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Title: A Microgrid Design Case Study: Synchrophasor Placement and Development of a Protection Laboratory for the Oregon State University - Corvallis Campus

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In the past two years, Oregon State University (OSU) Corvallis campus suffered several power outages. The estimated cost of one of those outages was close to a million dollars worth of equipment and impact on research projects. Meanwhile, the campus grid operates with severely aging power assets. The reliability of campus grid operations impact students, faculty and staff and is becoming a general concern. The university, as many other institutions that have critical loads within particularly weak power system areas, is seeking for a sustainable solution in order to cope with these reliability issues.

Moreover, due to the fast speed of power system upgrades, integration of renewable energy resources, increasing demands for grid reliability, and aging and retiring infrastructure, there is a growing set of operational and hands-on requirements for

the power system students who graduate from the college. Based on the feedback from job interviews and the local industry, utilities are more willing to hire students that familiar with both hardware and software operation of modern power system.

Motivated by the challenges described above, we propose two complementary research efforts: a microgrid synchrophasor placement approach, and the design of a power system protection laboratory. OSU campus grid is supported by the main grid with several feeders. There is an advanced cogeneration facility, and two large photovoltaic arrays inside the campus and owned by OSU. Also, many buildings are equipped with smart meters and energy management systems. Therefore, the campus grid has the potential to operate itself as a microgrid. Before applying microgrids technology to the OSU campus grid, the topic of optimization of synchrophasors placement will be an important initial step.

In addition, for a microprocessor-based relay, which is widely used in a typical microgrid, the principle and function are the main contents for the new power system curriculum. It is also including the coordination between multiple relays in both a radial system and a looped system by using a software that widely used in industry area. By using the relay testing system, an advanced microprocessor-based relay, which is commonly used in industry, will be tested as well.

A Microgrid Design Case Study: Synchrophasor Placement and
Development of a Protection Laboratory for the Oregon State
University - Corvallis Campus

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Chen Huo, Author

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Chapter 1: Introduction

Smart grid technologies are considered as the evolution of electricity grids, and have been promoted in the energy systems field for many years. They are also regarded to be the solution for balancing increasing energy demand, growing renewable energy penetration, rising environmental pollution, and cumulative energy costs. However, what is exactly a smart grid, or what makes our current power grid smarter? Two organizations in North America, the Department of Energy (DOE) and the Electric Power Research Institute (EPRI), gave their definitions for smart grids:

- U.S. DOE: *"Grid 2030 envisions a fully automated power delivery network that monitors and controls every customer and node, ensuring two-way flow of information and electricity between the power plant and the appliance, and all points in between [4]."*

- EPRI: *"The term 'Smart Grid' refers to a modernization of the electricity delivery system so it monitors, protects, and automatically optimizes the operation of its interconnected elements-from the central and distributed generator through the high-voltage network and distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliance, and other household devices [5]."*

From the definitions above we can see, when one is talking about smart grid, the concept of it is all about evolution instead of innovation. For the transmission level grid, based on the current system, this is achieved by implementing advanced communications equipment, control systems and protection schemes. In that way, power

grids will become more robust, reliable, economical, and environmentally friendly.

For a distribution level power system, the evolution is reflected by: first of all, implementing Distributed Energy Resources (DER), either self controlled or controlled by local distribution system operators; secondly, developing the communications system between end-users and utilities in order to enable local energy management; thirdly, using the technologies which are mature in transmission level, such as dynamic control techniques [6].

1.1 Microgrids - the Evolution of Modern Distribution System

The modern concept of microgrids was proposed after the July 2012 India blackout. Before this event, microgrids were considered more a typical power grid structure developed for some special area, like an island or some small villages which are far away from the main power grid or centralized power plants. However, the concept of microgrids is now considered as a solution to save energy, since it generates power locally, and a solution to increasing the reliability of the power system. Some even characterized it as the "building blocks of smart grids", and believing that it is perhaps the most promising and novel network structure [7]. This section will provide a brief introduction about microgrids.

1.1.1   What is a Microgrid?

There is a variety of definitions given by different countries or academic organizations.

The following are the most authoritative definitions in North America and Europe:

- U.S. DOE: *"A group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode [8]."*

- EU research project: *"Microgrids comprise low voltage distribution systems with distributed energy resources (DER) (micro-turbines, fuel cells, PV, etc.) together with storage devices (flywheels, energy capacitors and batteries) and flexible loads. Such systems can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid. The operation of microsources in the network can provide distinct benefits to the overall system performance, if managed and coordinated efficiently [9]."*

From both definitions, the concept of microgrid technology contains two main characteristics. First, the implementation of various DERs. Electricity is transferred from renewable sources, generated and consumed locally. This will not only reduce the contamination since it relies less on centralized fossil fuel power plants, but also enhances energy efficiency since there is less energy losses compared with long distance power transmission. From the customers' point of view, it also reduces the electricity bill, and even allows to sell electricity back to the upstream grid. From the utilities' point of view, microgrid technology could potentially help manage demand. DERs also help realizing the concept of dynamic pricing, which refers to the scenario where energy prices will be calculated by specific software or apps in real time, showing that the cheapest source of energy is from the main grid or the local

generation. By doing this, it is possible to shift or even shave the peak load demand. The second characteristic is two operation modes, which are a) connected with main grid and b) islanded mode. This special function will enhance the reliability of the local distribution system.

1.1.2   Challenges for Microgrids

One of the main challenges is the dispatch of the generation in microgrid because the large scale penetration of renewable energy for a particular microgrid, and nearly all of these renewable energy are difficult to predict. Therefore, optimizing between the generation and the consumption is becoming a significant challenge. This kind of situation is requiring a powerful measuring and monitoring control system. Synchrophasor placement is becoming essential for such a system. This will be introduced in Chapter 3. In fact, the capabilities of the control system is the condition that distinguishes a microgrid from a distribution system with distributed energy resources [10].

Another challenge is the protection issue. This can be exemplified by using a general microgrid model as shown in Figure 1.1 [1]. This microgrid is connected with the main grid by a transformer. It can switch between connected mode and islanded mode by closing or opening the circuit breakers 0 and 1. For the connected mode, circuit breakers 0 and 1 are closed, and open for islanded mode. Each load is coupled with a Distributed Energy Resource. Circuit breakers 3.2 and 6.2 are normally open.
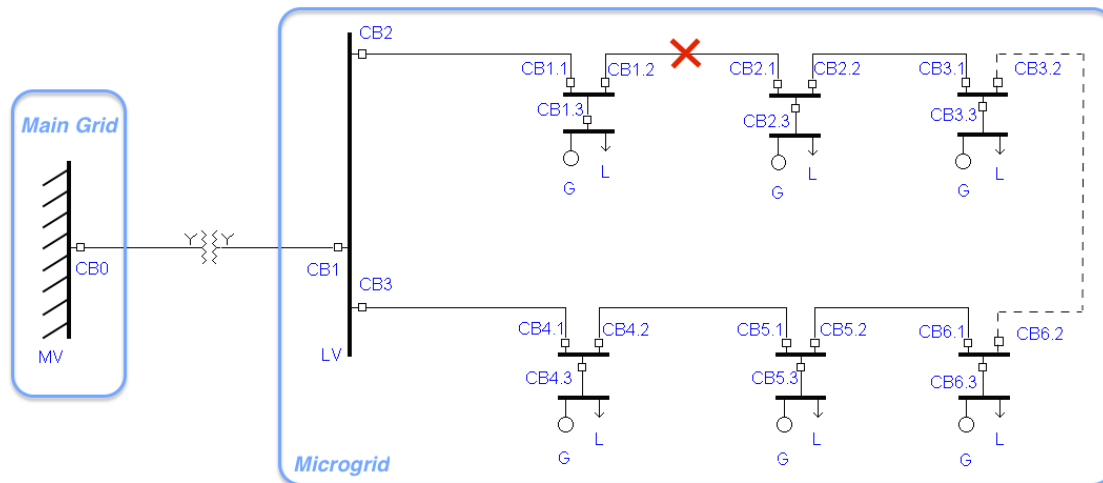
Figure 1.1: A protection example for a typical microgrid [1].

They can close so that this microgrid operates as a looped system. If there is a fault between circuit breakers 1.2 and 2.1, as shown in Figure 1.1, the difference of the fault current between connected mode and islanded mode is the absence of the high short-circuit current supplied by the main grid. Therefore, if circuit breakers 1.2 and 2.1 keep the relay settings used for the connecting mode during the islanded mode, or the other way around, keep the settings used for islanded mode during the connected mode, there will be a sensitivity and selectivity problem with isolating this fault. This issue will be even more significant and complicated for a larger system for example a campus grid. Some other challenges include the information and communication issue, conventional droop control for rural low voltage networks [11], legal challenges, and economic issues.

1.1.3 State of the Art

As one of the main smart grid technology topics, microgrid technology or structures are becoming more and more popular. Figure 1.2 shows the microgrid capacity in different regions of the world by the year 2012 [2]. North America, as the largest capacity area, takes almost three-fourths of the global capacity. Followed by Europe, with capacity of 384 MW. The capacity of Asia Pacific mainly refers to Japan. The majority of projects in South Korea and China are small-scale or laboratory based demonstration projects.
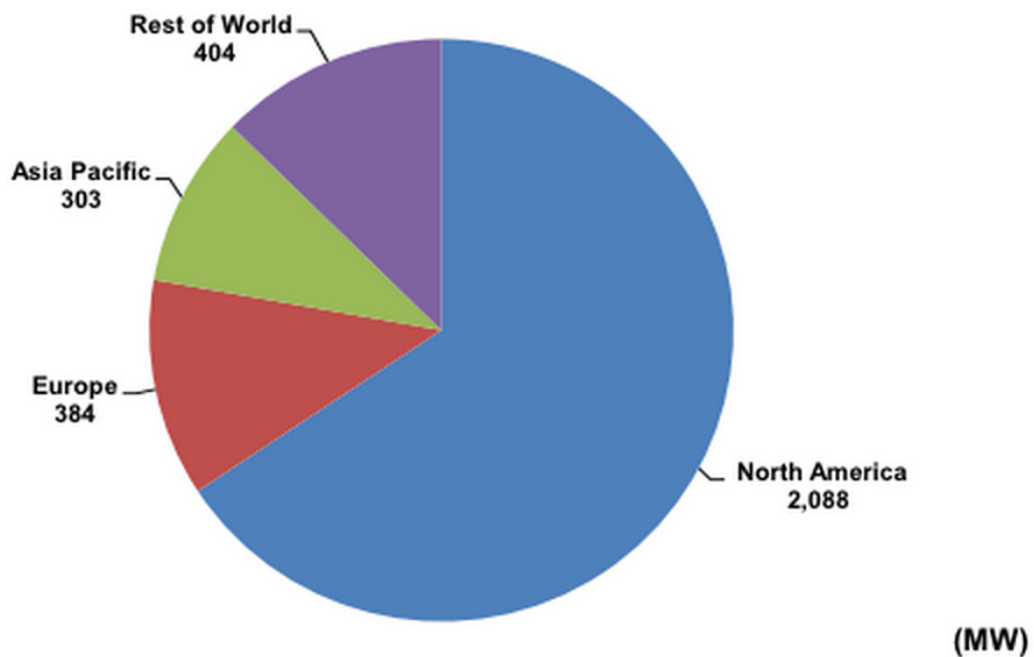
Figure 1.2: Microgrids capacity by different regions of the world [2].

In the US, there are many smart grid and microgrid projects, especially those

based on universities. At the Illinois Institute of Technology (IIT) main campus, Chicago, the investment on the campus based microgrid project is currently 14 million dollars. This project is equipped with new distributed energy resources, such as roof-top solar panels, wind generation units, flow batteries, and charging stations for electric vehicles (EV). It is also applying smart building automation technology, such as building controllers, Zigbee sensor networks, and controllable loads. IIT announces that the new campus microgrid will save approximately from 0.5 million to 1.5 million dollars per year by reducing electricity peak demand, electricity usage, and providing ancillary services to the grid [12]. They claim that the campus microgrid project is not only about saving the electricity bills, but also providing a distribution system that virtually never fails.

At the University of California San Diego (UCSD), microgrid technology has been considered as the solution to keeping the lights on. Similarly to the project at IIT, by implementing distributed energy resources (2.8 MW fuel cell, 2.3 MW roof-top photovoltaic panels, and 30 MW cogeneration), UCSD claims that 92 percent of the electricity usage will be covered. This will save about 8 million dollars, when compared with importing energy from the main grid [13]. Beyond these two universities above, Table 1.1 shows a summary of developed campus microgrid projects in the US. In addition, University of Hawaii, University of Minnesota, University of Wisconsin, Arizona State University, Ohio State University, Oregon State University, and others, are developing their own campus based microgrids as well.

University	Energy Storage	Generation
Colorado State	None	5.3 MW solar biomass boiler
Illinois Institute of Technology	500 kWh battery	1.4 MW solar 8MW gas turbines
Santa Clara University	None	1 MW solar 6.5 MW steam/elec
University of California Davis	20M gal H2O	solar steam plant
University of California Irvine	4.5M gal H2O	1.2 MW solar 13.5 MW gas
University of California San Diego	3.8M gal H2O	2.2 MW solar 27 MW gas steam
University of Texas Austin	4M gal H2O	500 kW solar 140 MW steam
University of New Mexico	None	500 kW solar 8.5 MW steam
University of Washington	4M gal H2O	steam

Table 1.1: University campus based microgrids projects in U.S.

At a larger scale, Japan is always enthusiastic with respect to developing micro-grids technology due to their geological characteristics (multi-island) and frequent earthquakes. The Hachinohe project in the Aomori Prefecture was the first stage of microgrids development in Japan. It operated from October 2005 to March 2008. In 2007, it operated in islanded mode for one week [14]. Like other modern microgrid projects, it only used renewable energy resources to provide electricity and heat-

ing. Although this project was abandoned in 2008 due to funding issues, Japanese engineers and microgrid operators achieved remarkable progress and accumulated a wealth of experience in this area. After that, Japan developed several other microgrid demonstration projects. Some of them even have been commercialized. The concept of microgrids has been extended to 'Smart Community' in the region [15].

Besides North America and Japan, Europe is another region extremely interested in microgrids. A research program called 'More Microgrids', funded partly by the European Union and partly by private investors, started in 2006. The total budget is 8.5 million € [16]. This program is aimed at increasing the penetration of microgeneration in the current power network through the extension of the microgrids concept. Meanwhile, they are investigating new microgenerator control strategies and alternative network designs, developing new tools for multi-microgrids management operation, and standardizing technical and commercial protocols [17]. This program implemented eight projects in different European countries. Compared to the other pilot projects or those operated in laboratories for research, the one in Bornholm Island, Denmark, become widely recognized as it operated in islanded mode for several months. An accident cut off the underwater high voltage cable, which is the only connection between the island and the main grid. However, the local generation (mostly wind) and control schemes kept 28,000 residents there living their daily life [10].

1.2   Synchrophasor Placement

The topic of synchrophasor placement in a transmission level power system has been discussed for a relatively long time. Electrical power engineers are trying to use the minimum number of synchrophasors or find the optimal locations for placing synchrophasors in order to achieve full monitoring of the power grid. For many smart grid or microgrid projects, especially those in distribution level and based on university campus, synchrophasors placement is also one of the most essential and uncharted topics. In this Section, we will give a brief introduction about the research contribution of this work in regards to this topic.

1.2.1   Synchrophasor Technology

A synchrophasor, or Phasor Measurement Unit (PMU), is a device used to monitor the power grid by measuring voltage magnitude, voltage angle, and frequency. It records data 60 times per second. By using a Global Positioning System (GPS) clock time stamp, it can synchronize data with other synchrophasors. A typical synchrophasor technology system contains GPS clocks, synchrophasors, a Phasor Data Concentrator (PDC), communication equipment, and visualization software.

Having a good monitoring and alarm system (e.g., synchrophasors) is of significance in smart grids. Synchrophasor technology has become more recognizable in industry over time and could meet the above need. Its synchronized and high-resolution monitoring system provides strong advantages in both real-time and off-line appli-

cations [18]. However, it is still relatively new and needs further study and practice. The real-time applications could help with data visualization, situational awareness, monitoring and alarming, protection, and control. The off-line applications would assist system planning, analysis, assessment, and other long term applications. In the context of microgrids, since the system inertia and damping are reduced, it is much easier to have voltage and frequency instabilities that could cause system failures. Synchrophasors can be very helpful for sensing those issues and enhancing control strategies.

