.

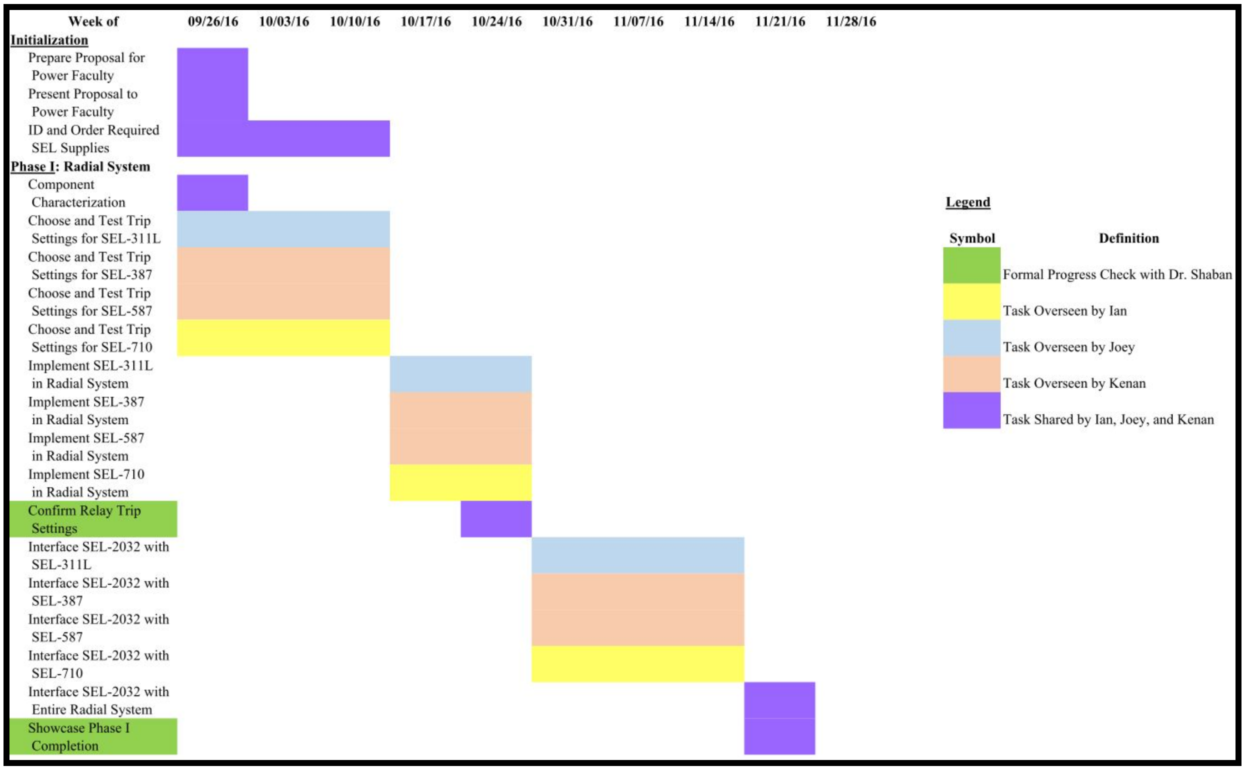

Figure 9. Project Schedule Fall 2016

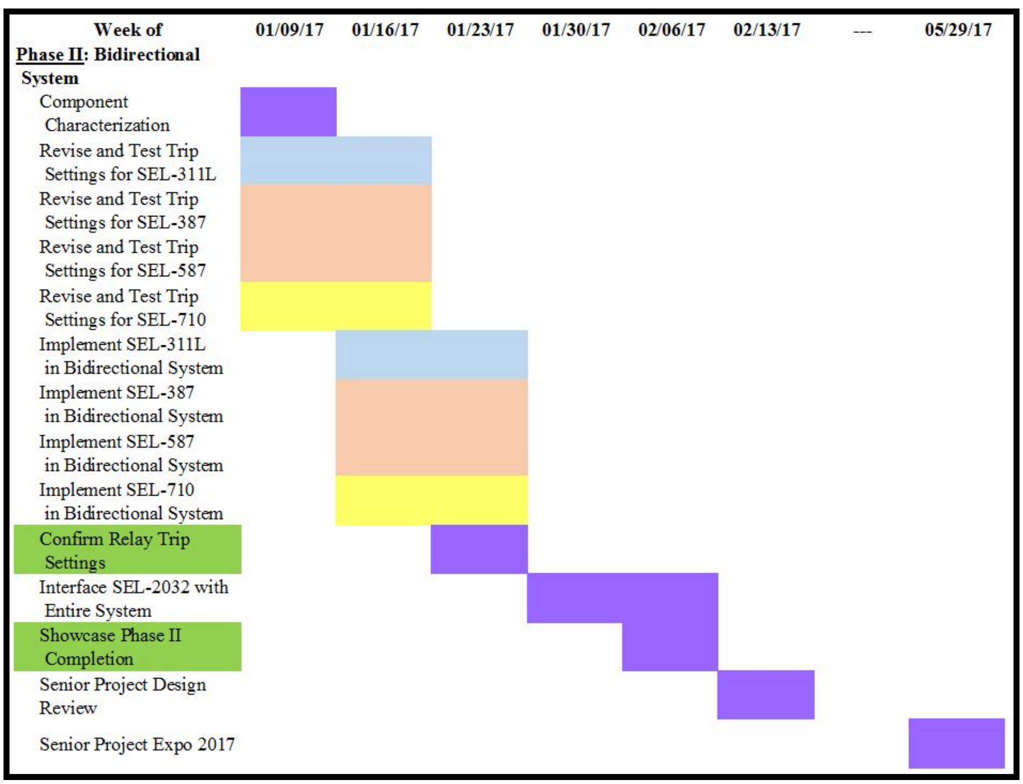

Figure 10. Project Schedule Winter/Spring 2016

High Risk Items:

There are two major items that threaten this timeline. The first being the integration of all relays on the power system to provide adequate protection for a given scheme. The second being the interfacing of the SEL 2032 Communications Processor providing remote accessibility.

X. References

[1] U.S. Energy Information Administration. (2015, Dec. 22). *What is the electric power grid and what are some challenges it faces?* [Online]. Available: http://www.eia.gov/energyexplained/index.cfm?page=electricity_delivery

General information about the U.S. power grid for background information.

[2] Microgrids at Berkeley Lab. (2016). *About Microgrids* [Online]. Available: https://building-microgrid.lbl.gov/about-microgrids

Information about microgrids. For the purposes of this project, the most information provided is probably a concise definition of a microgrid to distinguish it from the larger national grid.

[3] A. Shaban, "Power Systems Laboratory Manual," Cal Poly San Luis Obispo, San Luis Obispo, CA. Revised Spring 2016.

Overall description of Cal Poly's current power systems lab. Experiment 8 is relay coordination with only CO-6 electromechanical relays and no relay-controlled circuit breakers. This demonstrates the limitations of Cal Poly's existing curriculum and thus the gap our project will fill in protection engineering education.

[4] "University Education and Research Programs in the US and Canada for Power and Energy Engineering Careers," *http://www.ieee-pes.org/*, Apr-2015. [Online]. Available: http://www.ieee-pes.org/images/files/pdf/peec-survey/2014_peec_survey_university_program_descriptions.pdf. [Accessed: 21-Oct-2016].

Self reported data to IEEE Power and Energy Society. Reported data includes all universities that have programs that contain an emphasis on Power Engineering, their courses, research areas, program contacts, and other pertinent information about the programs.

