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Developing a Substation Design Curriculum for Electronics Engineering Technology

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Developing a substation design curriculum for an Electronics Engineering Technology program

Abstract

Background: The latest technologies have created an increasing demand for the generation, transmission, and distribution of electricity. Substations are a crucial segment of our power grid. Substations are used to step-up voltages for the long-distance transmission of energy and to step-down voltages for industrial and residential use.

The demand for substation design curriculum was discussed at a meeting of the Industrial Advisory Committee (IAC) for EET. Members of the IAC consisted of professionals from Black & Veatch and other companies that work with power systems such as substations and switchgear. The curriculum was developed in close cooperation with Black & Veatch to shape the curriculum with a practical approach.

Purpose: This paper describes the development of a substation design curriculum to be used in an Electronics Engineering Technology (EET) program at Pittsburg State University (PSU).

Method: In 2019, a PSU faculty participated in a series of NSF sponsored workshops for facilitating the teaching of electric energy (Workshops for Facilitating Faculty to Teach Electric Energy Courses for Combating Climate Change, 2019) since the EET faculty did not have a strong background in power systems. In addition, a graduate assistant with a background in power systems was recruited to create the substation design curriculum. In the same year, a visit to Black & Veatch was conducted where the substation design process was presented to a PSU faculty and the graduate assistant. It was discussed what topics should be included in the curriculum.

In 2020, the substation design curriculum was introduced into an existing Electric Power course. The substation curriculum included lectures on the basics of generation, transmission, and distribution; substation components; one-line diagrams; and circuit breaker topologies. The curriculum also consisted of two labs which used the PowerWorld software and an exam. A guest speaker from Black & Veatch concluded the substation curriculum with a presentation of substation design projects. The effectiveness of the substation design curriculum was assessed by analyzing student work on one of the labs and selected questions from the exam on substation design.

Results: A rubric was applied to the lab and the average was 1.86 out of 3 points. The percentage of correct answers on selected questions in the exam was 95%.

Conclusion: Assessment results for the labs and exam showed that students learned the material and the new curriculum was effective overall. Another benefit of the substation curriculum development was that the graduate student secured an internship at Black & Veatch where he worked in designing substations. In addition, Black & Veatch offered five full scholarships to

PSU students in the EET program in 2020-21 academic year and the broadening of students' knowledge in power systems.

Keywords: power systems, circuit breakers configurations, protection, PowerWorld, simulation, transformers.

Motivation

The decision to develop substation design curriculum was motivated by the increasing demand for professionals with power systems knowledge due to the continuous expansion of power grids. Black & Veatch has representatives on the IAC for the EET program at PSU. They expressed their interest in students from PSU based on their positive experiences from hiring alumni. They gave the following testimonial:

> *"Black & Veatch has a long track record of success with Pittsburg State Electronics Engineering Technology (EET) graduates. Their graduates produce quality engineering work and have been valued members of our team over the years. It has been an honor to work with Erik and Filipe on developing course content for substation design. This content will help graduates be effective from Day 1, and it will help us provide reliable power around the world for years to come."*
>
> *Garrett Johnson, Substation Designer, Black & Veatch.*

In the fall semester of 2019, a graduate assistant was hired to work with faculty in developing a new curriculum on substation design for EET majors. The graduate assistant had recently completed a degree in electrical engineering with an emphasis in power systems. The substation design curriculum at PSU was developed to be practical and was adapted to EET students with emphases in embedded systems and industrial automation.

Curriculum

The project started with a discussion of how to adapt power topics from a more theoretical engineering program to a more practical engineering technology program. The graduate assistant and faculty worked together in determining what modifications would be necessary in the EET program.

The first modification to the EET program happened in the fall semester of 2019 with the AC Circuit Analysis course which is a sophomore level class. The course was revised to be taught with more emphasis on single-phase power systems. This allowed a reduction in the coverage of single-phase circuit topics in the spring Electric Power course which created space to include substation topics. Simultaneously, the graduate assistant started working on material for the substation design curriculum.

Fig. 1: Model of a substation

To illustrate the physical layout of a substation, the 1:87 (HO) scale model of a substation shown in Fig. 1 was acquired and assembled (Northern Light & Power Substation -- Kit , n.d.). The model, manufactured by Wm. K. Walthers, Inc., consists of a small substation with one incoming line (right) that goes through oil-insulated circuit breakers, circuit switches, and connects to the high-voltage side of a three-phase transformer. The low-voltage side then is split into three outgoing lines using a radial bus circuit breaker layout. Details such as gravel, a bucket truck, linemen, and control house were added to create a realistic visual.