1.2.2   Oregon State University Campus Grid

The OSU campus is supported with multiple feeders, as shown in Figure 1.3. An advanced cogeneration facility (Energy Center) and two large photovoltaic arrays are coupled with the campus grid. The PV plant capacities are $5.5MW$ and $1.5MW$ respectively. This will cover one-third of the campus peak demand. In addition, there are 34 standby generators and 6 trailer mounted generators used for auxiliary generation. Many buildings on campus are equipped with smart meters and energy management systems. 80% of the buildings are controlled centrally at the Energy Center [19]. OSU has the potential to operate itself as a smart grid that is much more economical in energy consumption, and even isolate itself from the main grid as a microgrid. OSU initialized a smart grid demonstration project and started exploring methodologies to fulfill its smart grid potential.

SW Campus Way

SW Jefferson Way

Energy Center

PP&L Conn
PP&L 20.8kV
OSU 20.8kV
OSU 4160V
OSU secondary
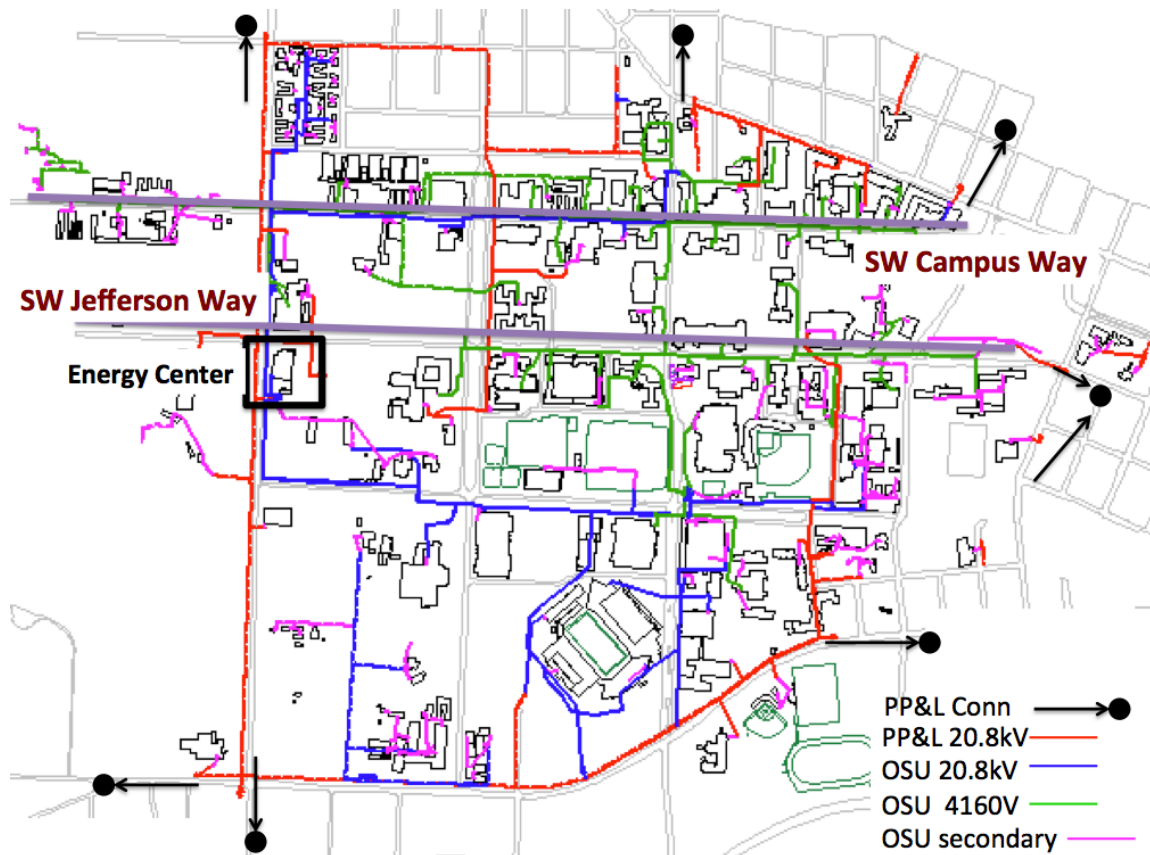
Figure 1.3: The overview of OSU campus grid.

Based on Figure 1.3, there are two voltage levels, $20.8kV$ and $4.16kV$. The blue $20.8kV$ and green $4.16kV$ distribution lines are owned by OSU, and the red $20.8kV$ lines are owned by Pacific Power. These two voltage levels are connected and transformed by three substations on campus, the 26th St. substation, the 35th St. substation, and the Coliseum substation. The green $4.16kV$ system is an old distribution loop. It supports almost all the remaining older buildings. The blue $20.8kV$ system is a newer one that aims at improving the reliability of the campus grid since the campus capacity and load demand has been steadily growing for the
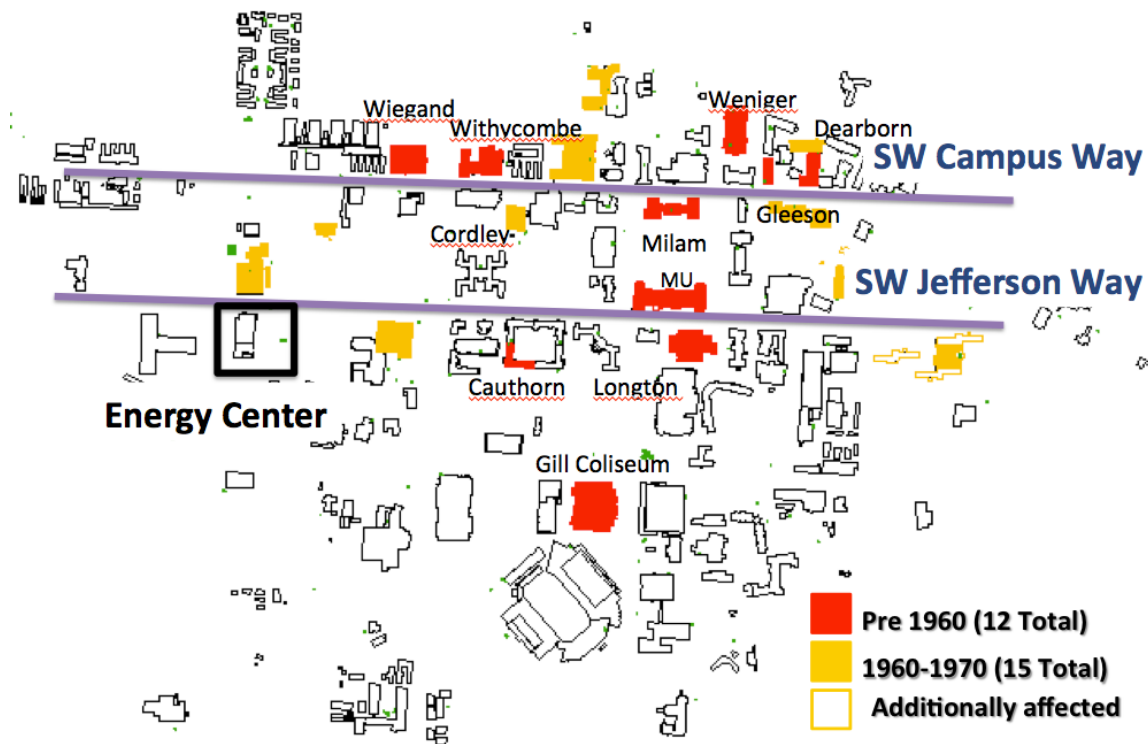
Figure 1.4: Layout of aging transformers in OSU campus.

past few years.

There are more than 120 transformers in our campus. Figure 1.4 indicates the condition of the aging ones. The yellow labeled buildings indicate that they are fed by transformers older than 1970. Those red buildings have transformers older than 1960. The oldest one was born in the year 1940, serving the Memorial Union (MU) for more than 75 years.

Number of buses	Number of branches	Number of transformers	Number of generators	Number of loads
285	288	124	4	185 (24.6MW)

Table 1.2: Case information for the OSU campus grid model

The campus grid data are provided by OSU facilities. Based on that information, we built a power flow model geographically and electrically in PowerWorld. Table 1.1 is a brief summary of the case information. A few assumptions and calculations were made in this model: 1) the values of line impedance are approximated through the electrical code of cables and the geographical distance between each node; 2) the active power consumption of each building is assumed to be about 80% of the listed peak demand, and reactive power is postulated as 10kVar for each load in order to build a representative power flow snapshot; 3) the impedance of the transformers are approximated according to their power ratings. Figure 1.5 shows the OSU campus grid model in PowerWorld. All the colors correspond to the description above. Other low voltage levels at the secondary side of transformers are not noted in Figure 1.5. Coming from the North and Southwest of campus, there are two main feeders/substations to the main grid that are equivalenced to two representative generators in this model.

1.3   Power System Protection Laboratory

A portion of this Thesis is dedicated to the development of a power system protection laboratory with a focus in microgrid design and protection. This is useful in
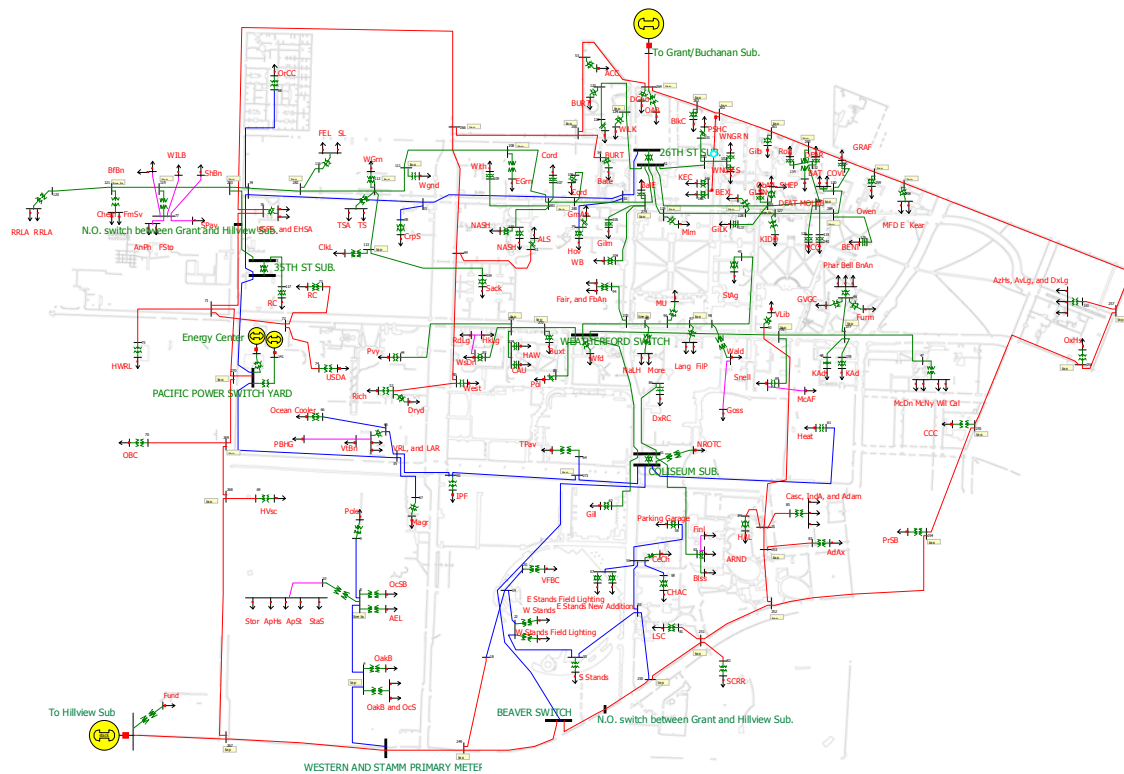
Figure 1.5: Oregon State University campus grid model in PowerWorld.

both education and training. The modern power system is changing rapidly. New techniques and advanced equipment are widely used. With the purpose of keeping the power system reliable and sustainable, electrical power engineers must be familiar with the concept of microgrid protection. Theoretical as well as practical skills must be a standard content of the power system curriculum. In addition, it has been forecasted for a long time that there will be an impending large scale retirement of power engineers. Table 1.3 shows data collected by the Oregon and SW Washington Energy Consortium, describing three regional employers (Portland General Electric (PGE), PacifiCorp, and Bonneville Power Administration (BPA)), and their pro-

jected retirements for the term of 2015-2020 [3]. There will be a large demand for workforce in this area in the next five years.

	Current Workforce	Eligible for Retirement 2015	Projected to Retire 2015	Eligible for Retirement 2020	Projected to Retire 2020
PGE	95	44	68%	42	62%
PacifiCorp	200	27	80%	38	90%
BPA	450	144	66%	216	84%

Table 1.3: Eligible and projected retirements of power engineers in 2015 and 2020 for three large entities [3].

By designing and implementing this power system protection laboratory, we believe the students that graduate from OSU will be more competitive in job interviews and their careers. It is also a unique opportunity for OSU to garner a stronger reputation within the regional power systems industry [3].

In order to make sure that right from the start we are delivering a qualified power system protection laboratory, we developed the initial stages based on a successful model from Portland State University (PSU). Experiments include fuse testing, electromechanical relay testing, microprocessor-based relay testing, and software simulation. In our case, we start the laboratory by covering all the software portion and the microprocessor-based relay testing portion. Those contents are organized in five experiments, and each one lasts for one hour. There are four working stations in the teaching laboratory area. Each station accommodates no more than three students. The assignments after the laboratory session are a written report and a feedback

report. After the initial stages of this laboratory, the number of sessions will be expanded.

Chapter 2: Literature Review

This Chapter will introduce the previous studies on both optimal synchrophasor placement and power system protection education.

2.1 Optimal Synchrophasor Placement

Based on the previous chapter, synchrophasor placement is one of the first things to consider for a microgrid project since a better monitoring system is fundamentally required. There are some studies on locating appropriate buses to placing synchrophasors and optimizing the number of them in a system. Reference [20] introduces a new concept, the degree of unobservability, and utilizes spanning trees of the power system graph and a tree search technique to identify optimal locations for synchrophasors. Sensitivity analysis plays an important role in the optimal synchrophasor placement problem. In [21–25], optimal PMU placement is achieved with Integer Linear Programming (ILP) algorithms and sensitivity analysis based on electrical structure. Based on these, [26] describes an improved idea that addresses the optimal synchrophasors placement problem by using the singular value decomposition (SVD)-based analysis to derive the electrical distance matrix. By using the decoupled Newton-Raphson power flow calculation, Reference [27] computes the sensitivity of a test system with respect to the increased voltage magnitude and/or angle. The authors in [28] integrate a simulated annealing algorithm with sensitivity

analysis to achieve optimal PMU placement. A minimum cost function has been used to verify the feasibility of this approach. Other techniques are also being developed in this area. For instance, Reference [29] adapts a hybrid method based on Binary Particle Swarm Optimization (BPSO) algorithm and the $N-1$ principle. Reference [30] obtains optimal PMU placement by the theory of convex relaxation. Reference [31] proposes an information-theoretic method to deal with synchrophasor placement problem. Departing from the conventional topological method, it proposes a mutual information criterion that uses for modeling the uncertainty reduction of power system states based on synchrophasors sensing data.

Most of the above methodologies are designed and implemented at the transmission systems, which are high or medium voltage level highly meshed network, and almost no literature indicates the application of synchrophasors at the distribution system, which is low voltage level, especially for a radial power system such as the OSU campus grid. There are two questions we want to answer: First, do those methods work for distribution level networks? Second, will synchrophasor technology better facilitate distribution level systems operation and transition to a microgrid structure?

2.2 Power System Protection Pedagogy

The first electrical engineering educational program was created in 1891 [32]. Over the past more than one hundred years development, power system education has al-

ways focused on the hands-on experience for students. In the beginning of the 1900s, University of Washington started their Electrical Engineering laboratory curricula, such as the "Dynamo" generator, power transmission, telephone and telegraph, etc. Since the end of World War II, there were large research grants from the government. In the late 1970s, the industry began to realize that the employees who graduate from college had more theoretical skills than practical skills [32].

Due to the end of cold war in the beginning of 1990s, academia started paying attention to the practical skills once again. Reference [33] introduces the development of a teaching and research laboratory in the area of microprocessor-based power system protection in the University of Saskatchewan, Canada. The main functions of this laboratory is designing, simulating, and testing microprocessor-based relays and protective relaying systems. In the 21th century, universities and colleges are more willing to connect the textbook knowledge with experimental courses. In the University of North Carolina at Charlotte, the power system teaching laboratory can provide the basic exercises that train the students in the concepts of electric machines and drives, power electronics, and power system protection. All the experiments are equipped with different switching and pre-installed control logic. If devices are connected or switched improperly, it will provide alerts so that the students will not worry about damaging the equipment [34]. Reference [35] introduces the project in the University of Texas at Arlington, which utilizes a model scale power system using microprocessor-based relays inside a looped system with multiple generation sources and modeled transmission lines. Reference [36] represents a four-bus, model-scale

microgrid laboratory in the Anhui University of Technology in Ma'anshan China. It models a variety types of generation and employs the testing of different kinds of faults. Due to the rising of system complexity, it is getting more challenging for students and young engineers to understand the modern distribution networks. Therefore, Reference [37] indicates a simulation based training platform used for training both students and power system professionals in different Smart Grid applications. Reference [38] introduces a method that modifies the classic Perrine-Baum diagram due to the role of of vector diagrams has been replaced by computational power and numerical methods. This method is a more practical representation that allow students have a better understanding of the behavior of a high voltage level transmission line under different load levels.