Appendix A: Senior Project Analysis

Project Title: Microgrid Laboratory System Protection (MLSP)
Students: Ian Hellman-Wylie, Joey Navarro, Kenan Pretzer
Advisor: Ali Shaban

1. Summary of Functional Requirements
   a. Overall Capabilities
      i. The MLSP is a laboratory power system to be used for system analysis and protection experiments in a university setting.
      ii. The MLSP will be composed of simulated transmission lines, transformers, passive resistive loads, and a motor load, protective relays and circuit breakers.
      iii. The system shall allow faults to be inserted at arbitrary points in the system.
      iv. The system shall use solid-state microprocessor-based relays to detect faults and operate low-voltage air circuit breakers to clear faults.
2. Primary Constraints
   a. Challenges associated with the project
      i. Relay coordination becomes complicated as each relay provides primary protection for part of the system and backup protection for other parts.
      ii. SEL relays are somewhat costly for a university, and must be purchased from a single supplier.
      iii. Initial prototype will be physically complex in terms of wiring.
      iv. Relay settings and programming will require a deep understanding of SEL programming as well as protection theory, requiring the project team to dedicate considerable time to research and troubleshooting.
3. Economic
   a. What economic impacts result from the project?
      i. Human Capital: This project can generate capital capable of supporting jobs in assembly, sales, support, and application engineering.
      ii. Financial Capital: Customers in our target market will be able to provide practical laboratory experience to engineering students at an affordable price.
      iii. Natural Capital: This project uses microprocessor-based electronic components, which are costly to recycle.
      iv. Costs: The price of the MLSP is largely defined by hardware. SEL relays cost several thousand dollars each, and this forms the bulk of the cost.