The EET 641 Electric Power course, taught since 2016, already contained curriculum on three-phase circuits, three-phase transformers, and complex power which are relevant for substation design. The more rigorous coverage of single-phase circuits in AC Circuit Analysis in the fall semester opened up four weeks to cover the substation design curriculum in the Electric Power course in the spring semester of 2020. An overview of the substation design curriculum is shown in Table 1. Each week consisted of two days of lecture (50 minutes each) and one day of lab (110 minutes).

A textbook previously used as a reference in Electric Power was changed to being a required text for the course and was used to cover substation design topics as it contained chapters on generation, transmission, and distribution systems (Wildi, 2006).

Additional materials were also used as references for the curriculum. These materials included general information about substation design (Design Guide for Rural Substations, 2001), US power grid data (U.S. Energy Information Administration, s.d.), power demand studies (National Energy Education Development, s.d.), billing information (Understanding My Bill, s.d.), one-line diagrams, and PowerWorld examples (Glover, Sarma, & Overbye, 2012). Pictures of equipment and structures were also provided by Black & Veatch. The graduate assistant also created additional figures, one-line diagrams, graphs, and tables for the PowerPoint lectures. In addition, an Excel spreadsheet with calculations of voltage drop in a transmission line was created for Lab 2.

Table 1: Substation design curriculum

Week	Lecture topics	Description
Week 1	History of power systems	Thomas Edison versus Nikola Tesla
	Electric Power Systems	Overall view of generation, transmission, and distribution
	US electric power regions	How the US power grid management and regulation is divided
	Generation	Types of power plants
	Daily and yearly demand of energy	How energy demand varies throughout the day and the with the seasons
	Transmission and distribution	Power grid interconnections
	Technical requirements for power systems	Maximum allowable variation of frequency and voltage
	Power balance	How generating plants adapt to load variation
	Voltage levels	Voltage levels commonly used in the power systems
	General formulas for complex power	Apparent power, real power, reactive power, power factor, line-to-line voltage, line-to-neutral voltage
	Energy billing	How utility companies measure and charge its customers for energy consumption

	Lab 1	**Introduction to PowerWorld simulator**
Week 2	Substation Equipment	Disconnecting switches Circuit breakers Circuit switches Fuses Transformers Instrument transformers Capacitor banks Reactors Surge arresters Insulators Conductors
	One-line diagrams	How three-phase systems are represented with one-line diagrams
	Transmission line voltage drop	Dimensioning conductors for a transmission line
	Lab 2	**Power grid problem (Appendix A).**
Week 3	Circuit breaker arrangements	Single Bus Main and Transfer Single Breaker Double Bus Ring Bus Breaker and a Half Double Breaker Double Bus
	Black & Veatch guest speaker	Presentation of substation design projects
Week 4	**Power Grid Exam**	**Contained questions from theory, calculations, and simulator (Appendix B).**

As shown in Table 1, the first week of lectures introduced electric power systems by explaining how Thomas Edison and Nikola Tesla revolutionized the power industry. The power path from the power plant to the consumer was explained. This starting with a discussion on the different types of power sources and technologies of power generation. Then, it was followed by discussing the interconnected power transmission grid that carries power over long distances at high voltages. Finally, it was discussed how power is distributed by utility companies to the consumer.

The second week of lectures introduced the equipment in a substation, its function, and how it is represented in one-line diagrams. In addition, the concept of voltage drop over a transmission line was introduced. The effects of the voltage level, conductor size, and conductor material on the power loss in a transmission line was also explained.

Substation design topics discussed in the third week of lectures included circuit breaker configurations and a review for the exam. Due to the COVID-19 pandemic, the lectures were moved to online delivery for this week. The lecture on circuit breaker configurations showed the different circuit breaker layouts commonly seen in substations and explained the advantages and disadvantages of each.

Lab activities

A practical approach was used with lab activities using the PowerWorld simulator. PowerWorld is a simulation tool used to visualize and calculate power circuits including generators, transmission lines, distribution lines, and substations. The PowerWorld simulator can be used as a planning and monitoring tool of power grid or as an educational tool to visualize power systems theory (PowerWorld, n.d.).