As described by the definition of Pedagogy, how we perform a better teaching behavior is one of the most significant ideas for developing the power protection laboratory. Reference [39] introduces the Engineering Criteria 2000, also called EC2000, which is a set of criteria that educational programs must satisfy in order to be accredited by the Accreditation Board for Engineering and Technology (ABET, a nonprofit non-governmental organization that accredits college and university educational programs in the area of applied science, engineering, and computing at the associate, bachelor, and master degree levels [40]). EC2000 is also named ABET Student Outcomes a-k, as shown below [40]:

a. an ability to apply knowledge of mathematics, science and engineering;

b. b. an ability to design and conduct experiments, as well as to analyze and inter-

pret data;

c. an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability;

d. an ability to function on multidisciplinary teams;

e. an ability to identify, formulate, and solve engineering problems;

f. an understanding of professional and ethical responsibility;

g. an ability to communicate effectively;

h. the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context;

i. a recognition of the need for, and an ability to engage in life-long learning;

j. a knowledge of contemporary issues;

k. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

By deploying weekly laboratory report and grading rubrics, the ability of understanding and applying power system protection knowledge from the lecture and utilizing the mathematics and engineering theory will be evaluated. Moreover, since the experiments are completed in teams, how to cooperate with others and how to communicate effectively is also assessed. We design the laboratory to focus on outcomes a, b, d, and g.

Chapter 3: Synchrophasor Placement for the Oregon State University Campus Microgrid

In this Chapter, two popular approaches for transmission level synchrophasor placement are preliminarily applied in a benchmark distribution level network, and subsequently compared in order to evaluate their performance. The first method utilizes a linear optimization approach given the network electrical distances. This method considers both topological structure and electrical structure of the network. The second method inspects the sensitivities of bus voltage and angle with respect to power injection by running the ac power flow. Moreover, it considers additional constraints and rules such as the size of system and local operating policies/priorities. Finally, a few candidate solutions are identified for the placement of synchrophasors on the OSU campus.

This Chapter is organized as follows: Section 3.1 introduces the methodologies that we used for this study. Section 3.2 presents the results from our methods, identifies the candidate locations for the placement of synchrophasors, and discusses the feasibility for each method and additional rules that need to be considered.

3.1   Methodology

3.1.1   Optimizing Synchrophasor Placement Using Integer Linear Programing (ILP)

The synchrophasor placement problem can be formulated as an integer linear program with an additional inequality constraint [23]. Provided a power system with N buses and M branches, let $\mathbf{A}$ be an $N \times N$ matrix with binary elements denoting the connectivity between each bus, and x be an $N \times 1$ vector that indicates the binary decision as follows:

$$x_i = \begin{cases} 1 & \text{if a synchrophasor is installed at bus i} \\ 0 & \text{otherwise} \end{cases} \tag{3.1}$$

where $i = 1, \ldots, N$, and $j = 1, \ldots, M$. b is an $N \times 1$ unit vector. The optimal placement problem is formulated below:

$$\min \sum_{i=1}^{N} x_i \tag{3.2}$$

such that

$$\mathbf{A}x \geq b \tag{3.3}$$

where $x_i \in \{0, 1\}$. When constraints (3.2)-(3.3) are satisfied, it indicates full observability, which means that the measurement sets and distribution are sufficient for determining the current system state [20]. This is achieved with a minimum number

of synchrophasors.

The unit vector b is also called goal vector. By applying such a vector, the calculation result from multiplication of $\mathbf{A}$ and x will equal or greater than 1. Therefore, we need to minimize the amount of nonzero elements in the decision vector x, which is represented by Equation 3.2.

The matrix $\mathbf{A}$ could be derived from the topological structure, as shown below:

$$a_{ij} = \begin{cases} 1 & \text{if bus i connected with bus j} \\ 0 & \text{otherwise} \end{cases} \tag{3.4}$$

This method only considers the physical connectivity of the network. It contains very few electrical properties when one uses topological structure metrics.

The matrix $\mathbf{A}$ could also be obtained from the electrical structure by weighing the electrical distance matrix with a threshold [21,23]. The certain threshold is a parameter that would change from network to network. In order to choose a value for a specific project, the engineers would look at the number of available synchrophasors, Phasor Data Concentrator slots, or even the project budget. If an element in the electrical distance matrix is smaller than the selected threshold, we define the buses indicated by the row and column numbers of this element as electrically connected, even though sometimes in the physical world, they are not directly connected. For the ones that are greater than the threshold, the involved buses are defined as not

connected.

Previous studies describe the process of how to get electrical distance matrix. It is considered that [41] is the earliest study of electrical distance in power systems. Based on voltage magnitude sensitivities, it proposes a distance metric used to divide a network into different voltage control zones. Afterward, [42] proposes the concept of resistance distance, which is another approach to obtain electrical distance (known as Klein resistance matrix) shown below:

$$Z_{ij}^{thev} = Z_{ii} + Z_{jj} - Z_{ij} - Z_{ji} \qquad (3.5)$$

where Z_{ij} represents the element in i^{th} row and j^{th} column of the Z_{bus}. This Thesis adapts to the method elucidated in [21], which is derived from Klein resistance matrix. Instead of considering the geographic connection, it proposes a new approach that represents electrical structure by using electrical distance of the network. The distance for a pair of nodes a and b in a network is shown as:

$$e(a, b) = g_{a,a}^{-1} + g_{b,b}^{-1} - g_{a,b}^{-1} - g_{b,a}^{-1} \qquad (3.6)$$

where $a \neq b \neq r$.

3.1.2   Sensitivity Analysis Based on Power Injection

The approach described in this Section can be used to allocate other electrical elements as well, for example, energy storage devices [43]. Derived from the Newton-Raphson power flow formulation, shown as Equations 3.7 and 3.8, the sensitivity of reactive and active power injections with respect to voltage magnitudes and phase angles can be described as Equations 3.9 and 3.10:

$$P_k = |V_k| \sum_{n=1}^{N} |V_n| \left[G_{kn} \cos\left(\theta_k - \theta_n\right) + B_{kn} \sin\left(\theta_k - \theta_n\right) \right] \tag{3.7}$$

$$Q_k = |V_k| \sum_{n=1}^{N} |V_n| \left[G_{kn} \sin\left(\theta_k - \theta_n\right) - B_{kn} \cos\left(\theta_k - \theta_n\right) \right] \tag{3.8}$$

$$\Delta P = \left[\frac{\partial P}{\partial \theta} \right] \Delta \theta + \left[\frac{\partial P}{\partial |V|} \right] \Delta |V| \tag{3.9}$$

$$\Delta Q = \left[\frac{\partial Q}{\partial \theta} \right] \Delta \theta + \left[\frac{\partial Q}{\partial |V|} \right] \Delta |V| \tag{3.10}$$

The two partial derivatives for each equation indicate the sensitivities and can be used to form an electrical distance matrix as well. In this work, instead of computing the two partial derivative terms, we will implement the sensitivity analysis by injecting unit power into each node and inspecting the changes in angle and voltage magnitude. If the voltage or angle changes at any other buses are over a certain threshold, it means these buses react to this power injection. We argue that these buses could be good candidates for the placement of synchrophasors. Additional

constraints will be considered to identify the critical nodes.

In general, sensitivity analysis measures the amount of influence between two quantities [21]. One could consider this sensitivity analysis as analogous to the ILP method based on electrical structure as measured by the power flow Jacobian. The sensitivity analysis method we applied focuses on the first quadrant of the ac power flow Jacobian matrix as shown below:

$$J = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial |V|} \end{bmatrix} \tag{3.11}$$

where the first quadrant $\frac{\partial P}{\partial \theta}$ represents the incremental change on voltage angles when there is a active power injection. By applying Newton-Raphson power flow solution, shown below:

$$\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta |V| \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{3.12}$$

$$\begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial |V|} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta |V| \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{3.13}$$

we can obtain pseudoinverse [44] for the ac power flow Jacobian matrix. This process will lead to the following result for first quadrant:

$$\frac{\Delta \theta_{ij}}{\Delta P_{ij}} = \left(J_1^{-1}\right)_{ii} + \left(J_1^{-1}\right)_{ij} - \left(J_1^{-1}\right)_{ji} - \left(J_1^{-1}\right)_{jj} \tag{3.14}$$

which implies that sensitivity analysis and electrical structure method will have similar results.

The fourth quadrant of the ac power flow Jacobian matrix, $\frac{\partial Q}{\partial |V|}$, is another part we are interested in. It reveals the impact of the reactive power changes with respect to the voltage magnitude. Due to the large deployment of variable power generation resources for a microgrid, the control of voltage oscillation and reactive power compensation are also vital to us. Therefore as future work, we will apply similar algorithms to the fourth quadrant to further improve locations for synchrophasor in a microgrid.

3.2   Results and Discussion

The results from the above two algorithms will be compared and evaluated in this Section. A discussion on whether these placement algorithms work well at the distribution level will be provided as well.

3.2.1   Results by Using Topological and Electrical Structure

As mentioned in Section 3.1, optimization of synchrophasor placement can be achieved by solving (3.2)-(3.3). When using the topological structure, the connectivity matrix A (as shown in Figure 3.1) is directly obtained from the Y_{bus} matrix based on the physical connections. The optimization results from the topological structure method suggests 110 synchrophasors for the OSU campus in order to achieve full

observability. This amount of installations would put sychrophasors on almost half of the buses on campus. This solution is financially unrealistic. As a typical distribution level system, the OSU campus grid is highly radial, so that many load buses connect to very few input feeders. Based on the definition of observability, a system like this will need many installations to meet complete observability. Taking the IEEE Case 9 as a comparison, the optimal locations of synchrophasors by using the ILP method based on topological structure are shown in Figure 3.2. Three locations will create the a full observability situation. If nine buses connected as a 'line', it will need at least four locations. Therefore, for a highly meshed network, which is the common structure type for transmission level systems, ILP based on topological structure will perform better.

As mentioned before, we could also build the connectivity matrix, A, by constraining the electrical distance matrix with a threshold τ. Comparing to the one using the topological structure, the outcome matrix (displayed in Figure 3.3, when the given threshold is 0.004) shows more electrical connections. Although many load buses are not directly connected in a distribution system, they have shorter electrical distance than the preset threshold, and are consequently treated as full connections. In other words, by varying the threshold τ, we can manipulate the matrix A to satisfy the amount of synchrophasors we have available.

The results from ILP based on electrical structure suggest 20 installations for the OSU campus grid, and shows a more reasonable recommendation than the one
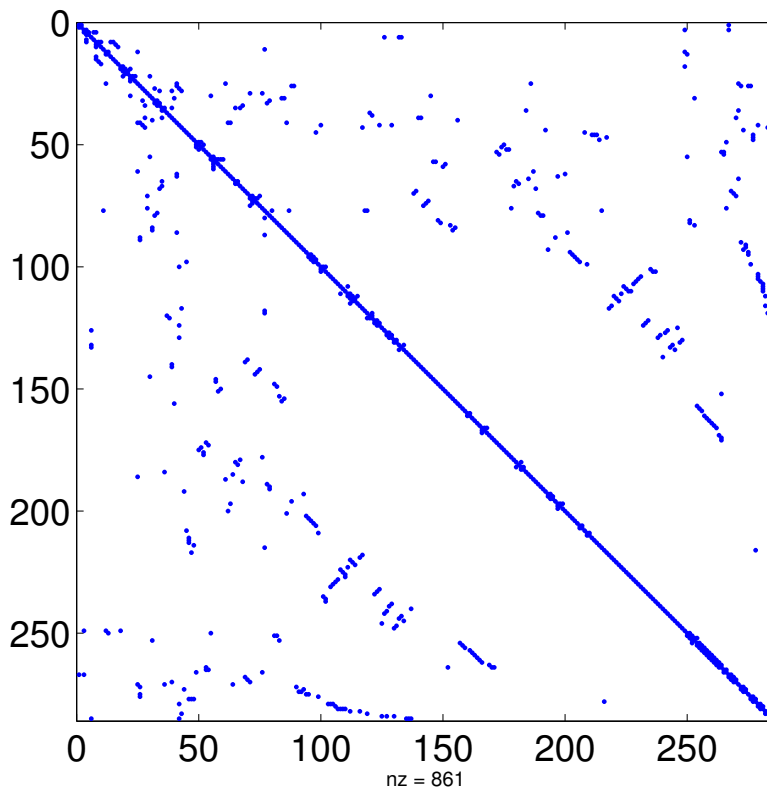
Figure 3.1: The connectivity matrix A used in the integer linear programing method based on topological structure.

using the topological structure. These potential locations are labeled in green in Figure 3.4. However, if one looks at those labeled locations, some of them are still parallel load buses that are connected with the same feeding line. Furthermore, the main feeding lines originate from either a substation or a switch yard. We propose to cluster those locations. A couple of constraints are considered: 1) the clustered buses are connected with the same main feeding branch; 2) each clustered area contains no more than one substation and switch yard, which are treated as the center of
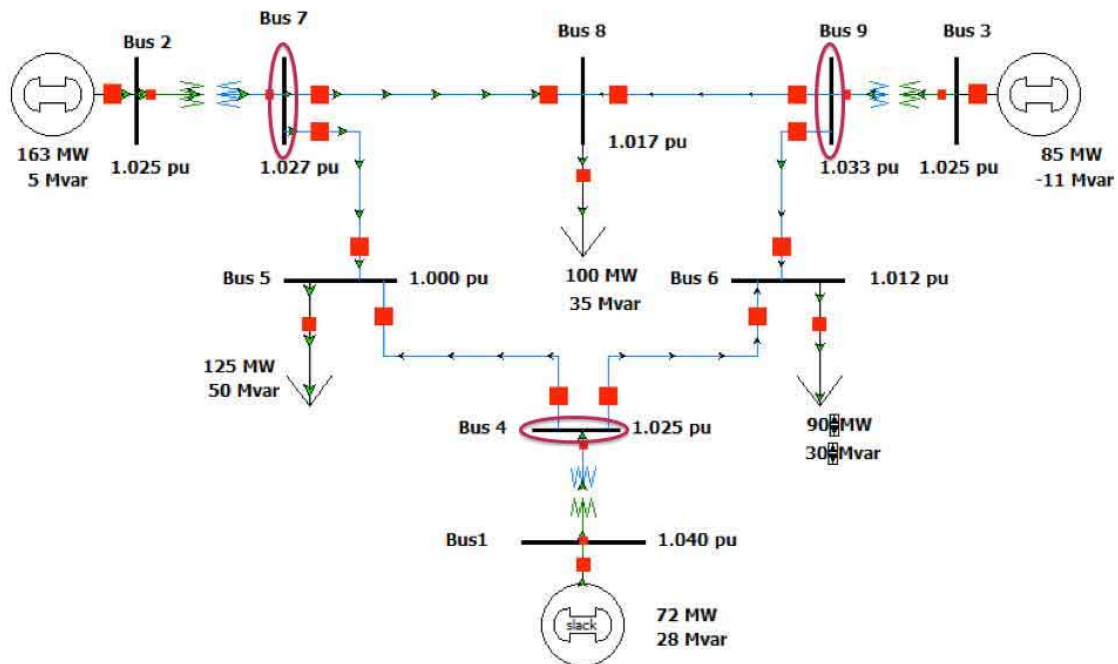
Figure 3.2: The ILP based on topological structure method result for IEEE 9 buses system.

proposed clusters. This campus grid ends up with 4 clusters which are separated by orange dashed lines in Figure 3.4.