Other components such as test leads, small motors, and laboratory transformers are routinely part of existing power laboratories. The cost may be reduced somewhat on a case by case basis, as SEL routinely offers discounts for academic institutions with dedicated power systems curricula.

Table A.1: Project Costs

Item	**Qty.**	**Supplier**	**Price Each ($)**
10Ω Power Resistor	6	Eisenmann	28
25Ω Power Resistor	3	Eisenmann	35
100 mH Inductor	6	ERSE	19
1/3hp Induction Motor	1	Trane	90
SEL-387	1	SEL	5250
SEL-587	1	SEL	2080
SEL-311L	1	SEL	5000
SEL-710	1	SEL	2500
SEL-2032	1	SEL	2840
Custom Circuit Breaker	7	Project Team	314
TOTAL			20345

4. If manufactured on a commercial basis:
    a. Expect 3 systems to be sold in first year.
    b. The total cost of the prototype, from Table A.1, is $20,345.
    c. Estimated purchase price for each package is $40,000.
    d. First year profit at estimated purchase price will be $58,965 less labor.
    e. Estimated cost for user to operate device per unit time: At three hours of operation per week, 2 times a week, for 10 weeks (for a typical 10-week university lab course), the total running time would be 60 hours maximum per quarter. At an average current draw of 1 A at 240 V at $0.19/kWh, the cost per year is $8.20.
5. Environmental
    a. The main environmental impact of the project comes from the manufacture of the components, especially the relays. Manufacturing electronic equipment indirectly

affects the environment through the use of chemicals, in addition to factory emissions and energy usage. As with all electronic components, proper recycling procedures are necessary to prevent toxic chemicals and heavy metals from being released into the environment.

6. Manufacturability
    a. The project requires assembly, but no primary manufacturing. Complete components are purchased from producers, and wired together with test leads using common electrical wiring practices.
7. Sustainability
    a. Issues or challenges maintaining the completed project: Minimal. The project uses laboratory equipment designed to be robust and reliable, even under heavy use.
    b. Project impacts on the sustainable use of resources: The project uses solid-state electronic devices, which use materials which must be mined around the world, potentially impacting the environment.
    c. Upgrades that would improve the design of the project: The addition of dedicated generation in place of or in addition to the grid, particularly solar or wind, would provide additional scope for experiments as well as advancing renewable energy.
    d. Issues or challenges upgrading the design: Project is designed to be easily modified. The topology of the system can be changed simply by adding components using laboratory test leads, or by removing components.
8. Ethical Considerations
    a. Ethical implications of product design: Minimal outside of safety. It is critical to deliver a product to universities that provides quality instruction in power system protection while ensuring the safety of students, faculty, and ensuring good return on investment for the university.
9. Health and Safety
    a. Health and safety concerns associated with the design, manufacture, or use of the project: The project operates at currents and voltages that may present a safety hazard if laboratory safety regulations are not followed. Users should follow electrical safety regulations and best practices appropriate to their situation.
10. Social and Political
    a. Social and political issues associated with design, use, or manufacture of the project: Reliable, economical, and safe power systems benefit society, making affordable electrical power available to individuals and businesses.
    b. Impacts on society, including direct and indirect stakeholders: Quality power systems programs produce quality engineering graduates. High quality personnel will benefit the power distribution industry directly by designing and maintaining reliable and safe systems. This gives lower prices and higher up-time to consumers, and increased profits and better service to utilities.

11. Development:
    a. The project uses industry-standard equipment. Support from the manufacturer, including documentation, application guides, and training, reduces development time and cost. As the project is being developed by current power systems students, the project is uniquely tailored to the needs of future students.