The lab for the first week, Lab 1, was an introduction to one-line diagrams and the PowerWorld Simulator which gave students their first exposure to the software that would be used throughout the substation curriculum. The lab contained a step-by-step tutorial on how to create the small power grid shown in Fig. 2 and run a simulation. A free version of PowerWorld was used for the lab which had a limitation of up to 13 buses.

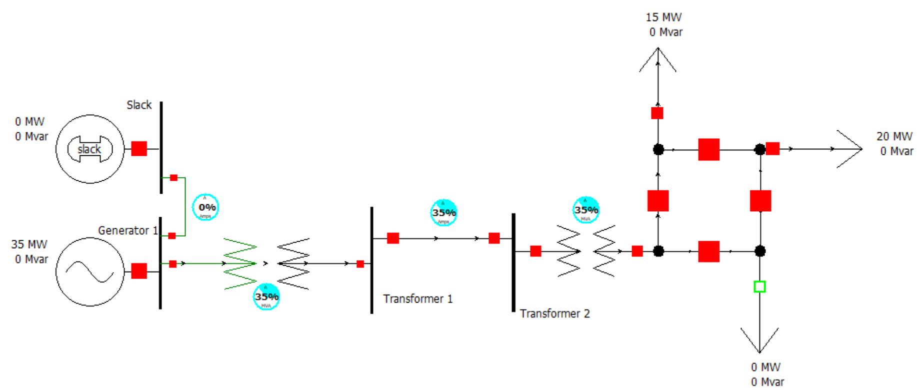

Fig. 2: One-line diagram from PowerWorld tutorial in Lab 1

The lab for the second week, Lab 2, is shown in Appendix A. Lab 2 presented a power grid problem in which students were asked to specify a transmission line and to design and simulate a power grid. Students had the option of using the PowerWorld software in their lab report. Due to the COVID-19 pandemic, Lab 2 was moved to online delivery. However, due to the use of a simulator in the lab, there was minimal impact.

The rubric in Table 2 was used to assess the effectiveness of Lab 2. The categories of the rubric were chosen based on skills that are most relevant to substation design. A goal of an average of 2.00 points was set for each category. Each student was assigned a point value for each category according to the rubric. The average number of points for each category were calculated and the results are shown in Table 3. Comments on the results for each category are also included in Table 3.

Table 2: Rubric used to evaluate Lab 2

Category	0 points	1 point	2 points (goal)	3 points (Met specifications)
Chose the appropriate breaker layout	Single Bus	Main and Transfer	Breaker-and-a-Half	Double Breaker Double Bus
Drew a one-line diagram	No diagram or totally incorrect	4 or more errors	1 to 3 errors	No errors
Chose appropriate conductor size	No conductor size specified	Conductor size did not match calculations	Voltage drop greater than 1% and less than 10%	Voltage drop less than 1%
Use of PowerWorld simulator (optional)	PowerWorld not used	3 or more errors	1 or 2 errors	No errors
Appropriate use of transformers	3 or more errors	2 errors	1 error	No errors

Table 3: Assessment of Lab 2

Category	Average Points	Comments
Chose the appropriate breaker layout	1.6667	This result shows a further need to concentrate on breaker layouts. This result may be skewed because single bus is not totally wrong, but the worst choice among the others.
Drew a one-line diagram	1.8889	The average is close to the goal, but still lower. This suggests a need for more practice with one-line diagrams.
Chose appropriate conductor size	1.7778	The lower average is most likely due to the complexity of calculations and the use of numerical methods to solve problems that students have not been exposed to previously. Early mistakes in calculations led to a choice of wrong conductor size.
Appropriate use of transformers	2.1111	The result for this topic was satisfactory and met expectations.
Overall average	1.8611	The overall average was calculated with the above required categories.
Use of PowerWorld simulator (optional)	1.2222	The use of the PowerWorld simulator was optional. The lower average shows that more work is needed to get students more comfortable with PowerWorld.

Exams

An exam on power grids was delivered online in the fourth week of the curriculum. The exam was originally scheduled for the week before Spring Break. Due to the COVID-19 pandemic, Spring Break at PSU unexpectedly started a week earlier and was extended to two weeks. The exam had to be rescheduled until after Spring Break. This may have affected student performance on the exam.

For further assessment of the effectiveness of the substation curriculum, the most relevant exam questions about substation design were identified and are listed in Appendix B. The goal for the class was to reach an average of 80% correct answers on these questions. After the assessment, the average number of correct answers for the class was found to be 95%. So, the goal for the class was met and exceeded. However, the lowest average points were recorded in Questions 3 and 4.