3.2.2   Results by Sensitivity Analysis

Power injection at load buses is conducted to figure out the bus locations that are sensitive to those changes. First, the initial state after a full Newton-Raphson power flow is set as the base case. Based on this base scenario, we apply a ΔP to a load bus and resolve the power flow; at the same time, all the voltage magnitudes and angles for other buses are monitored. ΔP is a vector of 4 elements that varies within
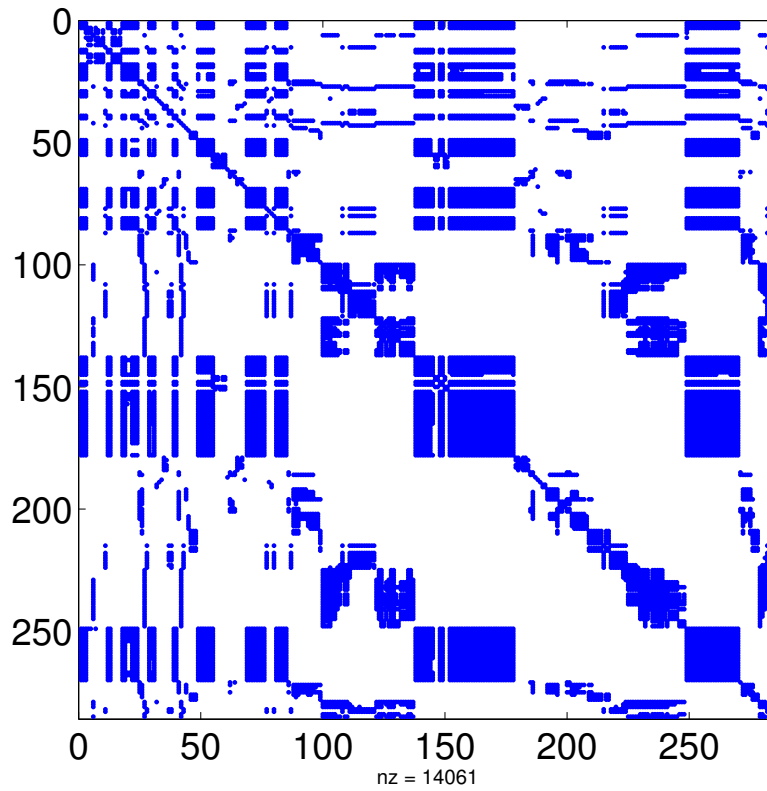
Figure 3.3: The connectivity matrix A used in the integer linear programing method based on electrical structure.

the range: $-$base, base, $3 \times$ base, and $7 \times$ base, which represents that the studied load goes from shut down, to doubled, quadrupled, and octupled. Every other load
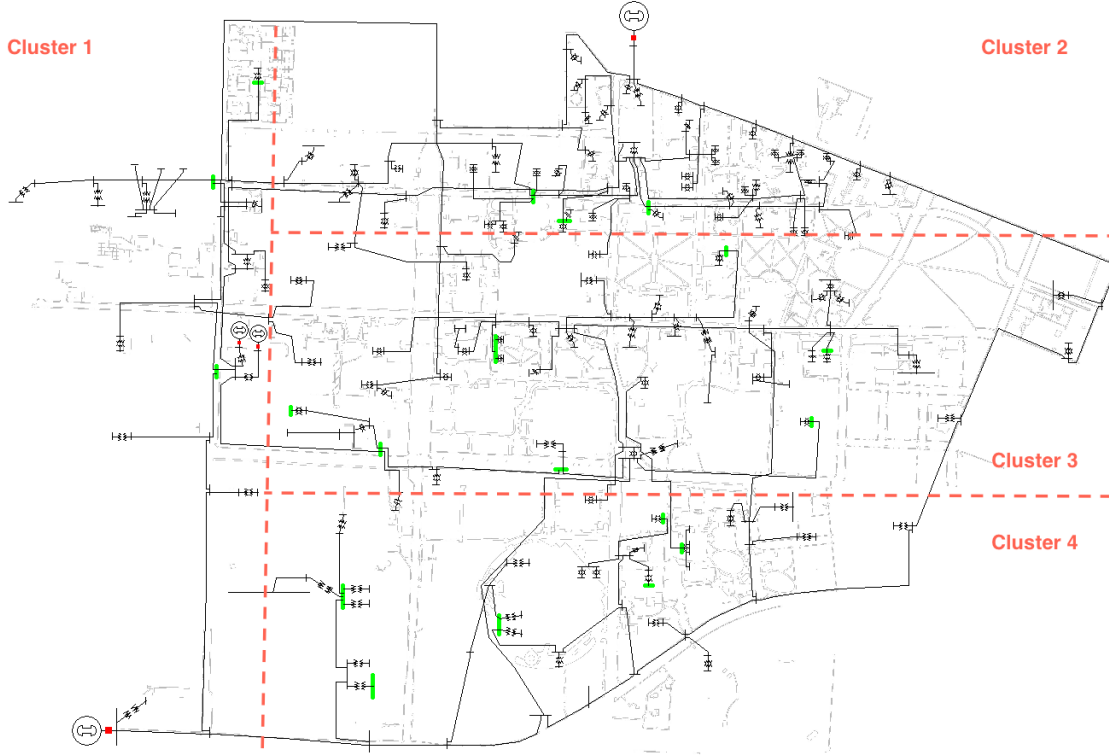
Figure 3.4: Candidate locations for ILP based on electrical distance approach and cluster solution.

bus goes through the same process, as shown in the matrix below:

$$
\begin{pmatrix}
base + \Delta P_1 & base & base & \ldots & base \\
base & base + \Delta P_2 & base & \ldots & base \\
base & base & base + \Delta P_3 & \ldots & base \\
\vdots & \vdots & \vdots & \ldots & \vdots \\
base & base & base & \ldots & base + \Delta P_n
\end{pmatrix}
\tag{3.15}
$$

where $n \in$ Number of loads. The injection vector for reactive power follows a similar algorithm.
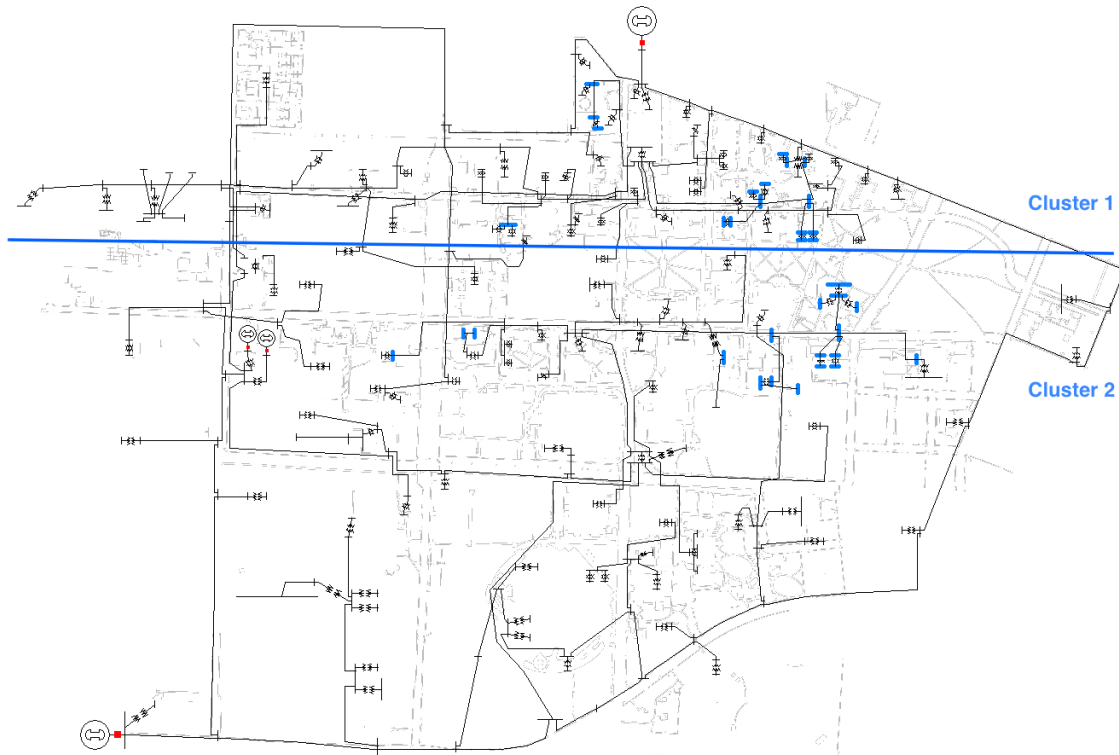
Figure 3.5: Candidate locations for sensitivity analysis and cluster solution.

After a load injection, if changes in voltage magnitude or angle at other buses occur and are over the preset threshold, we mark the associated buses as potential candidates because they respond to power changes sensitively. The buses that qualify as potential candidates most frequently are selected. This process results in 35 buses, which are all labeled as blue nodes in Figure 3.5. By applying the same rules of cluster selection as discussed before, those 35 buses are grouped into 2 clusters, which are

separated by blue lines in Figure 3.5. Combining Figure 3.4 and Figure 3.5, we give four recommended locations to place synchrophaosrs represent by red circles as shown in Figure 3.6.
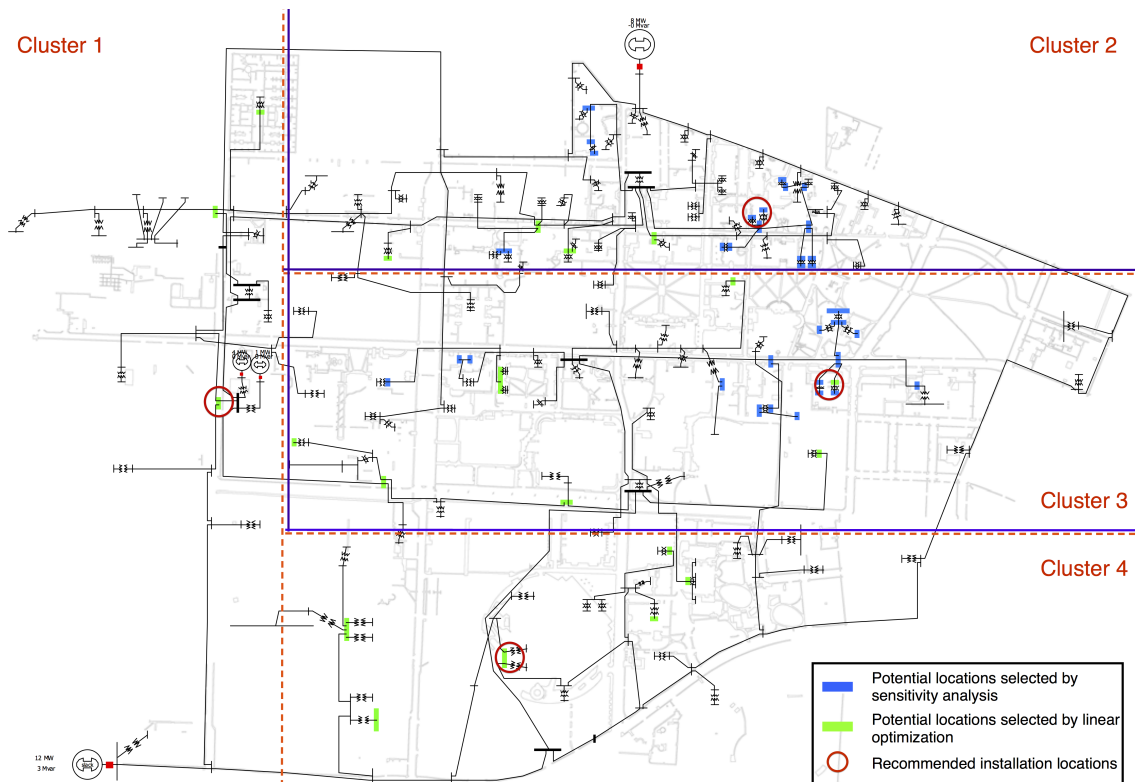
Figure 3.6: Recommended locations based on both ILP electrical structure method and sensitivity analysis.

Chapter 4: Design and Implementation of a Power System Protection Laboratory

To satisfy the requirements of industry and the development trends of power system education, Oregon State University (OSU), Portland State University (PSU), and Oregon Institute of Technology (OIT) proposed a cooperative project on power system pedagogy. As part of this project, we deployed a power system protection laboratory in Winter term, 2015. The main objectives for this power protection laboratory are to provide students with hands-on and software simulation experience so that their knowledge from lectures will be improved, and also letting students start getting familiar with the equipment they will handle with during their future career.

Device	Quantity
SEL-AMS (Adaptive Multichannel Source)	4
SEL-5401 software	4
SEL-351 (Directional Overcurrent and Reclosing Relay)	1
SEL-351S (Overcurrent and Breaker Control Relay)	3
SEL-5030 (ACSELERATOR QuickSet software)	4
SEL-C662 (USB to Serial Port Cable)	4
ASPEN OneLiner software	4
19-inch rack	4

Table 4.1: Protection laboratory hardware and software summary.

Table 4.1 shows the list of hardware and software utilized in this laboratory. Most of the Schweitzer Engineering Laboratories (SEL) equipment are donated by the vendor or retired from industry. The SEL-AMS, also named SEL-4000, is designed for testing protective relays. By using the SEL-5401 configuration software, these devices can simulate different power system operating conditions. Configuration values in SEL-5401 are sent to the SEL-AMS through SEL-C662 cables.

The SEL-351 and SEL-351S are members of the SEL overcurrent relay family. The main difference is that the latter one is not equipped with directional function. The SEL-5030 software, also called AcSELerator QuickSet, is a computer tool that provides settings to the relays also via cable.

ASPEN OneLiner is a software tool for power engineers to analyze short circuit and relay coordination. According to the research of 87 utilities in 34 countries (55 in the US, 12 in Europe, 3 in Latin America, 7 in Asia Pacific, 5 in the Middle East and Africa, and 5 in Canada) by Newton-Evans Research Co., Inc. in 2009, ASPEN OneLiner is the leading short circuit and relay coordination program with a 46% market share [45]. We purchased four licenses for the academic version, limits the number of buses to 15, enough for our protection teaching experiments. It also covers almost all the functions and databases compared with the full version.

In this Chapter, the detail of our power protection experiments will be introduced in Section 4.1. The key points for each experiment are also included. After that,

Section 4.2 discusses students' feedback with respect to the protection laboratory. All the experiment instructions are shown in Appendix A, and students feedback forms are included in Appendix B.

4.1   Laboratory Instructions

4.1.1   Laboratory 1: Overview of Power System Characteristics 1

This experiment introduces students to the power protection equipment and simulation software that is used in subsequent laboratory assignments. Students will build a single-source, three-phase radial power circuit model by using ASPEN software. Since this protection laboratory is registered as part of the course power system protection (ECE 436/536), knowledge from previous course power system analysis (ECE 433/533) is required, by inheriting the pre-requisition. Therefore, students also need to review symmetrical components and analyze the fault by comparing simulation results to the analytical ones. The detailed objectives are listed below:

- Create simple cases in ASPEN OneLiner. Including positive-, negative-, and zero-sequence impedances of line and generators as well as proper transformer connections.

- Run ASPEN Power Flow on a power system case and perform basic analysis on the results.

- Identify the results of the power flow that have an influence in the fault study.

- Perform a basic fault study, obtaining results for three-phase, single line-to-ground and line-to-line faults in the relevant parts of the system and interpret the results.

These objectives are the main components of the laboratory report checklist.
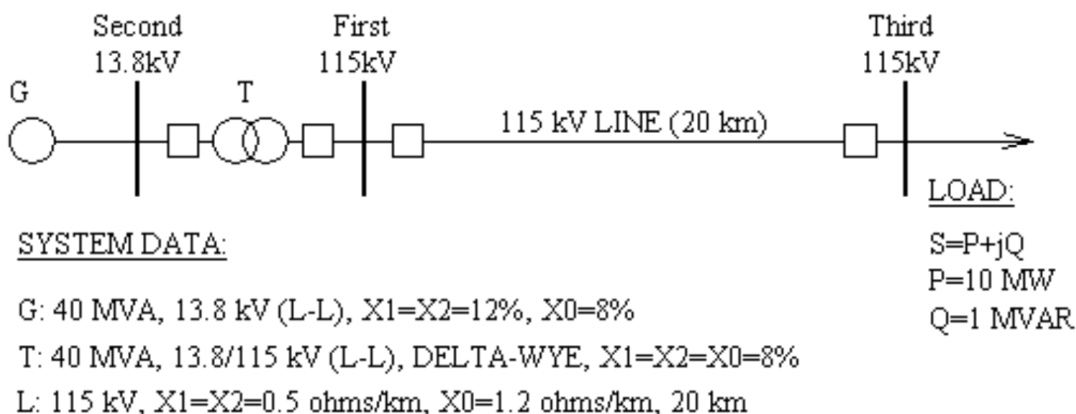
Figure 4.1: Radial system in ASPEN.

The system diagram is shown in Figure 4.1. Students need to choose a proper S_{base} for this system. All the given per unit values need to be recalculated if the chosen S_{base} is not $40MVA$ by using Equation 4.1. The line impedance also needs to be converted from ohmic value to per unit. All the fault simulation results are shown in the TTY form, which is a window that displays the program outputs in traditional text format.

$$Z_{pu.new} = Z_{pu.old} \times \left(\frac{V_{base.old}}{V_{base.new}} \right)^2 \times \left(\frac{S_{base.new}}{S_{base.old}} \right) \tag{4.1}$$

4.1.2 Laboratory 2: Overview of Power System Characteristics 2

For Laboratory 2, students need to apply all the skills learned from the previous week to work with a more difficult loop system, as shown in Figure 4.2.
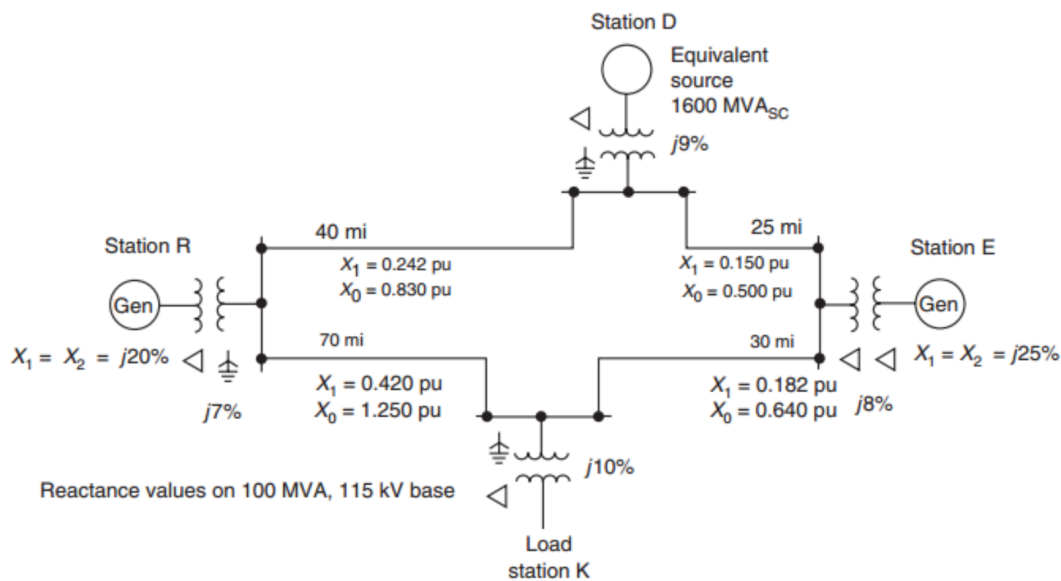
Figure 4.2: Loop system in ASPEN.

Students are required to simulate three-phase, single line-to-ground and line-to-line faults at each of the breakers at buses and in all four stations. Hand calculations are not required for this experiment due to the complexity of the system configuration. Instead, students need to analyze the changes for fault currents if there is a new line added between station D and station K.

4.1.3 Laboratory 3: Coordination of Overcurrent Relays in a Radial System

In this laboratory exercise, students will be introduced to the coordination of overcurrent relays in a radial power system by using ASPEN OneLiner. The radial power system is shown in Figure 4.3. This Figure is modified from Laboratory 1 (Figure 4.1) by removing load and adding Bus 4 and a new transmission line. The objectives for Laboratory 3 are:

- Create a radial case in ASPEN OneLiner containing the required information to do fault studies and overcurrent relay coordination.

- Introduce data of phase overcurrent relay elements into the model.

- Simulate faults and determine the behavior (including timing) of overcurrent relay elements.

- Perform a coordination study to determine the relay settings.
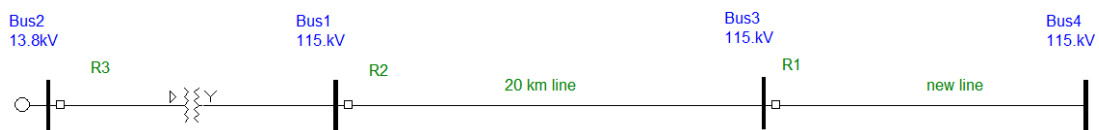
Figure 4.3: Modified radial system in ASPEN for coordination.

As shown in Figure 4.3, there are two locations for adding relays, $R1$ and $R2$. For this experiment, we choose an electromechanical overcurrent relay, General Electric

IAC53, since it is commonly used in industry. The relays are given different CT ratios and time dial values in order to let the two relay curves have an intersection, which means these two relays are not well coordinated. By varying the CT ratios and time dials, students need to realize that $R1$ is the first relay to trip if there is a fault that occurs in the transmission line between Bus 3 and Bus 4, and $R2$ is the backup protection for the same fault.

4.1.4   Laboratory 4: Protective Relaying Coordination of a Loop System

Laboratory 4 covers the exercise of coordinating directional/non-directional overcurrent relays in a loop system, as shown in Figure 4.4. It is adapted from Laboratory 2, Figure 4.2. In contrast with Laboratory 3, in which we have relay coordination in a radial system, the loop one is more complicated, and the problem is closer to a real world project.

There are 11 relays as shown in Table 4.2. Students need to decide which ones must be regular overcurrent relays without directional function, and which relays must be directional, based on their locations in the system, and the settings in ASPEN.

There are six relays ($R3$, $R4$, $R6$, $R8$, $R9$, and $R10$) located inside the loop that must be directional. $R3$, $R8$, and $R10$ are called clockwise sequence relays. Assum-
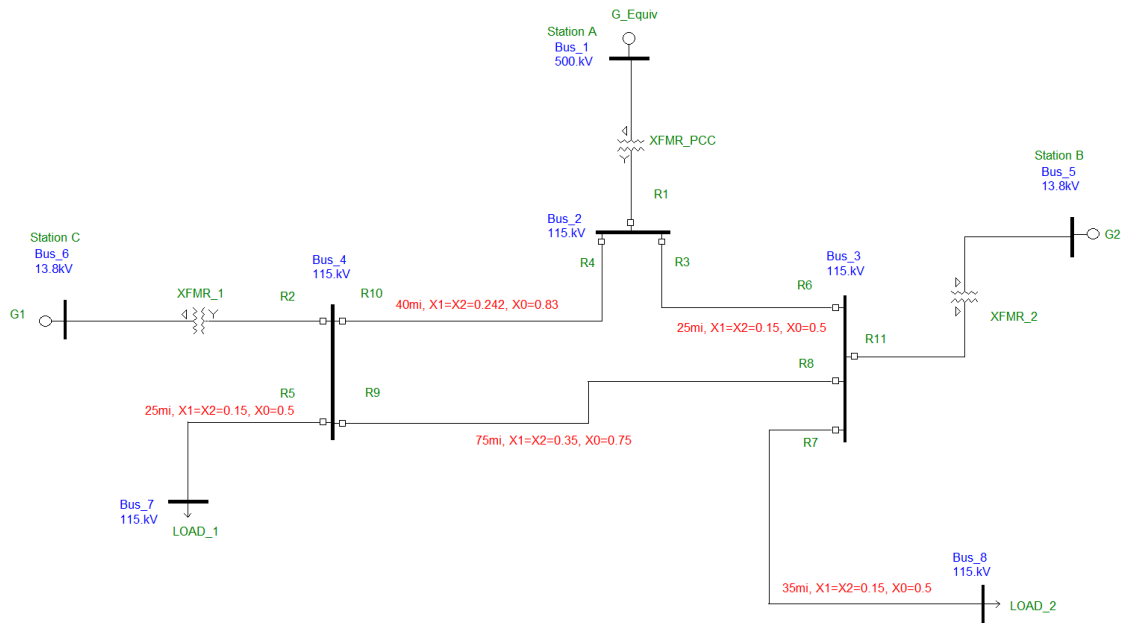
Figure 4.4: Modified loop system in ASPEN for coordination.

ing there is a fault ($F1$) in the line between Bus 2 and Bus 3 (as shown in Figure 4.5), $R3$ is the first relay that needs to trip among the clockwise sequence. $R10$ is the first-tier backup relay with a certain time delay. $R8$ is the second-tier backup with even a longer time delay. $R4$, $R6$, and $R9$ are called counter-clockwise sequence relays. With respect to $F1$, they have the same rule as the clockwise sequence relays: $R6$ trips first, $R9$ and $R4$ are first- and second-tier backup respectively. If these six relays are not directional relays, it will cause a selectivity issue for such a fault like $F1$. In addition, $R5$ and $R7$ must be directional as well. For this system, the goal for these two relays is simply to watch on their respective loads. If something happens on the load side, they need to trip in order to cutoff the fault impacting the rest of the system. If a fault occurs internal to the loop, for instance $F1$, they do not have

Relay	From Bus	To Bus
R1	2	1
R2	4	6
R3	2	3
R4	2	4
R5	4	7
R6	3	2
R7	3	8
R8	3	4
R9	4	3
R10	4	2
R11	3	5

Table 4.2: Relay identification for Laboratory 4.

to trip or act as backup protection since power still can be sent to the load if primary protections isolate the fault correctly.

Since there are three power generation units in this system, $R1$, $R2$, and $R11$ are the only protection for each unit. Therefore, they must be non-directional with a certain time delay as well. Considering the same fault occurs inside the loop, $F1$, and assuming relays $R3$ and $R6$ do not trip by some reason, $R1$ and $R11$ must trip since we want to isolate the fault impact from the generators. In other words, $R1$, $R2$, and $R11$ can be considered as the first-tier backup protection with respect to the relays inside the loop. This kind of situation has similar outcomes when the fault occurs on the bus, for example $F2$ shown in Figure 4.5. In conclusion, the blue arrows in Figure 4.5 show the final decision of implementing directional functions or not for each relay.
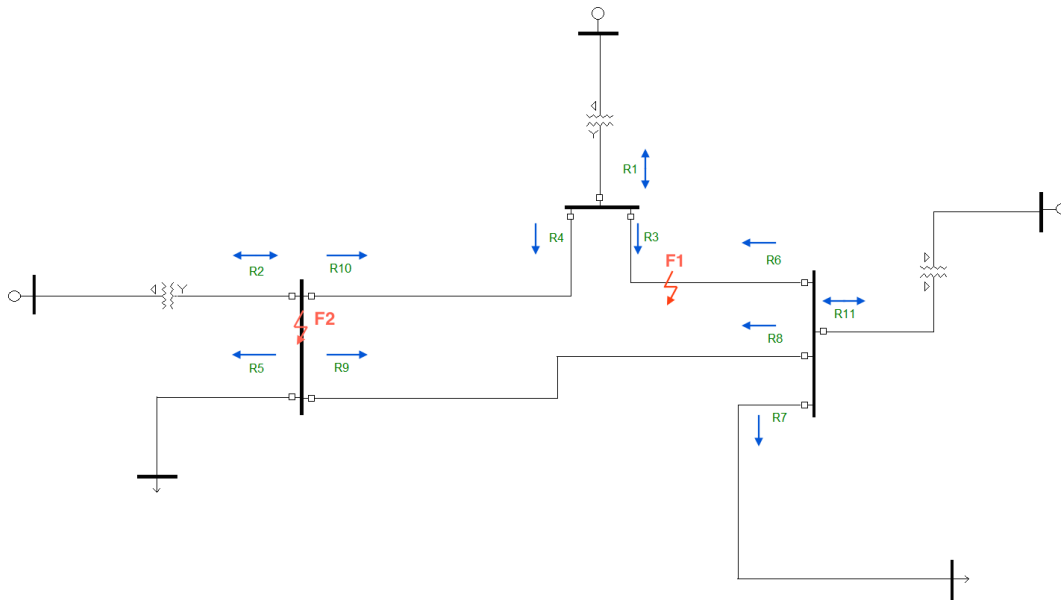
Figure 4.5: A sample fault to illustrate the relay coordination.

4.1.5   Laboratory 5: AC Time Overcurrent Relays (51) Testing

In this laboratory exercise, students will learn about the testing of microprocessor based overcurrent relays. Compared with the traditional electromagnetic relays, one microprocessor relay provides more functions in a single device. Although most of the electromechanical relays have long service life, microprocessor relays are widely used for various smart grid projects since they have become smaller and cheaper.

The objectives for this experiment are listed below:

- Implement physical set-up to test SEL-351 using the SEL-AMS.

- Upload settings to the relay (phase and neutral ground elements).

- Test the SEL-351 relay with SEL-5401 software.

This experiment contains potentially dangerous steps. Therefore, the revision of power safety guidelines is highly recommended.

Figure 4.6: A full set of hardware devices for the power system protection laboratory.

We implemented four sets of equipment like the one shown in Figure 4.6. The higher device is an overcurrent relay, and lower one is the relay test box. Figure 4.7 shows the back panel of these two devices. Students need to connect them based
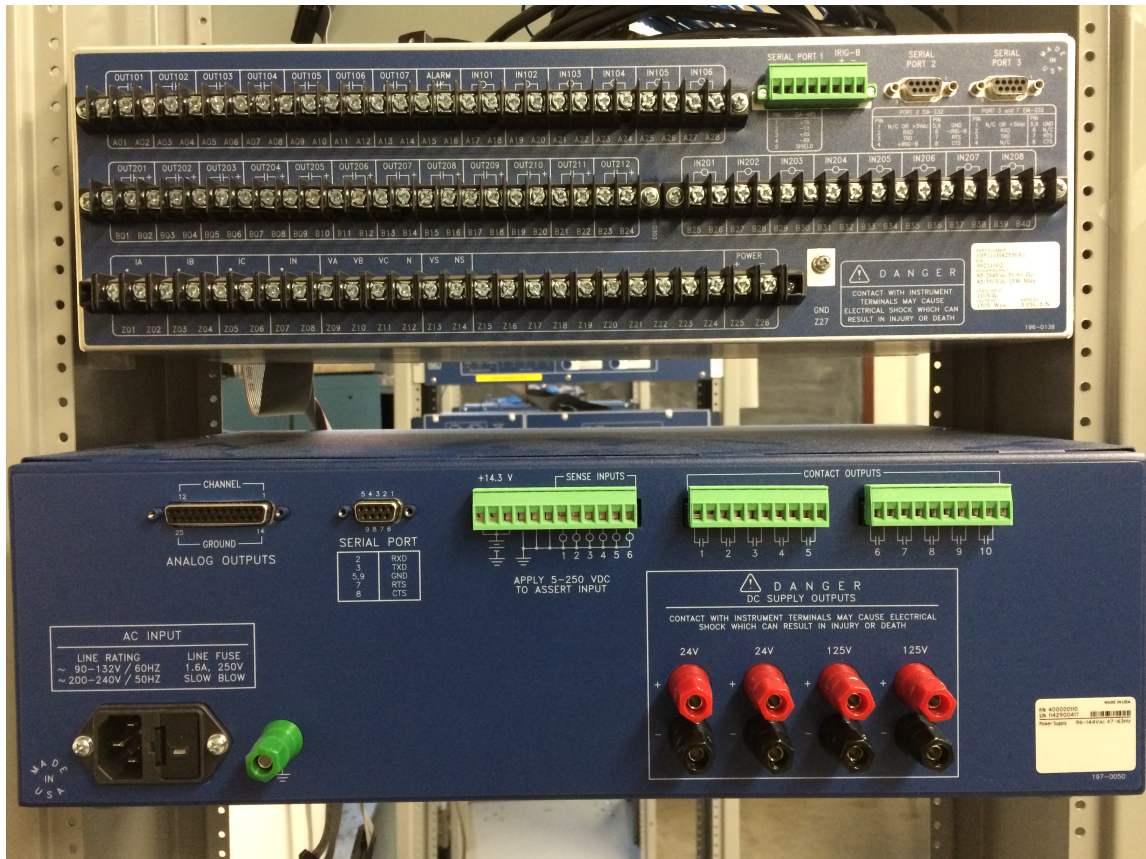
Figure 4.7: Back panels for SEL equipments.

on the schematic shown in Figure 4.8. Afterwards, students can send the preset values from the computer to the overcurrent relay by using the SEL-C662 cable. In the SEL-5401 software, the fault condition will be set up, including pre-fault stage, fault-stage, and post-fault stage. Figure 4.9 shows the relay testing result for a three-phase fault.
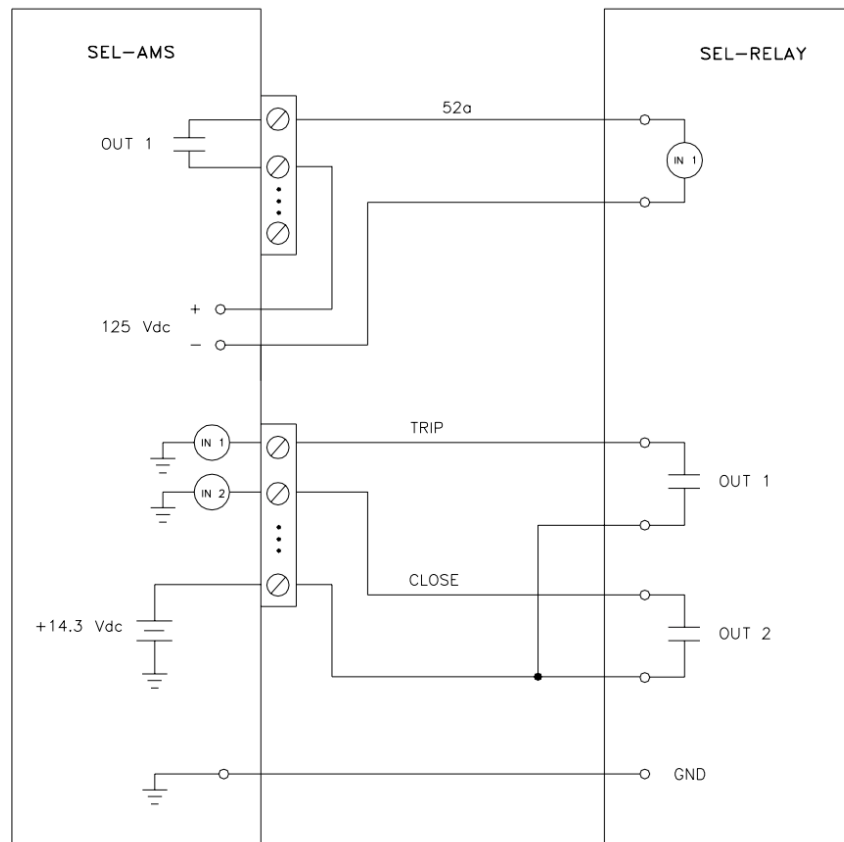
Figure 4.8: The connection schematic between a relay and a test box.