The instructions for Question 3 specified, “Check all answers that are true.” This format made the question more difficult than a multiple-choice question. In addition, all the answers were true which was probably disconcerting to the students.

The matching items in Question 4 that had the lowest averages were Potential Transformers, Lightning Arresters, Surge Arresters, and Relays. All of these components are related to monitoring and protection of a substation. This seems to indicate that these are topics need to be covered more in detail. There may also have been student confusion related to the similarity in the terminology used for the matching items, for example the difference between “Protection from electrostatic discharge” and “Protection from spikes of electricity.”

Conclusion

It was seen that new substation curriculum was developed and included in the EET 641 Electric Power course. The development of this curriculum was motivated by the needs of companies on the IAC who expressed a need for employees skilled in substation design. In addition to lectures and an exam, the new curriculum included labs using the PowerWorld simulator. Assessment results for the labs and exam showed that students learned the material and the new curriculum was effective overall.

Another benefit of the substation curriculum development was that the graduate student secured an internship at Black & Veatch where he worked in designing substations. He gained practical experience and when he returned to PSU, taught a one credit hour course covering more details of substation design. In addition, Black & Veatch offered five full scholarships to PSU students in the EET program in 2020-21 academic year.

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Appendix A: Power grid lab

Using the PowerWorld Introduction lab and our classes content, design a power grid using a one-line diagram that includes the generation, transmission, and distribution components.

You may use the PowerWorld software or draw the power grid by hand. If you choose to draw it by hand, make sure your drawing is organized and easy to understand.

Calculations and drawings must be included in this Word document or submitted on paper.

Make sure you use phasors in your calculations.

You will be designing a grid for Mayer Island that is isolated from the rest of the world. There is one power plant in this island and a city called Shark City that is 160 miles away from the generator in a straight line.

Your design should include three substations: one substation connects the generator to a transmission line, one substation connects the transmission line to industrial loads (see below), and the other substation will connect the transmission line to residential loads (see below). Keep in mind that a bus can have more than one connection.

The residential loads consist of four neighborhoods that have a consumption of 20 MVA at a power factor of 0.95 inductive. Each neighborhood consumes 5 MVA and should have its own branch from the substation.

The industrial loads consist of three industrial plants. Each plant has a consumption of 20 MVA at a power factor of 0.90 inductive and should have its own branch from the substation.

The voltage drop between the generator and load substations should be less than 1%. Use Table 1 to choose the conductor size and material for your transmission line. In a case of a fault, the substations should be able to provide power to all other loads and isolate the fault.

Table 1

Conductor Size		Resistance at 75C [ohms/km]		Ampacity [A]		Price (USD/km)	
AWG	mm^2	copper	ACSR	copper	ACSR	copper	ACSR
10	5.3	3.9	6.7	70	--	$820.21	--
7	10.6	2	3.3	110	--	$1,312.34	--
4	21.1	0.91	1.7	180	140	$2,395.01	$492.13
1	42.4	0.5	0.9	270	200	$4,855.64	$656.17
3/0	85	0.25	0.47	420	300	$9,645.67	$1,607.61
300 kcmil	152	0.14	0.22	600	500	$18,044.62	$2,755.91
600 kcmil	304	0.072	0.11	950	750	$24,606.30	$5,905.51
1000 kcmil	507	0.045	0.065	1300	1050	$32,808.40	$9,317.59

Make sure you describe your design by showing power, voltages, and currents.

For your generators:

- Use any nominal voltages of 69 kV, 13.8 kV, or 6.9 kV.
- Make sure you draw all your circuit breakers.
- Make sure you define how much power the generator must provide in MW and Mvar.
- Do not use slack generators. Assume your loads have no variation. You must match your total generation power to your total load power.
- Assume a three-phase balanced system.

For your transmission line

- Use any nominal voltage of 115 kV, 345 kV, or 500 kV.
- Make sure you include transformers in your drawing.
- Make sure you include circuit breakers for each side of your transformer.
- Use may use the PowerWorld lab report as a reference.
- Make sure you identify your transmission line nominal voltage in kV.
- Make sure you identify your transformer primary and secondary voltages in kV.
- Design your transmission line for a maximum voltage drop of 1% at the distribution side by balancing price, voltage level, and material properties between copper and ACSR (aluminum conductor steel-reinforced cable). Use the Table 1 for prices and material impedance.
    - Example: if you define your generation side at 69 kV and your transformer's secondary side at 765 kV, the minimum voltage allowed to comply with 1% voltage drop at the distribution side is 757.35 kV. That means you will have 765 kV at the beginning of your transmission line and 757.35 kV at the end of your transmission line.
- Make sure you use line-to-line voltage and three-phase power in your drawing's information.
- Use line-to-neutral currents in your drawing's information.
- Assume you have ideal transformers.
- Using the information on table 1, calculate how much it would cost using copper or ACSR to have a maximum voltage drop of 1%. Calculate both scenarios and make a comparison.