4.2 Outcomes and Discussion of Student Feedback

For the reason of keeping the laboratory educational and sustainable, relevant evaluation must be taken with respect to the curriculum. Student feedback is a proper way to satisfy it [46]. We delivered two feedback forms aimed at collecting ideas from students of how to improve this laboratory in the future. It is anonymous and voluntary. The feedback will also help us investigate if each experiment satisfied the objectives shown on the laboratory instruction manual.
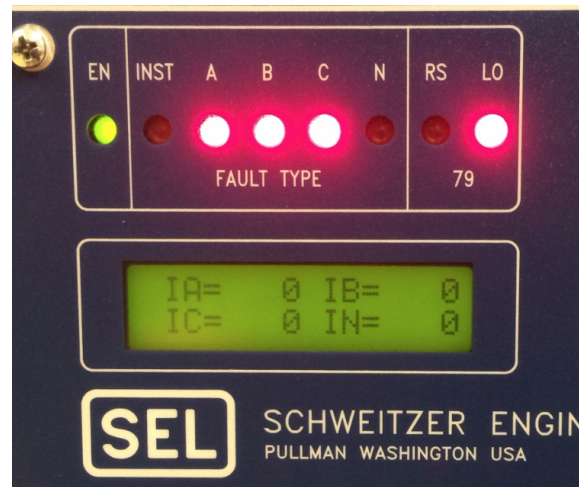
Figure 4.9: The fault testing result shown on the overcurrent relay's front panel.

Figure 4.10 illustrates some highlights of both feedback 1 and 2. Half of the students are willing to see more hardware testing. Some students even claim that they mainly register for this lab due to the hardware experiments. This will be the main task for us before starting this laboratory next year. There are eight students claiming that they have some trouble to understand the relay coordination in a loop system. Experiment 4 is the most complicated so far. Before this experiment, the laboratory teaching assistant should give a brief explanation on the coordination principle. If this laboratory could be registered as a three hours block, students will have more time to analyze and understand this problem. Six students mentioned both having a steep learning curve on how to operate new software and confused about the laboratory instructions. After Experiment 2, students are getting more familiar with the software tool. There are some ambiguous descriptions in the manuals. This will be also updated for next year. There are three students suggesting that

Experiments 1 and 2 could combined as one, and one student believes 3 students per group are too many since it affects the efficiency. These two ideas could be settled by extending the duration of this laboratory to three hours for next year.
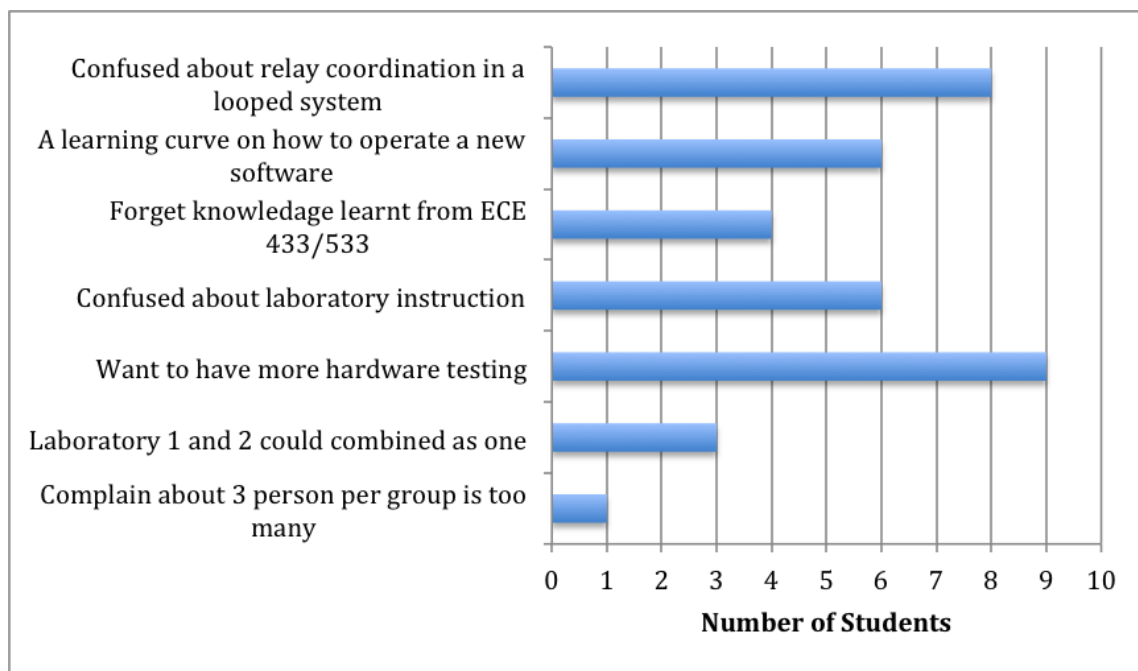
Figure 4.10: Some highlights from student feedback.

In addition, with regards to the survey question "Do you think this laboratory reach the objectives shown on the manuals", just one student said "Kind of", all the other students said "Yes". Based on this and all the above analysis for the student feedback, we believe that the first iteration of this power system protection laboratory was successful. The student feedback strengthens our ideas that continuing to develop an educational protection laboratory will benefit electrical engineering students at OSU.

Chapter 5: Conclusions

Around the main idea of microgrid technology implementation, we propose the topic of optimal placement of synchrophasors at the OSU campus, and develop a power system protection laboratory as part of the course ECE 436/536: Power System Protection.

For the synchrophasor placement problem, we adapt linear optimization and sensitivity analysis, which are two of the most popular methodologies used at the transmission level, to investigate optimized locations for synchrophasors at a distribution level system — the OSU campus grid. We found that the optimized results from the topological structure are not realistic for this case, because this approach suggests installing synchrophasors for about half of the buses in the system. The linear optimization using the electrical structure and sensitivity analysis recommends reasonable potential locations. However, because of the geographical size of the distribution level system, these potential locations need to be grouped based on their electrical connections and distances in order to be cost efficient. For the OSU campus grid, four clusters are recommended and one synchrophasor is proposed for each location.

The power protection laboratory is the preliminary idea aimed at improving OSU power protection students' hands-on skills and the awareness of teamwork so that

they are better prepared for the future challenges in this field. There were 18 students registered for this laboratory. Ten are graduate and eight undergraduate students. Two time slots were open for registration, so that no more than three students were allocated per working station. There are five experiments in total, and one hour duration for each one. Although there were some flaws and improvements need to be done for this laboratory, we gained the experience of how to run and maintain a power protection laboratory successfully. Based on students feedback and the performance during the course, we believe this laboratory is worthy to develop within the energy system group's course catalog.

5.1   Future Work

As mentioned before, campus based microgrid projects are developing nationwide. The OSU campus microgrid is in preliminary stages, and there are still various challenges to implement microgrid technology. One of the most important future task for this project is to develop a proper protection scheme. The OSU campus grid has a similar structure to Figure 1.1. Based on that, we could create a table that shows all possible events [1] (similar to Figure 5.1), where m is the amount of circuit breakers, and n are the meaningful cases for OSU campus grid. Based on this, we could then create a $n \times m$ action table that includes relay settings, activation commands, switching commands etc. By applying such a table with advanced communication and control algorithms, we anticipate that the OSU campus grid could provide a quick response to a variety of operation conditions in the future.

Figure 5.1: The table of different event for a microgrid [1].

As one of the initial conditions for implementing microgrids, we will refine the algorithm of synchrophasor placement in the future. Reference [47] gives an entire summary of various ways to get electrical distance. We adapted the method that was derived from the first quadrant of the ac power flow Jacobian matrix. In the future, we will also analyze the fourth quadrant of it, which reflects the impact of the reactive power changes with respect to the voltage magnitude.

Based on students feedback, the future work for this power protection laboratory will focus on developing more hardware testings, and this laboratory will extend to full term laboratory course (ten weeks). There will be more devices on the 19-inch racks for next year that capture different generations of relays. Moreover, we will also consider how to cut down the learning curve for the new software tool that students

will also use in the field.

Bibliography

[1] N. Hatziargyriou, Ed., *Microgrids - Architectures and Control.* WILEY, 2014.

[2] S. Marcacci. [Online]. Available: http://cleantechnica.com/2013/04/03/over-400-microgrid-projects-underway-en-route-to-40-billion-market/

[3] R. Bass and E. Cotilla-Sanchez, "Oregon power engineering education project, phase iii," Portland State Univerisity and Oregon State University, Tech. Rep., 2015.

[4] ""grid 2030": A national vision for electricity's second 100 years," United States Department of Energy, Tech. Rep., July 2003.

[5] D. V. Dollen, "Report to NIST on the smart grids interoperability standards roadmap," Electric Power Research Institute, Tech. Rep., August 2009.

[6] J. P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities," *Electric Power Systems Research*, vol. 77, no. 9, pp. 1189–1203, 2007.

[7] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids: An overview of ongoing research development and demonstration projects," *IEEE Power and Energy Magazine*, vol. 5, no. 4, pp. 78–94, August 2007.

[8] [Online]. Available: http://energy.gov/oe/services/technology-development/smart-grid

[9] N. Hatziargyriou, N. Jenkins, G. Strbac, J. A. Pecaslopes, J. Ruela, A. Engler, J. Oyarzabal, G. Kariniotakis, and A. Amorim, "Microgrids - large scale integration of microgeneration to low voltage grids," in *CIGRE C6-309*, 2006.

[10] [Online]. Available: http://microgrids.eu/default.php

[11] R. Majumder, G. Ledwich, A. Ghosh, S. Chakrabarti, and F. Zare, "Droop control of converter-interfaced microsources in rural distributed generation," *Power Delivery, IEEE Transactions on*, vol. 25, no. 4, pp. 2768–2778, Oct 2010.

[12] "Microgrid project at IIT." [Online]. Available: http://www.iitmicrogrid.net/microgrid.aspx

[13] "Microgrid: Keeping the lights on." [Online]. Available: http://alumni.ucsd.edu/s/1170/emag/emag-interior-2-col.aspx?sid=1170&gid=1&pgid=4665

[14] "Hachinohe microgrid." [Online]. Available: http://microgrid-symposiums.org/microgrid-examples-and-demonstrations/hachinohe-microgrid/

[15] Y. Kojima, M. Koshio, S. Nakamura, H. Maejima, Y. Fujioka, and T. Goda, "A demonstration project in hachinohe: Microgrid with private distribution line," in *System of Systems Engineering, 2007. SoSE '07. IEEE International Conference on*, April 2007, pp. 1–6.

[16] S. Borlase, *Smart Grids - Infrastructure, Technology, and Solutions.* CRC Press, 2012.

[17] N. Hatziargyriou, "Advanced architectures and control concepts for more microgrids," European Commission, Tech. Rep., 2006.

[18] J. H. Chow, P. Quinn, L. Beard, D. Sobajic, A. Silverstein, and L. Vanfretti, "Guidelines for siting phasor measurement units: Research initiative task team (RITT) report," North American SynchroPhasor Initiative (NASPI), Tech. Rep., June 2011.

[19] M. T. Osborn, "Oregon state university smart grid strategy guidepost," FIVE STARS INTERNATIONAL, LTD., Tech. Rep., January 2014.

[20] R. F. Nuqui and A. G. Phadke, "Phasor measurement unit placement techniques for complete and incomplete observability," *Power Delivery, IEEE Transactions on*, vol. 20, no. 4, pp. 2381–2388, 2005.

[21] E. Cotilla-Sanchez, P. Hines, C. Barrows, and S. Blumsack, "Comparing the topological and electrical structure of the north american electric power infrastructure," *Systems Journal, IEEE*, vol. 6, no. 4, pp. 616–626, Dec 2012.

[22] R. Sodhi, S. Srivastava, and S. Singh, "Optimal PMU placement to ensure system observability under contingencies," in *Power Energy Society General Meeting, 2009. PES '09. IEEE.* IEEE, July 2009, pp. 1–6.

[23] K. Nagananda, "Electrical structure-based PMU placement in electric power systems," *arXiv preprint arXiv:1309.1300*, 2013.

[24] K. G. Nagananda, K. S., and B. R. S., "A PMU scheduling scheme for transmission of synchrophasor data in electric power systems," *arXiv preprint arXiv:1405.6790*, 2014.

[25] D. Dua, S. Dambhare, R. K. Gajbhiye, and S. A. Soman, "Optimal multi-stage scheduling of PMU placement: An ILP approach," *Power Delivery, IEEE Transactions on*, vol. 23, no. 4, pp. 1812–1820, Oct. 2008.

[26] K. G. Nagananda and S. Kishore, "A unifying framework for the electrical structure-based approach to PMU placement in electric power systems," *arXiv preprint arXiv:1312.0336v1*, 2013.

[27] G. Mueller, P. Komarnicki, Z. Styczynski, C. Dzienis, I. Golub, and J. Blumschein, "PMU placement method based on decoupled newton power flow and sensitivity analysis," in *Electrical Power Quality and Utilisation, 2007. EPQU 2007. 9th International Conference on.* IEEE, 2007, pp. 1–5.

[28] Z. Hongshan, L. Ying, M. Zengqiang, and Y. Lei, "Sensitivity constrained PMU placement for complete observability of power systems," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES.* IEEE, 2005, pp. 1–5.

[29] P. Chunhua and X. Xuesong, "A hybrid algorithm based on immune BPSO and N-1 principle for PMU multi-objective optimization placement," in *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on.* IEEE, 2008, pp. 610–614.

[30] V. Kekatos, G. B. Giannakis, and B. Wollenberg, "Optimal placement of phasor measurement units via convex relaxation," *Power Systems, IEEE Transactions on*, vol. 27, no. 3, pp. 1521–1530, Aug 2012.

[31] Q. Li, T. Cui, Y. Weng, R. Negi, F. Franchetti, and M. Ilic, "An information-theoretic approach to PMU placement in electric power systems," *Smart Grid, IEEE Transactions on*, vol. 4, no. 1, pp. 446–456, 2013.

[32] P. D. Hines, "A power systems capstone design project and associated simulation software designed to meet the changing needs of the electrical power industry and engineering accreditation requirements," Master's thesis, University of Washington, 2001.

[33] M. Sachdev and T. Sidhu, "A laboratory for research and teaching of microprocessor-based power system protection," *Power Systems, IEEE Transactions on*, vol. 11, no. 2, pp. 613–619, May 1996.

[34] B. Chowdhury, B. Parkhideh, A. Martin, Z. Salami, J. Enslin, V. Cecchi, S. Kamalasadan, and N. Maciej, "Enhancing power and energy systems concepts with laboratory experience," in *Power and Energy Society General Meeting (PES), 2013 IEEE*, July 2013, pp. 1–5.

[35] W.-J. Lee, J.-C. Gu, R.-J. Li, and P. Didsayabutra, "A physical laboratory for protective relay education," *Education, IEEE Transactions on*, vol. 45, no. 2, pp. 182–186, May 2002.

[36] X. ping Wang, Y. Li, and Y. yang Yu, "Research on the relay protection system for a small laboratory-scale microgrid system," in *Industrial Electronics and Applications (ICIEA), 2011 6th IEEE Conference on*, June 2011, pp. 2712–2716.

[37] T. Strasser, M. Stifter, F. Andrén, and P. Palensky, "Co-simulation training platform for smart grids," *Power Systems, IEEE Transactions on*, vol. 29, no. 4, pp. 1989–1997, July 2014.

[38] R. Horta-Bernus and M. Rosas-Casals, "Modification of the perrine-baum diagram to improve the calculation of high-voltage transmission lines," *Education, IEEE Transactions on*, vol. 56, no. 3, pp. 274–279, Aug 2013.

[39] N. Soundarajan, "Engineering criteria 2000: the impact on engineering education," in *Frontiers in Education Conference, 1999. FIE '99. 29th Annual*, vol. 1, Nov 1999, pp. 11A1/25–11A1/30 vol.1.

[40] [Online]. Available: http://www.abet.org/about-abet/

[41] P. Lagonotte, J. Sabonnadiere, J. Leost, and J. Paul, "Structural analysis of the electrical system: application to secondary voltage control in france," *Power Systems, IEEE Transactions on*, vol. 4, no. 2, pp. 479–486, May 1989.

[42] D. Klein and M. Randic, "Resistance distance," *Journal of Mathematical Chemistry*, vol. 12, no. 1, pp. 81–95, 1993.

[43] J. Song, T. K. A. Brekken, E. Cotilla-Sanchez, A. von Jouanne, and J. D. Davidson, "Optimal placement of energy storage and demand response in the

pacific northwest," in *Power and Energy Society General Meeting (PES), 2013 IEEE*, July 2013, pp. 1–5.

[44] T. Greville, "Some applications of the pseudoinverse of a matrix," *SIAM Rev.*, vol. 2, no. 1, pp. 15–22, Jan. 1960.

[45] "Oneliner: The leading short circuit and relay coordination system." [Online]. Available: http://www.aspeninc.com/web/index2256.html?option= com_content&view=article&id=91&Itemid=64

[46] J. Ferris, "The design, implementation, assessment, and evaluation of a power systems protection laboratory curriculum," Master's thesis, Portland State University, March 2014.

[47] P. Cuffe and A. Keane, "Visualizing the electrical structure of power systems," *Systems Journal, IEEE*, vol. PP, no. 99, pp. 1–12, 2015.

APPENDICES

Appendix A: Laboratory Instructions

Oregon State University

Electrical & Computer Engineering

ECE 436/536 Power System Protection

-Lab #1. Overview of Power System Characteristics 1-

Week 2, 1/15/2015

Introduction

This lab introduces students to the power protection equipment and simulation software that will be used in subsequent laboratory assignments. Students will build a single-source, three-phase radial power circuit model by using ASPEN software. Students also need to review symmetrical components and will analyze the fault results by comparing simulated results to calculated results.

Objectives

At the end of the laboratory exercise, student will be able to do the following:
• Create simple cases in ASPEN OneLiner. Including positive-, negative- and zero-sequence impedances of line and generators as well as proper transformer connections.
• Run ASPEN Power Flow on a power system case and perform basic analysis of the results.
• Identify the results of the power flow that have an influence in the fault study.
• Perform a basic fault study, obtaining results for three-phase, single line-to-ground and line-to-line faults in the relevant parts of the system and interpret the results.

Distributed System:
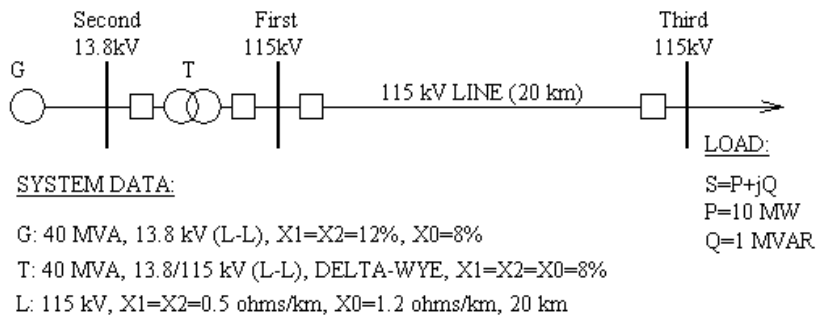
Figure 1: System diagram

Notes:
- Make sure the Device Palette is selected under View
- How and what data is displayed on the one-line can be changed by selecting the Faults menu and choosing Show Fault Solution on 1-line.
- The OneLiner Help Contents are extremely useful.
- Convert any ohmic values to per unit (e.g. the line values).
- Choose a system base of 100MVA.

STEP 1. In ASPEN OneLiner and Power Flow, choose an appropriate MVA$_{base}$ for the system, then enter the basic system data in the following order:
- FIRST bus (115kV)
- SECOND bus (13.8 kV)
- Enter Cable line information (Neglect susceptance, B, and conductance, G.). Be sure to convert cable information to p.u. values. This will automatically connect to a third bus (115 kV). Rename this new bus as THIRD.
- Transformer (IMPORTANT: First click the mouse on, or mark, bus FIRST and then mark bus SECOND. The FIRST bus cannot contain the DELTA side of the transformer). Enter the per unit values of the data listed in Figure 1.
- Add generator to SECOND bus. For transient and subtransient impedance values, use the same values as X1 and X2.
- Add Load information (Must be entered in MW and MVAR. Do not use per unit quantities.)
- Add the Circuit Breakers (Called "RELAY GROUPS" in OneLiner) by clicking on a line near a bus, selecting Relay from the menu, selecting New Relay Group and Done. **Do not** click ADD button to add relays

to the circuit breakers.

Note: The provided basic system data may need to be adjusted for chosen MVA_base, if MVA base differs from element MVA nominal rating.

STEP 2. Simulate a three-phase fault close to the breaker on the line side of bus FIRST by clicking on the relay group. On the Fault Specification window, choose CLOSE-IN FAULT with NO OUTAGE and 3LG. Save the TTY results for the assignment report. Include a snap shot of the result of the fault on the one-line diagram for phase A as well as for the sequence component currents.

STEP 3. Simulate a single line-to-ground fault at the same point and save the same information as requested in STEP 2. Discuss balanced versus unbalanced faults. Discuss the contributions of positive, negative and zero sequence components for each of these kinds of faults.

STEP 4. Determine the neutral currents for both faults, at the transformer and generator neutral connections.

STEP 5. Determine accuracy of fault calculation by hand or by writing a script in MATLAB using theoretical calculations. Include this calculation in your report.

Note: Reference tutorial in section 2-8 of the ASPEN OneLiner on-line help. Use the IEEE09.OLR file in the library for this tutorial if you feel you need practice before beginning the assignment.

Deliverables

Compile your results from the TTY outputs into tables that are easy for the report reader to interpret. Also include images of the system one-lines. Identify the relevant parts of the results to the fault study. Include in your report analysis and discussion of each of the faults in the study. Report is due in the beginning of next lab (1/22/2015).

Note: Be sure to save copies of your ASPEN OneLiner models as they will be used in future lab assignments.

Oregon State University

Electrical & Computer Engineering

ECE 436/536 Power System Protection

-Lab #2. Overview of Power System Characteristics 2-

Week 3, 1/22/2015

Introduction

This lab continues introducing students to the power protection equipment and simulation software that will be used in subsequent laboratory assignments. Students will build a three-source, single load, looped power circuit model using ASPEN software. Students also need to review symmetrical components and will analyze the fault results by comparing simulated results to calculated results.

Objectives

At the end of the laboratory exercise, student will be able to do the following:
- Create simple cases in ASPEN OneLiner, including positive-, negative-, and zero-sequence impedances of line and generators as well as proper transformer connections.
- Identify the results of the power flow that have an influence in the fault study.
- Perform a basic fault study, obtaining results for three-phase, single line-to-ground and line-to-line faults in the relevant parts of the system and interpret the results.

Looped System:
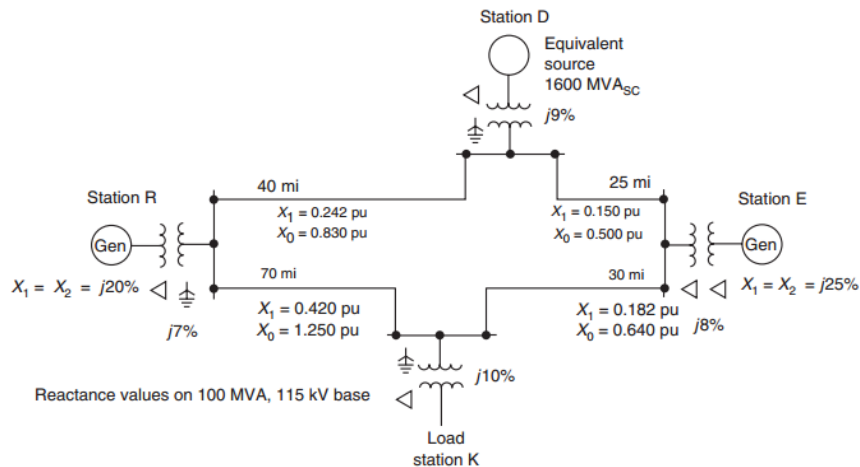
Figure 2: Power system example from Blackburn Relaying Principles (Figure 4.32)

STEP 1. Create the system from Figure 2 using in ASPEN OneLiner, adding circuit breakers to all lines and transformer ends, similar to Part 1 above. Do not add relays to the circuit breakers, this will be done in a future lab exercise.

STEP 2. Reference Appendix A for the complete system information. Put these settings into your ASPEN model.

STEP 3. Simulate three-phase and line-to-ground faults on each of the breakers at buses in all four stations. Determine the 0-1-2 sequence currents, phase a-b-c currents and voltages for each of the two circuit breakers at the bus where each of the faults is located. At which busses are faults higher? Why?

STEP 4. Add new line between stations D and K with parameters of L = 100 mi, X1 = 0.5pu, X0 = 1.5pu.

STEP 5. Repeat the simulations from STEP 3) with the additional line in the system between stations D and K. Determine the 0-1-2 sequence currents, phase a-b-c currents and voltages for each of the two circuit breakers at the bus where each of the faults is located. Note

the similarities and differences in the system behavior.

STEP 6.   Simulate a line-to-line fault at the midpoint of the new line and determine the sequence 0-1-2, phase a-b-c currents and voltages at the breakers at each end of the new line. Note the system behavior.

Deliverables

Compile your results from the TTY outputs into tables that are easy for the report reader to interpret. Also include images of the system one-lines. Identify the relevant parts of the results to the fault study. Include in your report analysis and discussion of each of the faults in the study. Report is due in the beginning of next lab (1/29/2015).

Note: Be sure to save copies of your ASPEN OneLiner models as they will be used in future lab assignments.

Appendix A: ASPEN looped system component details

Station D:

From BUS5 to BUS1:

Station R:

From Bus1 to Bus7:

Station K:

From Bus 7 to Bus3:

Transmission Line Data

BUS3   115.kV -   BUS7   115.kV

Name= L4   Ckt ID= 1

Length= 30.   mi   Type

Branch Parameters

R= 0.08802	X= 0.182		
R0= 0.2358	X0= 0.5		Recompute from table
G1= 0.	B1= 0.03285	G2= 0.	B2= 0.03285
G10= 0.	B10= 0.01237	G20= 0.	B20= 0.01237

Current Ratings (A)

A: 100.   B: 200.   C: 300.   D: 400.

Metered at: BUS3   115. kV
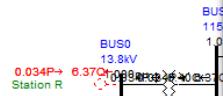
Memo:

Tags: None

Mutuals...   OK   Cancel   Help

Last changed Dec 21, 2012

BUS3
115.kV
1.006pu

0.375P ← 0.641Q←

0.375P → 8.46Q→

0.375P → 0.667 Q→

0.398P → 1.79Q→

0.016pu Load

Station E:

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-Lab 3. Coordination of OC Relays in Radial Systems-

Week 6, 2/12/2015

Introduction

In this laboratory exercise the students will be introduced to the coordination of overcurrent relays in a radial power system using an industry software program (ASPEN OneLiner).


Objectives

At the end of the laboratory exercise the student will be able to do the following:

➢ Create a radial case in ASPEN OneLiner containing the required information to do fault studies and overcurrent relay coordination
➢ Introduce data of phase overcurrent relay elements into the model
➢ Simulate faults and determine the behavior (time) of overcurrent relay elements
➢ Perform a coordination study to determine the relay settings

Distributed System:
Using the distributed system model from Lab 1, re-save model under new name.

STEP 1.   Simulate a 3LG fault at the same point as done in Lab 1, near **Bus1** on the 20 km line side, to affirm the results found in lab 1 are still the same. Record fault current values of simulation with a figure of the model. Verify these results with TA to make sure your system model is correct.
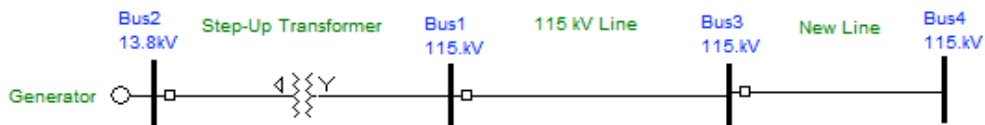
System Data:
G: 40 MVA, 13.8 kV (L-L), X1=X2=12%, X0 = 8%

T: 40 MVA, 13.8/115 kV (L-L, Dy11), X1= X2 =X0 = 0.2 (for 100 MVA system base)
L: 115 kV, X1=X2= 0.5 ohms/km, X0 = 1.2 ohms/km (adjust values to Z_{pu})
Figure 1:   ASPEN radial system model

STEP 2.   Make the following alterations: Delete the *load* on the Bus 3 and add new 10 km, 115 kV line from Bus3 (program will automatically create Bus 4) with the following impedances:

> $Z_{L1}=Z_{L2}= j0.1$ p.u.

> $Z_{L0} = j0.3$ p.u.

STEP 3.   Insert a circuit breaker located at Bus3 on the 10 km line side, as shown in Figure 1, using the Relay →New Relay Group.

STEP 4.   Insert a group of phase relays in the circuit breaker located at Bus3 on the 10 km line side by selecting the circuit breaker and choosing the OC Phase Relay under Properties (highlight CB and right click) →Add. Set the following characteristics for the relay:

ID: R1

Relay Type (Curve…): General Electric IAC53

CT Ratio: 400/5 = 80

I_{pu}: 5 Amp

Time Dial: 3

Instantaneous: 100,000 Amps

STEP 5.   Insert a group of phase relays in the circuit breaker located at Bus 1 of the 20 km line side:

ID: R2

Relay Type (Curve…): General Electric IAC53

CT Ratio: 600/5 = 120

I_{pu}: 5 Amp

Time Dial: 1.5

Instantaneous: 100,000 Amps

STEP 6.   Again, using the same procedures as in Lab 1, simulate a three-phase fault close to the circuit breaker located close to Bus3 on the 10 km line side.

Examine and record the fault currents on the one-line diagram with a figure of the model.

STEP 7. Display all relay operation times by choosing the clock icon on the program toolbar. Examine and record the relay operation times on the one-line diagram with a figure of the model. Analyze results and determine if the relay operation sequence is correct and explain why? Compare with relay curves in STEP 8.

STEP 8. Choosing View Relay Curve and Protection Scheme… in the Relay menu, display the relay curves at the marked relay group (circuit breaker). Choose the Add command in the Relay Curves window then select Relay Curves… and add the relay from the other relay group. Under the Show menu choose Relay Operations for 1 Fault. Record the relay curves for this fault with a figure of the curves. Verify coordination (0.3-0.5s delay) with the curves, adjusting settings for proper coordination, if necessary.

STEP 9. Change the impedance value of the line between Bus1 and Bus3. This makes it virtually longer and shorter. Re-simulate the three-phase fault each time. Notice what this does to the coordination of you relays. Regarding coordination, how would you compensate for these differences? Note these differences for inclusion in your lab write-up. Change line back to your original impedance value.

STEP 10. Add another IAC53 relay on the 13.8 kV side of the transformer near Bus2. Calculate the CT rating using I_{sc} of Bus2 as 13,943A and choose the appropriate rated CTR for the phase relay. Choose $I_{pu} = 5$ A for this new relay and calculate the time dial settings for a proper coordination with the rest of the system and put your systems in the ASPEN relay data window. Plot the relay and the transformer damage curves together with the curves of the rest of the relays. Verify coordination graphically with these curves. Write your conclusion with regard to coordination result.

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-Lab 4. Protection Coordination of Looped Systems-

Week 8, 2/26/2015

Introduction

In this laboratory exercise the students will be introduced to the coordination of over-current relays in a looped power system using an industry software program (ASPEN OneLiner).