For your distribution side

- Use any of the following circuit breaker combination
    - Single Bus
    - Main and Transfer
    - Breaker-and-a-Half
    - Double Breaker Double Bus
- Use the following voltage levels:

    - Residential area: 120 V line-to-neutral
    - Industrial area: 6.9 kV line-to-line
- Your choice of circuit breaker layout should match your number of loads.
- Make sure you identify each load MW and Mvar

Appendix B: Sample Exam Questions

Question 1.

According to the lecture in class, describe the path energy flows from generation to the final consumer. (Multiple choice)

A. Power Plant -> Step up transformer -> Transmission Line -> Step up transformer -> Load
B. Power Plant -> Step up transformer -> Transmission Line -> Step down transformer -> Load
C. Power Plant -> Step down transformer -> Transmission Line -> Step down transformer -> Load
D. Power Plant -> Step down transformer -> Transmission Line -> Step up transformer -> Load

Question 2.

[Select: 6.9 kV, 220 V, 115 kV, or 13.8 kV] is commonly used in long distance transmission lines while **[Select: 69 kV, 120 V, 115 kV, or 745 kV]** is most likely to be used on the generation side. Also, **[Select: 69 kV, 120 V, 115 kV, or 13.8 kV]** is commonly used for residential supply while **[Select: 345 kV, 120 V, 115 kV, or 13.8 kV]** is commonly used by industrial customers.

Question 3.

Directions: Check all answers that are true.
According to the textbook, which statements are true about power systems?
The system must...

a. Maintain a stable, nominal voltage that does not vary by more than 10%
b. Maintain a stable frequency that does not vary by more than 0.1 Hz
c. Meet standards of safety
d. Supply energy at an affordable price
e. Provide, at all times, the power that consumers need

Question 4.

Match the statements from the left column with the right column below

1. Disconnect Switches
2. Circuit Breakers
3. Transformers
4. Buses
5. Potential Transformers
6. Current Transformers
7. Lightning Arresters
8. Surge Arresters
9. Relays

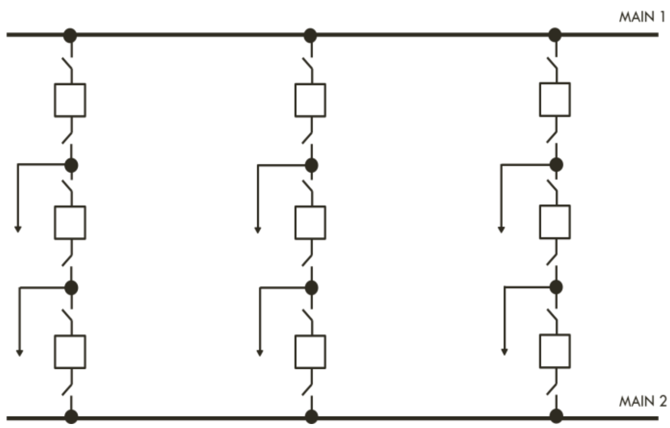
a. Used to have a visual confirmation that a circuit is disconnected and de-energized
b. Can use an air blast or an internal insulator such as a vacuum, oil, or SF6 to extinguish an electric arc.
c. Used to step-up or step-down voltages
d. Flexible or rigid conductors
e. Used for voltage measurements
f. Used for current measurements
g. Protection from electrostatic discharge

10. Grounding

h. Protection from spikes of electricity
i. Protection devices that constantly monitor the grid
j. Low impedance wiring used to keep the exterior of equipment at a safe potential

Question 5.

Which breaker layout is shown in the figure below?



A. Single Breaker Double Bus
B. Ring Bus
C. Breaker and a Half
D. Double Breaker Double Bus
E. Main and Transfer

Question 6.

According to the figure below, which breaker should I open first in order to open SW15?

Note: Only type in the number of the breaker (1, 2, 3, etc.)