Objectives

At the end of the laboratory exercise the student will be able to do the following:

➢ Create a looped case in ASPEN OneLiner containing the required information to perform fault studies and overcurrent relay coordination.
➢ Introduce data of phase and ground directional overcurrent relay elements into the model.
➢ Simulate faults and determine the behavior (time) of overcurrent relay elements.
➢ Perform a coordination study to determine the relay settings.
➢ Draw a relay coordination scheme for a loop system.

Looped System:

Using the distributed system model from Lab 2, re-save model under new name and make the following alterations outlined in the steps below.
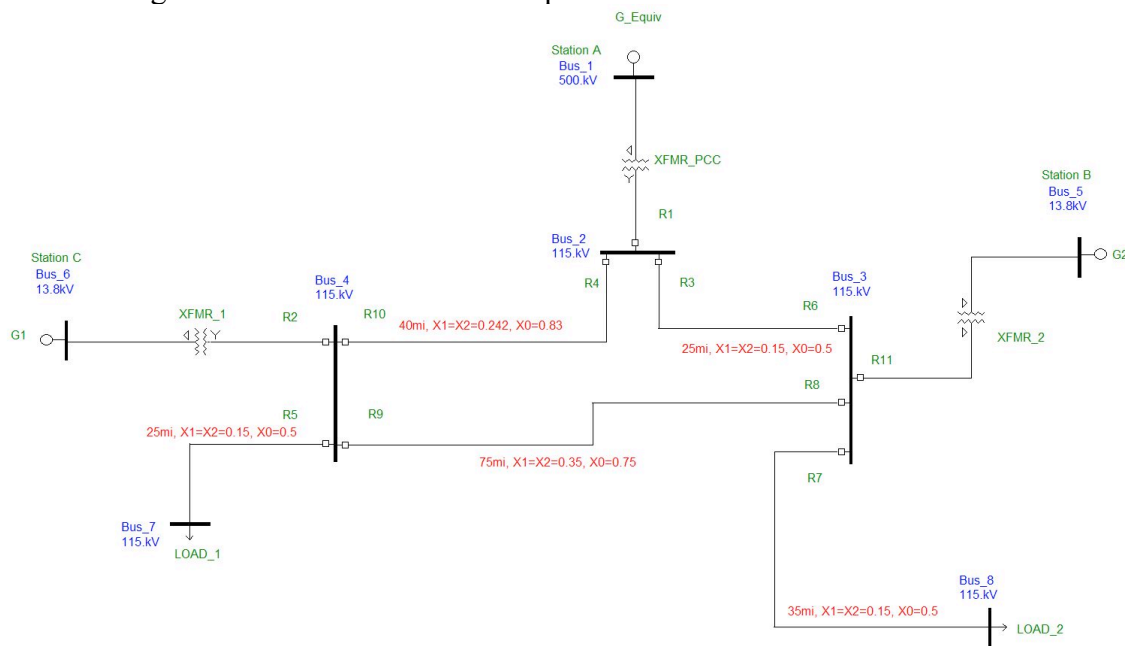
Figure 1: Power system example

Relay	From Bus	To Bus
R1	2	1
R2	4	6
R3	2	3
R4	2	4
R5	4	7
R6	3	2
R7	3	8
R8	3	4
R9	4	3
R10	4	2
R11	3	5

Table 1: Relay identification for power system in Figure 1

STEP 1.   Alter the system from Lab 2 by using the same notations as shown in Figure 1. Alter all values for the Generators, Transformers, and Transmission Lines as follows:

- G_Equiv: 1600 MVA, 500 kV, X1 = X2 = 0.01 p.u., X0 = 0.05 p.u.
- G1: 80 MVA, 115 kV, X1 = X2 = 0.16 p.u., X0 = 0.1 p.u.
- G2: 100 MVA, 115 kV, X1 = X2 = 0.135 p.u., X0 = 0.09 p.u.
- LOAD_1: 115 kV, 10 MW, 1 MVAR
- LOAD_2: 115 kV, 10 MW, 1 MVAR
- XFMR_1: 13.8/115 kV, X1 =X0 =0.1
- XFMR_2: 13.8/115 kV, X1 =X0 =0.09
- XFMR_PCC: 500/115 kV, X1 =X0 = 0.02

STEP 2.   Add (67) phase relays on both ends of each line and on the network side on each transformer using the relay identification numbers indicated in Table 1. Decide which relays must be regular overcurrent, based on their placement in the system, and set in ASPEN.   You can start by using the same settings for each relay inside the loop (there will be different default settings for relays outside the loop):

- **Relay Type:** GE JBC51
- **CT Ratio:** 400/5 = 80
- **TAP:** 5 A
- **Time Dial:** 3
- **Instantaneous:** 100,000 A
- **Directional Time Element:**   (student discretion)
- **Directional Instantaneous:** unchecked

**Note: You should use directional units for all the relays in the loop. For R1, R2, R5, R7, and R11, use directional units wherever you think is necessary, and regular OC everywhere else. In your report, explain why you use directional or non-directional for those five relays? **

STEP 3.   Neglect the fact that the pickup values should be well above load currents. Assume that relay R1 has a CTR = 100, TD = 0.5, and I pu = 0.5 A. Assume that relays R5 and R7 have a time dial of 1.0 and an I pu = 1 A. The relays looking into generator units G1 and G2 have a time dial setting of 0.5 and I pu = 1 A with CTR = 80.

STEP 4.   Perform 11 faults in this looped system: fault on bus 2, 3, and 4; fault on those six relays in the loop; fault on R5 and R7.

For the loop, first the coordination pairs must be determined; this is done by performing a close-in, 3-phase fault. Relays are analyzed first with the necessary simulations for both clockwise and counter clockwise analysis around the loop, starting at the equivalent source, in order to determine the time dial settings of the relays in the loop. Use the example on page 435 from section 12.8 in the Blackburn text, referencing Figure 12.7 as your guide for looped coordination.

Simulate the faults and adjust the time dial and current pick-up setting until all relays are

properly coordinated as explained in lecture theory and Chapter 12 (i.e. section 12.8) of the Blackburn text. If necessary, slightly adjust CTR values. Use a loop coordination interval range of 0.3 to 0.4 seconds for the far-bus faults. Reference suggested operating times for close-in faults outlined in section 12.8. Discuss your criteria in your written report.

Deliverables

Produce a report with your system screen shot along with the final settings of the relays, and the performance and operational times for each of the faults. Include a figure of coordination results as same format as figure 12.9 of textbook. Note that there may be several different solutions to this problem. Discuss how your solution can be improved. Report is due in the beginning of next lab (3/5/2015).

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-Lab #5. AC Time Overcurrent Relays (51) Testing-

Week 9, 3/5/2015

Introduction

In this laboratory exercise, the student learns about digital overcurrent relays.

Objectives

At the end of the laboratory exercise the student will be able to do the following:

➢ Implement physical set-up to test SEL-351S using the SEL-RTS (AMS)
➢ Introduce settings to the relay (Phase and Neutral Ground elements)
➢ Test the SEL-351S relay with SEL-5401 software

Materials/Equipment

➢ SEL-351S Protection System relay
➢ SEL-AMS
➢ SEL-5401 software
➢ AcSELerator QuickStart software
➢ C724 ribbon cable
➢ C662 USB to serial port cable

STEP 1. Connect the AMS to the SEL-351S based on Figure 1, using the appropriate ribbon cable. Have TA check connections before proceeding.
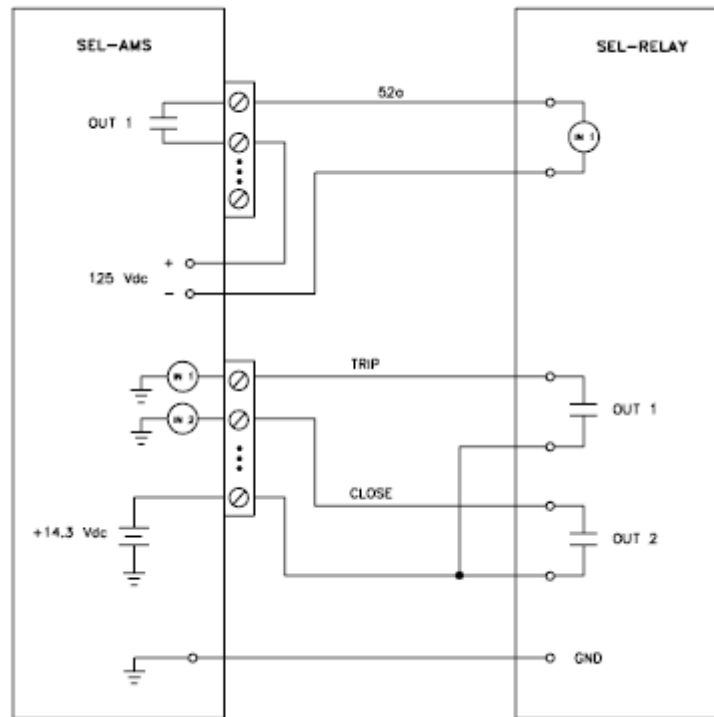
Figure 1: Digital relay testing physical set-up with SEL-AMS

STEP 2. Turn on the two switches on the physical panel of SEL-AMS. Observe the signal lights for both SEL-351S and SEL-AMS. Connect the SEL-351S to the computer using C662 cable. Then open AcSELerator Quickset, and establish communication by using the proper communication settings in the AcSELerator. Set the SEL-351S according to the table shown in the end of this document.

STEP 3. Connect the AMS testing system to the computer with the C662 cable. Open the SEL-5401 program, go to *UUT Database* and update your SEL-351S relay to be a 5 Amp device. Verify *Scale Factors* have been adjusted, save and close the *UUT Database* window and then select the SEL-351S relay model from the menu for the new settings. Before set the State Values (IA, IB, IC, IN), perform the *METER test* with the *Front Panel* command on the tool bar. Verify that the values shown on the relay front panel meter (in primary units) are consistent with the CTR programmed into the SEL-351S.

***Meter test: To verify internal CTR settings are acting as expected and that SEL-AMS is communicating with SEL-351S, select the **Meter** button on the SEL-351S physical front*

*panel. Then select the virtual Front Panel (FP) button on the SEL-5401 program toolbar. In the **Front Panel** window set **IA = 1.00 @ 0º, IB = 0.5 @ -120º, IC = 1.5 @120º, IN = 2.00 @ 0º**. Then select **Start** under **No Test Executing**. Monitor the SEL-351S phase currents on the front panel of the relay, verify that these match with the expected primary currents, as taken through the relay CTR settings. Once these values are as expected, the fault test to verify relay operating time can be set.***

STEP 4.   If *Front Panel* METER test results are inaccurate, adjust the Scale Factor of the SEL-351S proportionally until values read as expected. Each time the *Scale Factor* is adjusted, a new case with a new SEL-351S relay must be opened to include this adjusted *Scale Factor.* The Scale Factor adjusting steps are shown as follow: SEL-5401 → Configuration → UUT Database → Relay Name → SEL-351S → UUT File Selection → 5Amp Relay File → Apply → Update → Change the Scale Factor → Save → Close → New Test → SEL-351S → FP Icon → Start (under No Test Executing) → observe the physical front panel to see if the reading is what you expect according to the CTR. If not, redo the previous process with different Scale Factor.

STEP 5.   Click two times Append State on the toolbar. Apply the settings in the SEL-5401 software as given in Table 1 and 2 below. Case 1 is a balanced 3-ϕ fault. Case 2 is 1-ϕ fault. Click Download & Run This Test on the toolbar. Observe the physical front panel.

State No. 1			State No. 2			State No. 3		
Pre-Fault State			Fault State			Post-Fault State		
I_A	2	0	I_A	20	0	I_A	0	0
I_B	2	-120	I_B	20	-120	I_B	0	-120
I_C	2	120	I_C	20	120	I_C	0	120
V_A	67	0	V_A	11.6	0	V_A	67	0
V_B	67	-120	V_B	11.6	-120	V_B	67	-120
V_C	67	120	V_C	11.6	120	V_C	67	120
Time	60.00		Time	180.00		Time	60.00	
OUT1	O		OUT1	C		OUT1	O	

Table 1: 3-phase fault parameters

State No. 1			State No. 2			State No. 3		
Pre-Fault State			Fault State			Post-Fault State		
I_A	2	0	I_A	24	0	I_A	0	0
I_B	2	-120	I_B	0.5	-120	I_B	0	-120
I_C	2	120	I_C	0.5	120	I_C	0	120

V_A	67	0	V_A	17	0	V_A	67	0
V_B	67	-120	V_B	46	-120	V_B	67	-120
V_C	67	120	V_C	46	120	V_C	67	120
Time	60.00		Time	180.00		Time	60.00	
OUT1	O		OUT1	C		OUT1	O	

Table 2: 1-phase fault parameters

STEP 6.   Based on your pickup current setting, and applying different sets of values for I_A, I_B, and I_C, try to roughly guess what is the minimum fault value for this SEL-351S. When you close AcSELerator and SEL-5401, please click close without save.

****
****

In AcSELerator QuickStart, click Read to access the settings of SEL-351S:

Use the following settings to program the SEL-351S for testing:

Set 1	Setting Symbol	Description	Units	Value
General Settings				
	CTR	Phase Current Xfmr Ratio	N/A	50
	CTRN	Neutral Phase Current Xfmr Ratio	N/A	50
	PTR	Phase Potential Xfmr Ratio	N/A	1137.47
	PTRS	Sync. Voltage Xfmr Ratio	N/A	1137.47
	VNOM	Phase PT Nom Volt (L-N)	V_{SEC}	67
Line Settings				
	Z1MAG	Positive-seq Impedance Mag	Ω_{sec}	1.5
	Z1ANG	Positive-seq Impedance Ang	Degrees	80
	Z0MAG	Zero-seq Impedance Mag	Ω_{sec}	5.2
	Z0ANG	Zero-seq Impedance Angle	Degrees	80
	LL	Line Length	%	100
	EFLOC	Fault Locator	N/A	Y
Phase Overcurrent Elements				
	E50P	Phase Overcurrent Elements	N/A	N
Neutral Ground Overcurrent Elements				
	E50N	Neutral Overcurrent Elements	N/A	N
Residual Ground Overcurrent Elements				
	E50G	Residual Ground Overcurrent Elements	N/A	N

Negative-Seq Overrcurrent Elements				
	E50Q	Neg-Seq Overcurrent Elements	N/A	N
Phase Time-Overcurrent Elements				
	E51P	Phase Time-Overcurrent Elements	N/A	1
	51P1P	Level 1 Pickup (Amps secondary)	A	3
	51P1C	Curve	N/A	U2
	51P1TD	Time Dial	N/A	2.5
	51P1RS	Electromechanical Reset Delay	N/A	N
	ALL OTHER SETTINGS LEAVE AS DEFAULT			
Neutral Ground Time-Overcurrent Overcurrent Elements				
	E51N	Neutral Ground Time-Overcurrent Elements Settings	N/A	1
		Neutral Time-Overcurrent Element	A	0.5
		Curve	N/A	U2
		Time Dial	N/A	2.5
		Electromechanical Reset Delay	N/A	N
	ALL OTHER SETTINGS LEAVE AS DEFAULT			
Residual Ground Time-Overcurrent Elements				
	E51G	Residual Ground Time-Overcurrent Elements Settings	N/A	N
Negative-Sequence Time-Overcurrent Elements				
	E51Q	Negative-Sequence Time-Overcurrent Elements Settings	N/A	N
Load Encroachment Element				
	ELOAD	Load Encroachment Element	N/A	N
Directional Elements				
	E32	Directional Control Elements Settings	N/A	AUTO
	ELOP	Loss-Of-Potential	N/A	N
	DIR 1 - 4	Level 1 - 4 Direction	N/A	F
	ORDER	Ground Directional Priority	N/A	V
	ALL OTHER SETTINGS LEAVE AS DEFAULT			

Leave all other *Set 1* settings as default. Click 'send active settings' on the toolbar.

Appendix B: Laboratory Feedback forms

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Lab 1 and 2 Feedback

1. The challenging steps for lab 1 and lab 2.

2. The helpful steps.

3. Is there anything you are expected to know from the lab?

4. The improvements or comments of this lab.

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Lab 3 and 4 Feedback

1. The challenging steps for lab 3 and lab 4.

2. Which steps you think are most helpful related to the Protection lecture?

3. Do you think lab 3 and 4 reach the goals based on the manual? (Circle one of the following)
   a. Yes   b. Kind of   c. Not really   d. No

4. Is there anything else related to power system protection that you are expected to know from lab 3 and lab 4?

5. The improvements or comments of lab 3 and lab 4.